Manufacturing processes for free-form optics

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ABSTRACT

Off-axis and “freeform” optical surfaces are in increasing demand. Such surfaces introduce additional degrees of freedom into the optical design optimisation, leading to simpler systems with fewer components and better performance. Key applications demand off-axis aspheres, the segmented astronomical telescope being one. The next generation of extremely large telescopes in the 30-40m aperture range will require many hundreds of hexagonal aspheric segments, each in the 1 to 2m size-range. Such ambitious applications, together with smaller parts for the defence and other industries, are driving the development of novel fabrication processes. This paper focuses on the *Precessions* CNC polishing and grolishing process for off-axis and freeform surfaces. It is hoped that the new techniques we describe will stimulate optical designers to be more ambitious in the designs they originate.

We fist review the way surfaces are described and the relationship to metrology, and to the data-input for the polishing machines. An outline of how the process can ‘polish’ a ground freeform part (improve the texture), and then ‘figure’ the part (reduce the form errors) is given. We also describe how the process has been moderated to remove tens of nanometres of stock material, rather then the more usual hundreds of nanometres and upwards as in the standard *Precessions* process. The relevance of this to improving the ultimate surface-precision that should be achievable by this method is described. As a final illustration, the potential of the process to the rapid fabrication of the hundreds to thousands of 1-2 metre class mirror segments required for extremely large telescopes is considered.

1. Introduction

The *Precessions*™ CNC polishing process has been described extensively in the literature (e.g.[1-9]) at various stages during its development. We summarize the operation of the process as follows. The *position* and *orientation* of a spinning, inflated, membrane-tool (the “bonnet”) are actively controlled as it traverses the surface of a part. The part’s surface may be any general form, including concave, flat, or convex, asphere or free-form.

A classical polishing tool is pressurized against the surface of the part, usually by the force of gravity acting on the tool’s mass, with no attempt to control actively the Z position of the tool in a local or global coordinate frame. In the technique we describe, the Z position and orientation (but not directly the contact-force) is actively controlled with a CNC machine tool. This provides seven CNC-controlled axes: tool X,Y,Z and two axes of rotation for the tool, plus the tool and part rotation.

The process may be configured to remove a constant layer of material to preserve the input form whilst improving texture and removing sub-surface damage. The part may typically have been taken off a previous precision aspheric grinding machine, although parts from coarser processes such as traditional generating can also be handled. The second stage of the process corrects the form, given a measurement of the absolute form or form-error, and experimental measurement of the tool’s foot-print (or, ‘influence function’, as it is called).Then, , a numerical optimization is performed to determine the dwell-times required across the surface, and these are implemented by changing the traverse-speed along a pre-determined tool-path.

The surface of the bonnet will tyically be covered with a standard polyurethane or Multitex pad, and for final smoothing it can be desirable to dress the pad with pitch. Slurries are temperature-controlled and re-circulated, and would usually be cerium or aluminium oxide. A new hybrid process between polishing and grinding has also been developed for bulk material-removal – ‘*grolishing*’[10]. Several different techniques are in use including:

- 3M Trizact ™ on a bonnet
- Bonded diamond pellets on a bonnet
- Metal pads on a bonnet, used with loose abrasives such as carborundum slurry, or diamond paste/slurry.

2. Process Flow

The process flow is shown in Figure 1.

On the right is the off-line preparation of the machine for a series of parts, and on the left the processing of a part itself. It is assumed for illustration that a previously unused bonnet is selected. This is mounted on the machine's Schunk chuck and inflated. Using the A and B rotary axes, the bonnet is machine true to a spherical form with its centre located at the virtual pivot of the machine. Machining is performed using either a fixed single-point tool or a small grinding wheel on a separate motorized spindle. The cloth is pressed into a mould to take the spherical form of the bonnet, then cemented in place. The bonnet is re-mounted and the cloth trued-in as before. The next stage is to determine the absolute radius of curvature of the bonnet/adhesive/cloth system. The machine is furnished with a precision ball mounted on a shaft that locates in the Schunk chuck that holds the part. This is used to probe the surface of the bonnet in an automated procedure.

