New developments in the Precessions process for manufacturing free-form, large-optical, and precision-mechanical surfaces

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ABSTRACT

The recent upsurge in the demand for off-axis and complex "freeform" optical surfaces is driving the development of novel processes for their fabrication. This paper focuses on recent developments of the *Precessions* CNC polishing process for freeform surfaces, including off-axis as a special case. First, the surface-prescription and metrology-data, and their relation to the data-input for the polishing machines, are considered. The relevance of consistent coordinate frames is emphasised. 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. Specific experimental case-studies are then presented, illustrating the versatility of the process on different materials and forms.

Recent work is included in which the process-speed has been moderated in order to remove tens of nanometres of stock material, rather then the more usual hundreds of nanometres to tens of microns 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 in three dimensions as it moves over the surface of a part. The part's surface may be any general form, including concave, flat, or convex. Moreover, it may be a rotationally-symmetric or off-axis asphere, or a true freeform. It is worth noting that in traditional polishing the 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 motion of the tool may be programmed to remove a constant 'skin' of material. If correctly set up, this will preserve the input form whilst improving texture and removing sub-surface damage. The input quality may typically be a part off a previous precision aspheric grinding operation, although parts from coarser processes such as traditional generating can also be handled. Alternatively, the form of the part can be corrected, given a measurement of the absolute form or form-error, and empirical measurement of the tool-s influence function. In this mode of operation, a numerical optimization is performed to determine the dwell-times required across the surface.

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Standard polishing consumables are used. For example, the surface of the bonnet will be covered with a 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. Recently[10], the process has been extended to bulk material-removal by '*grolishing*'. This is a new hybrid process between polishing and grinding. It uses an array of small diamond tiles on a flexible membrane, which is attached to the surface of the bonnet. 3M "Trizact", and 3M resin-bonded diamond have been successfully used.

2. PROCESS FLOW

The process flow is shown in Figure 1. This is divided into two parts – 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. On the preparatory side, 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 virtual pivot motions, the bonnet is trued-in to a spherical form centred on the virtual pivot of the machine, using either a fixed single-point tool or a small grinding wheel on a separate motorized spindle. The cloth (typically polyurethane or Multitex) 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.