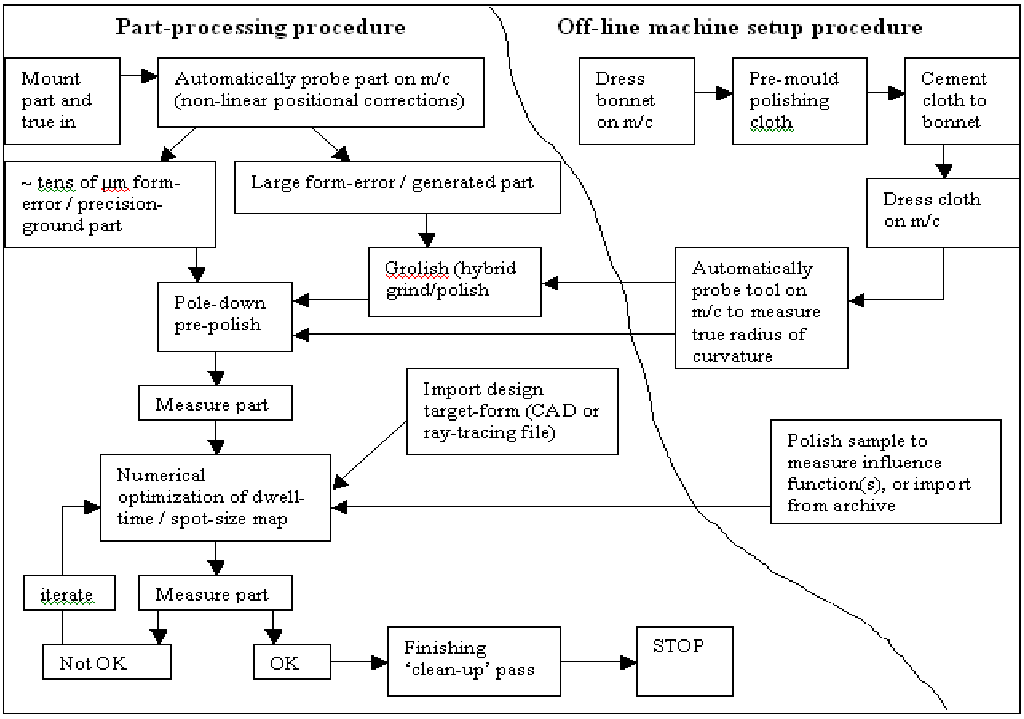

Figure 1. Process flow (part-processing and off-line setup).

Finally, one or more influence functions (off different sizes) are required as input to the form-control algorithm to characterize the footprint of the tool. These may be polished on a witness sample of the same material as the part to be worked. More often, archived influence functions will be used as the process has proved highly stable.

The software provides the capability to introduce a scaling factor, so that a first pass can be taken with a conservative removal rate, the part measured, and the scaling factor optimized for subsequent runs.

Regarding the part, this is mounted in a fixture and (depending on the mounting method) trued in using e.g. a dial-gauge. Typically small parts will be waxed to a holder that fits the Schunk chuck. The bonnet is then automatically traversed across the part and, by virtue of its in-built sensor, used to probe the part's surface in machine coordinates. The results of the probing provide a correction file to the machine CNC programme.

For parts requiring large depths of material removed (generated surfaces; aspherising a spherical surface), the next stage is to "grolish" the surface using a pole-down grolishing tool such as described above, which can deliver high removal rates. If the surface form and texture is already reasonable (e.g. parts of a precision aspheric grinding machine), the part can be directly "pre-polished" using the pole-down polyurethane tool.

After pre-polishing, the part is measured using (depending on its characteristics) a profilometer, interferometer, coordinate measuring machine etc. The measurement, the design-form, and the influence function data are input to a numerical optimizer ("*Precessions*") that computes the optimum dwell-time and spot-size map. Most frequently, it has proved satisfactory to maintain spot-size constant. After another measurement, the process can be either terminated or iterated (often using a smaller spot).

2. Surface prescription and metrology

The form-control algorithm performance can only be as good as the quality of the input metrology data, and so the integrity of this data is paramount, particularly as it relates to the machine coordinate frame.