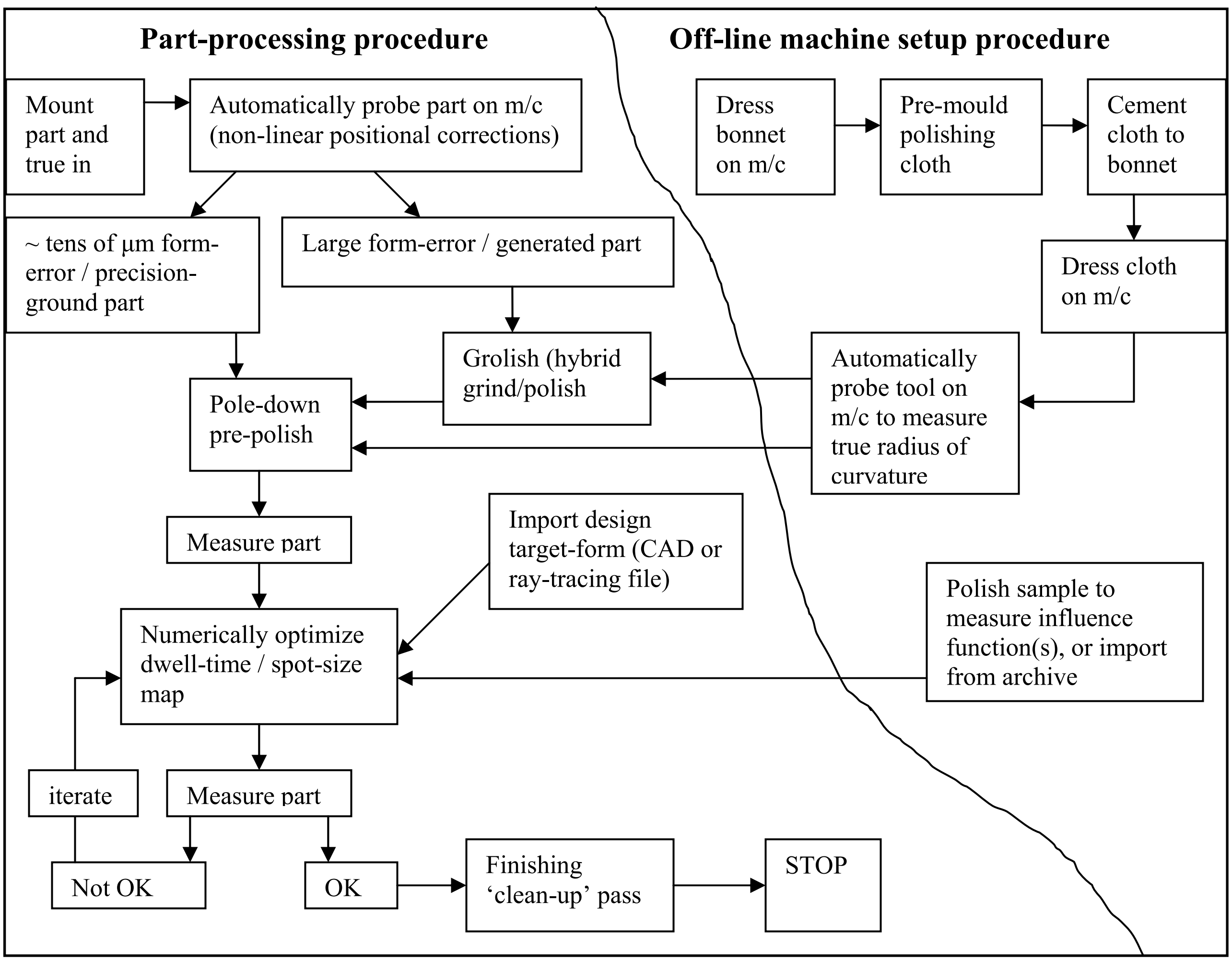

Figure 1 Process flow (part-processing and off-line setup)

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 bonnet covered with diamond pellets instead of polishing compound. This delivers high removal rates. If the surface texture 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.

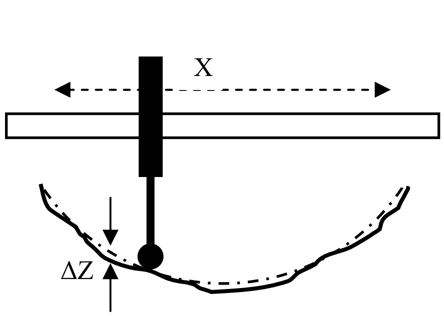

Figure 2 Metrology with linear profilometer

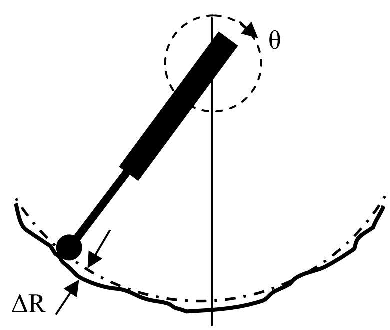

Figure 3 Metrology with swing-arm profilometer

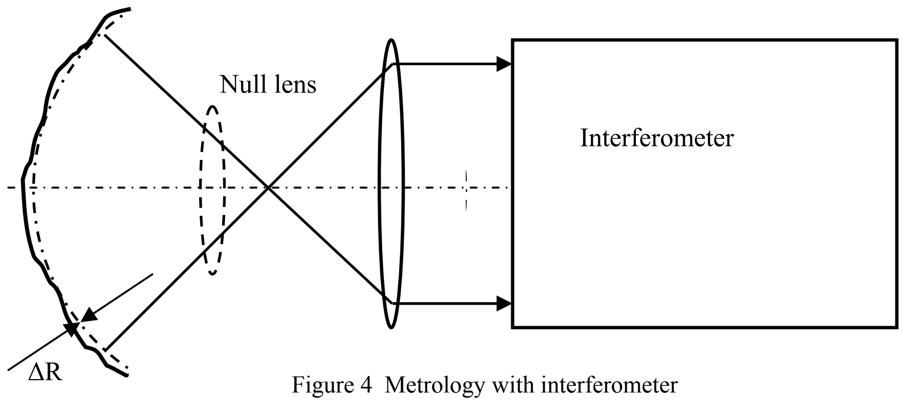

Figure 4 Metrology with interferometer

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.

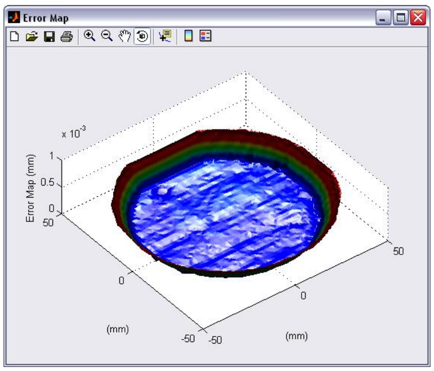

Figure 5 Wedged surface before corrective polishing

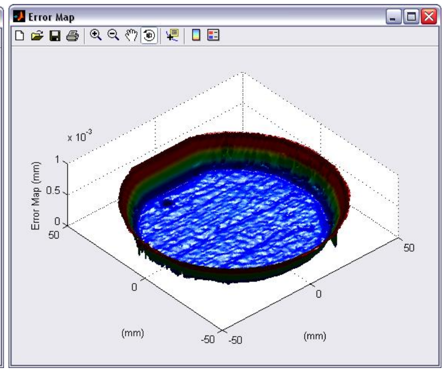

Figure 6 Wedged surface after one run of corrective polishing

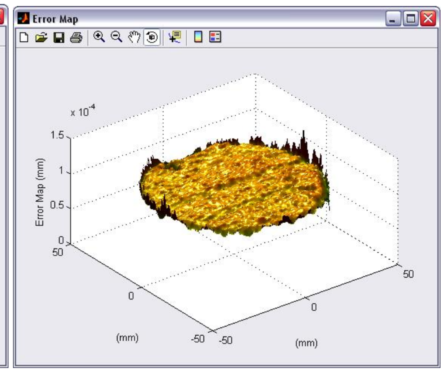

Figure 7 Same data as Figure 6 but trimmed and expanded

4. SELECTIVE POLISHING OF RAISED LANDS BY RASTERING

Polishing of selective areas on a part is relevant where there are features which must be preserved, and others which should be polished. A typical case would be addressing the edge of the part, or the boundary of a perforation (such as a Cassegrain primary mirror). If the tool simply passes over the boundary, it will become rounded.

The example shown in this section is not an optical surface, but demonstrates how complex surfaces can be selectively polished. The artifact (Figure 8) is a steel die used to make coins, which has been polished using the Zeeko 200mm machine in work commissioned by a national mint. The die is made convex in order that the pressed coin will be flat. It was important not to round off 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 (Figures 9, 10) on a standard domestic scanner. The digitized data was imported into the Zeeko software ("ZeeCAD"). This was used to create a tool path (Figure 11) which rastered across the surface, and which raised the tool when encountering the boundary of the depression and lowered it at the other side.

Figure 8 Die face prior to polishing

Figure 9 Coin-die face-down on domestic scanner

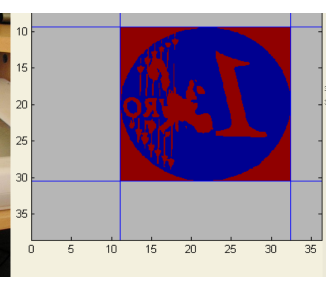

Figure 10 Scanner image

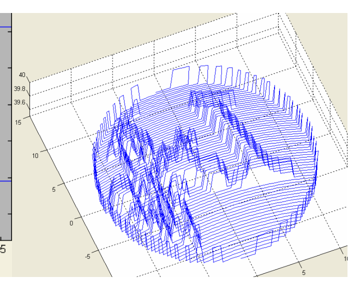

Figure 11 Tool-path over curved surface showing lift-off regions

The texture (Ra) of the polished stainless steel die surface was measured using a Form Talysurf (Figure 12). Results were 13.5 nm with a 0.25mm spatial-frequency cutoff, and 8.9 nm with a 0.08mm cutoff (Figure 8).