In traditional craft-based polishing, the optician manually makes the connection between a point on an interferogram and a point on the physical surface at the time of measurement. This can conveniently be done by marking the part with a felt pen whilst watching the interferometer image, in order to guide the optician's small tool to the high zones. This technique is insensitive to geometric distortions between the surface of the part and the data recorded by the interferometer. The same is not true of an automated small-tool polisher. In this case, if an incorrect assumption is made regarding the geometric relationship between part-surface and test-data, the machine may well focus its polishing action adjacent to a high zone, rather than to a peak itself. This error can convert a single zonal error into a double peak/trough with twice the spatial frequency. Such degradation of the surface can be considerably more difficult to remove in a subsequent operation.

Different metrology devices behave differently with respect to their geometric properties; three examples are given below.

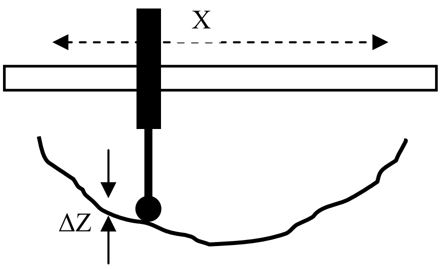

Figure 2. Metrology with linear profilometer.

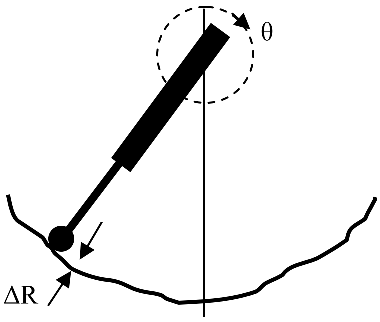

Figure 3. Metrology with swing-arm profilometer.

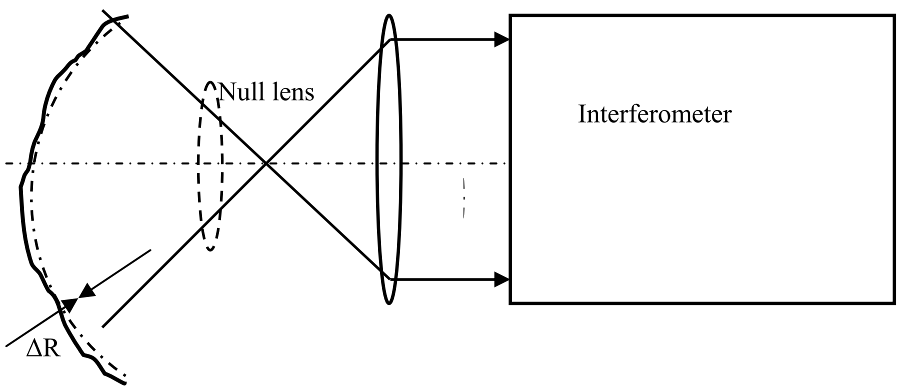

Figure 4. Metrology with a standard interferometer.

1. A linear scanning profilometer (Figure 2) uses a probe (contact or non-contact) which traverses the part in a straight path (usually a diameter) orthogonal to the axis of the part. The vertical displacements ΔZ of the probe-tip with respect to the mechanical datum in the instrument are then measured by the probe. Such instruments provide direct rectangular X-Z coordinates of a traverse across the surface, and the data is effectively a *projection* of the surface onto the XY pane. This method breaks down for surfaces with severe surface slopes, a hemisphere being an extreme case of particular interest for missile domes.

2. In a swing arm profilometer (Figure 3), the arm rotates in (typically) a precision air-bearing, and about a point in space which is usually adjusted to be the centre of curvature of the part's surface. The measurement process is then in polar coordinates, and lateral distances are measured *along* the surface itself (or more correctly, along the sphere defined by the axis of rotation of the arm). "Height" displacements recorded by the probe are measured along the *radial* direction.

3. An interferometer (Figure 4) set up with a transmission sphere is, from a geometric point-of-view, very similar to the swing-arm profilometer, as the datum for measurement is a spherical wavefront. The data is similar to the swing-arm in that lateral measurements are effectively *along* the reference sphere (effectively along the surface) and "height" is again in the radial direction .

There are two main sources of errors in interpreting interferometer data in the context of a machine-tool based on Cartesian coordinates. The first is the 'mapping problem' projecting a sphere onto a plane. If the plane is pixilated with equal areas and these are projected onto the sphere, the equal areas can not be conserved on the sphere. The second originates in the use of a transmission sphere with the interferometer, as this will exhibit its own Seidel geometric distortion term, as a result of the ray-tracing optimization used in its design (which will tend to favour minimizing wave-front rather than geometric distortions). Ideally, the entire system comprising interferometer, test part and any other optics such as a null lens would be ray-traced in order to compute the precise geometric distortion. As interferometer vendors will not release their lens-prescriptions, the only solution would appear to be a empirical geometric calibration of the distortion term.

In the case of the Zeeko polishing machines, software utilities have been written for different metrology devices encompassing profilometers and interferometers, in order that the correct geometric relationships can be established.

3. Corrective polishing of an 80nm depth by rastering

In this experiment, the part was a 100mm nominal diameter silicon disk. A circular depression had previously been polished with a wedge of ~ 15nm. The part was rastered to remove an average 80nm depth of material and correct the wedge by dwell-time control (implemented by feed-rate moderation). Figure 5 shows the part before this corrective run, and Figure 6 after the corrective run. The vertical scale in both cases is 0-1 micron. Figure 7 shows the same data as Figure 6, but with the peripheral land removed and the height re-scaled. The vertical scale is 0-1.5 microns. The absolute depth of material removed was as predicted at the level of 5nm.

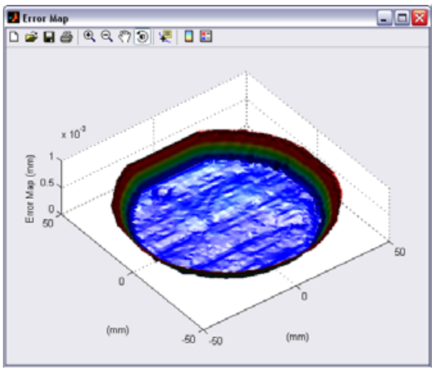

Figure 5. Wedged surface before corrective polishing.

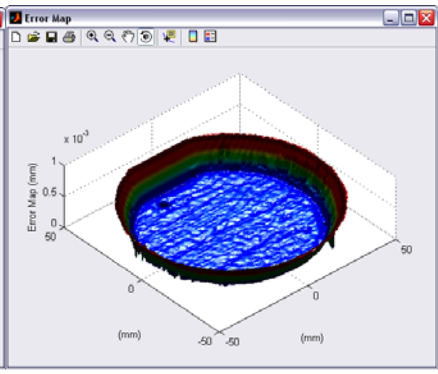

Figure 6. Wedged surface after one run of corrective polishing.

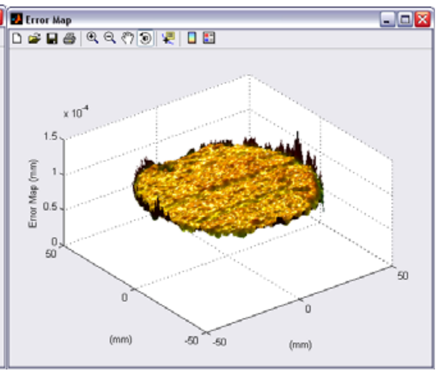

Figure 7. Same data as Figure 6 but trimmed and expanded.

4. Selective polishing of raised lands by rastering

Polishing of selective areas on a part is relevant where there are features to be preserved, and others which should be polished. The example shown in this section is not an optical surface, but demonstrates how complex surfaces can be selectively polished. The artifact is a steel die used to make coins, which has been polished using the Zeeko 200mm machine. The die is made convex in order that the pressed coin will be flat. It was important to control round-off of the depressions in the die (features which create the raised features on the pressed coins).

A CAD file of the die was not available, so the die was scanned in 3D (Figures 9) on a Form Talysurf. The data was then imported into the ZeeCAD software, and a threshold applied to define those areas to be polished (the coloured areas in Figure 9). The tool was rastered across the surface, and automatically raised and lowered to skip the areas not requiring polishing.

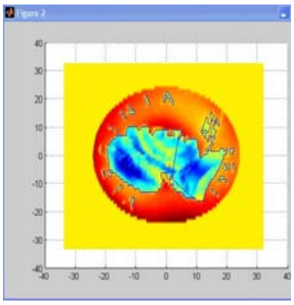

Figure 8. Form Talysurf scan of coin die.

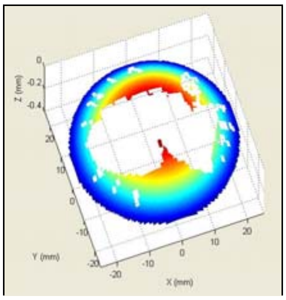

Figure 9. Thresholded digitized data.

Since the part was in a good condition (excepting traces of corrosion), a blue telum resin cloth was used for the first polishing run. Whilst a 20mm radius bonnet would have been ideal, the 40mm was used as this cloth would not adhere adequately to the tight curvature of the smaller bonnet. It followed that bigger spot sizes than originally planned had to be used, specifically, a 6mm spot. A 15 minute polishing run improved the surface texture from 300 to 35 nm Ra.

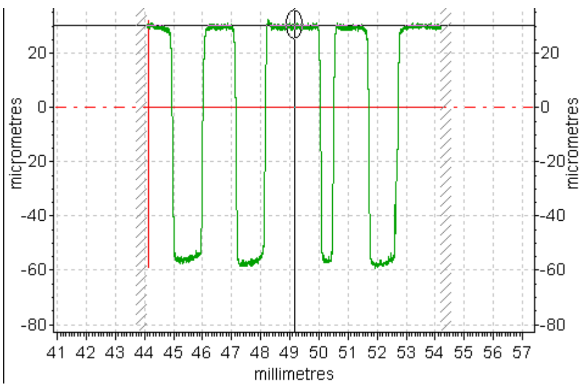

Figure 10. Scan of die before polishing showing edge-sharpness of features.

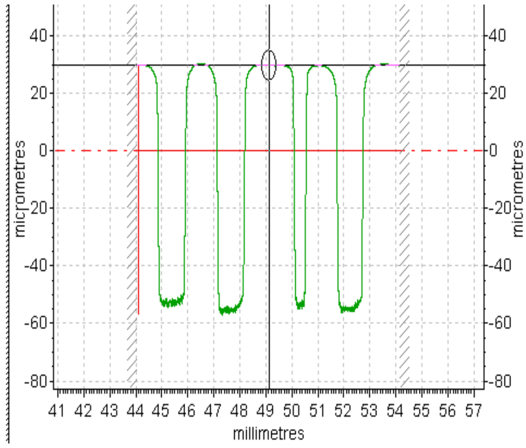

Figure 11. Scan of die after polishing showing level of preservation of edges.

Figures 10 and 11 show the preservation of the edge-features achieved by the selective polishing method. The edge-roll is minimal. A second polishing run improved the texture to 16nm Ra and *no additional rolling of the edges was observed*. This is shown in the detailed scans of one edge-feature: Figure 12 (after the first run), and Figure 13 (after the second run).

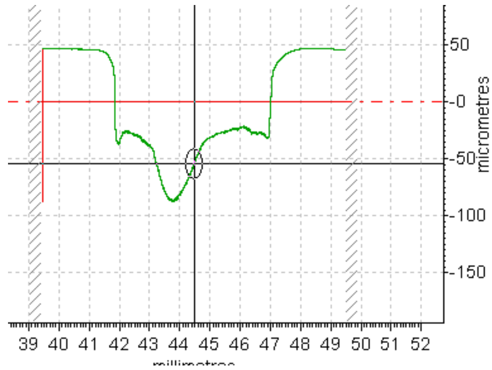

Figure 12 Detailed edge-scan of one of the features from Figure 11, before the second polishing run.

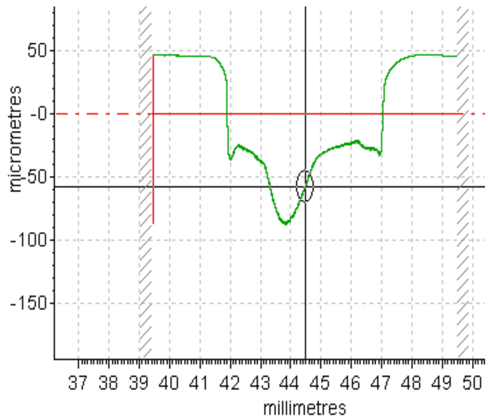

Figure 13. The same feature as Figure 12, but after the second polishing run.

5. Raster-polishing a section of a knee joint using a CAD file

This experiment concerns improving texture on a truly free-form surface by precisely tracking the tool-path around the complex surface. Specifically, the sample was not optical, but half the top section of a knee-joint implant, covering an area 25x50mm. This area was raster-polished (not rotated) in two runs, with the aim of achieving the best surface texture to improve service-life. An IGES CAD file of the part was available, which was imported in the *Precessions* Software.

Figure 14. Left area not polished, right area after polishing.

The first run was performed using a self-adhesive diamond bonded nickel cloth; subsequent runs used diamond bonded resin cloths supplied by Kemet International. Water was used as a coolant.

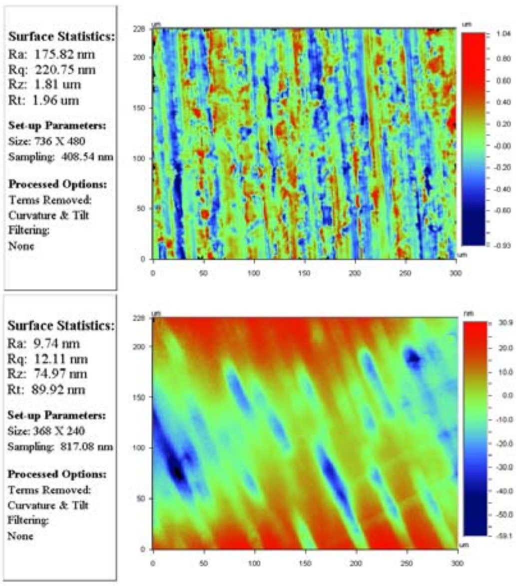

Figure 15. Surface Texture 175nm before, 10nm after the two polish runs.

6. Polishing of an arbitrary pre-defined complex form

The experiment reported here has been summarized elsewhere[10], and illustrates the capability to polish an arbitrary profile into a surface.

An example of where this is important is when the end-to-end wave-front-aberration of an optical system is measured after system-integration. The aberration will typically have some regular features such as power, spherical aberration or astigmatism, superimposed upon which may be irregular features. These can originate in local figuring errors, or in-homogeneities in optical glass in transmission. Given such a measurement, the inverse error can be polished into a single optical surface located near to a pupil plane. This can considerably improve image quality for narrow-field instruments, although its application to wide fields depends on the correction being applied in a pupil-plane. An historical example of this was the hand-figuring of one lens element in the Ultra High Resolution Spectrograph for the Anglo Australian Observatory[11], to compensate for measured end-to-end system aberrations. The design resolving power of $R \sim 10^6$ would have been extremely difficult to achieve otherwise.

The experiment in automated free-form figure control reported here was conducted on the convex surface (R=97mm) of a spherical lens of 88mm diameter. Firstly, the intensity-map in an image, as represented in a .bmp bitmap file (Figure 16), was directly converted into a map of surface height-error. This synthetic error-map was then imported into the *Precessions* 3D optimizer software. The code computed the dwell-time map to imprint the inverse of the error into the surface, based on a pre-specified raster tool-path and an imported influence-function.

The predicted result is shown in Figure 17. As usual, the dwell-time map was executed by the machine as a speed-moderation of the continuous path along each raster-track. Two crossed raster tool-paths were run on the part, with the dwell-times being shared equally between them (requiring double the traverse speeds compared with the original optimized values). The total polishing time (both traverses) was 20 minutes, and some 300nm of material was removed.

The representation of the original bitmap image imposed onto the surface topology of the lens is essentially perfect, within the spatial-frequency filtering imposed by the near-Gaussian influence function. The annular fine structures on the Zygo image (Figure 18) are relics of surface zonal errors in the original part.

Figure 16. Original bitmap image.

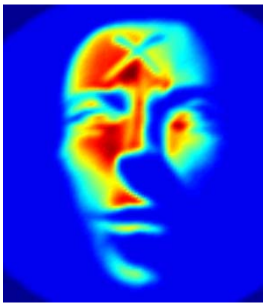

Figure 17. Resulting surface-map as predicted by optimiser.

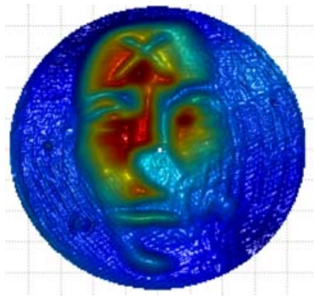

Figure 18. Raw Zygo image of resulting polished surface.

7. Application to Extremely Large Telescopes

The next generation of extremely large telescopes ("ELTs") are currently planned to be in the 30m to 40m diameter class – in the USA the Thirty Metre Telescope (TMT) is being built, formerly called the Californian Extremely Large Telescope (CELT). This adopts a classical Ritchey Chretien 2-mirror configuration[13]. It is intended that the aspheric primary segments will be produced [14] using the stressed-mirror technique. Essentially, the mirror is deformed in a pre-calculated way, polished spherical, then relaxed to the aspheric form. Elasticity considerations limit the asphericity that can be achieved without endangering the integrity of the mirrors. The primary is therefore to operate at the rather the conservative value of f/1.5[13]. Residual hysteresis in the mirror substrates limits the form-precision achieveable, and the mirrors will therefore require final correction e.g. by ion-figuring.

In Europe, the European Southern Observatory has widely published plans for a highly ambitious 100m aperture telescope using spherical segments together with a complex spherical-aberration corrector (the "Overwhelmingly Large Telescope")[12]. This has recently been de-scoped to the current 42m "European Extremely Large Telescope (E-ELT), having aspheric segments. At the time of writing, ESO is tendering for seven prototype segments.

One of the key science drivers is the detection of earth-like planets around other stars, and these planets may be on the order of 10^8 times fainter than the parent star. Without special techniques, the light of the star would dominate that of the planet, given the dynamic range and signal-to-noise ratios deliverable by current (or even planned) detectors. The innate quality of the telescope optics (surface-form and edges) becomes paramount, in terms of the point-spread-function delivered and the near-field and far-field stray light.

The challenge of rapid fabrication of fast off-axis aspheric segments is being addressed in the UK by a consortium led by UCL and Cranfield University, of which Zeeko Ltd is a part. This consortium is building a pilot segment fabrication plant at the OpTIC Technium in N. Wales. The facility has a nominal 1m size capability, and is being used to demonstrate an alternative process-chain. Zeeko Ltd has supplied a 1.2m CNC polishing machine delivering Zeeko Classic bonnet-based polishing, the hybrid grolishing process, and fluid-jet polishing. Cranfield has built a 1m-class ultra-precision grinder, and a Reactive Atomic Plasma Technology machine is under construction.

The results presented in this paper provide important steps to the full implementation of segment fabrication at the 1-2m scale. In particular, the ~5nm precision of removal shown in Section 3 provides confidence that the basic processes are under control at the required level. The selective polishing of Section 4 provides a key part of the solution to controlling the edge and corner profiles of the hexagonal segments. The algorithms for raster polishing of complex surfaces in Section 5 provide the control-tools for tracking the form of an off-axis segment. Finally, the ability to remove material following a complex local-prescription, and on a curved surface as in Section 6, provides the capability to control form errors that are complex in their spatial extent.

7. Conclusion

We have described the *Precessions* process and the specific process-flow for machine-preparation and for processing a part. The need has been highlighted of maintaining a consistent coordinate frame between the metrology data-set and the CNC positioning of a localized polishing tool (whatever the physical process by which it removes material). This has been illustrated by comparing an interferometer with swing-arm and linear profilometers.

This paper has shown the ability of the *Precessions* process in several important regimes that are crucial to ambitious projects such as manufacturing the segments for extremely large telescopes. Moreover, ability to polish arbitrary forms, and impose or remove complex local signatures with an unprecedented level of versatility, should stimulate optical designers to explore new design concepts for more down-to-earth applications.

8. Acknowledgements

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