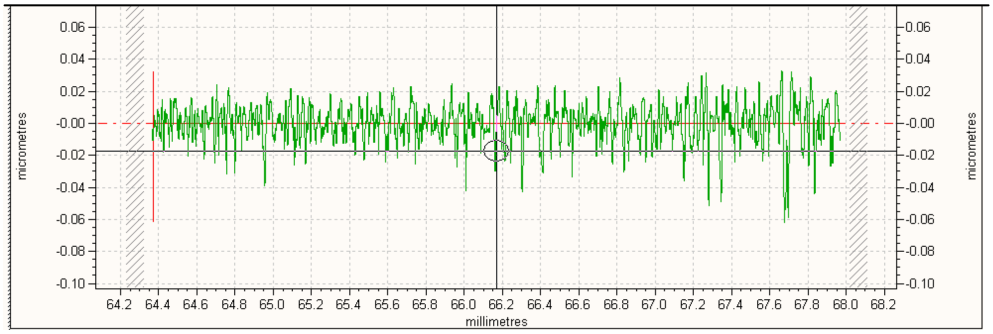

Figure 12 Form Talysurf scan of surface of stainless steel die after polishing with Zeeko IRP200

5. RASTER-POLISHING OF A TORROIDAL RING FROM A CAD FILE

In this experiment, one side of a narrow platinum torus (Figure 13) some 35mm diameter was raster-polished (not rotated) in four runs. The first two runs were performed by using self-adhesive MSF polishing pad on a 40mm bonnet, with 3 micron diamond paste. The third and the fourth run were performed by using the pad with 0.5 micron diamond paste. Polishing pads, diamond pastes and lubricating fluid were supplied by the Kemet International. The process converge well, (Figure 14) achieving 4.5nm Ra after a total polishing time of 20 minutes.

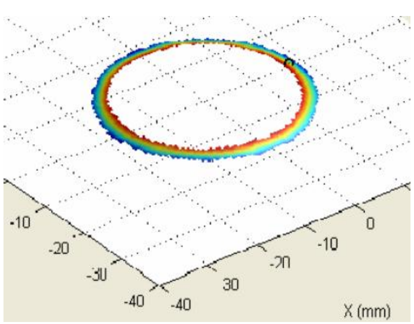

Figure 13 CAD model of platinum torroidal area to be polished

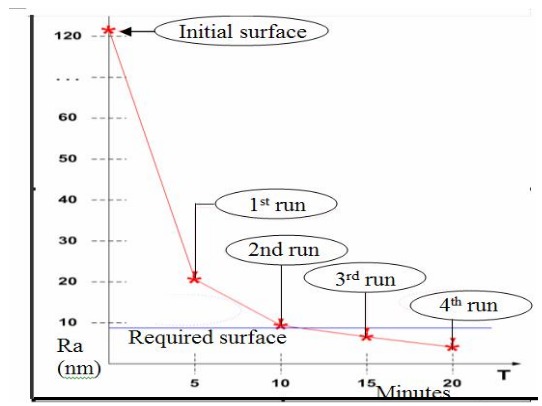

Figure 14 Progression of surface texture (Ra) over four polishing runs

6. POLISHING OF AN ARBITRARY PRE-DEFINED COMPLEX FORM

Figure 15 Original bitmap image

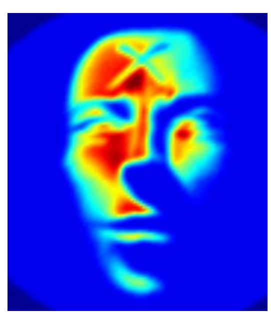

Figure 16 Resulting surface-map as predicted by optimiser

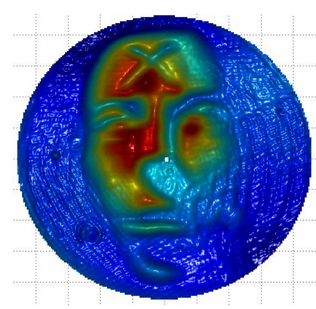

Figure 17 Raw Zygo image of resulting polished surface

The experiment reported here was recently summarized elsewhere[10], and illustrates the capability to polish an arbitrary profile into a surface. An example of where this could be 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 inhomogeneities 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 of view is obviously more limited. An historical example of this was the hand-figuring of one element in the Ultra High Resolution Spectrograph for the Anglo Australian Observatory[11], where 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 15), 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 16. 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 17) are relics of surface zonal errors in the original part.

7. APPLICATION TO EXTREMELY LARGE TELESCOPES

The next generation of extremely large telescopes ("ELTs") are planned to be in the 30m – 100m diameter class. 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. One technique for preferentially attenuating the star light is by using a 'coronagraph'; that is, by creating an artificial eclipse. In this case, a physical obstruction in the focal plane of the telescope is used to prevent the star-light entering the imaging instrument and detector system. Unfortunately (and unlike a natural eclipse of the sun), the stray light generated within the telescope is not rejected by a down-stream coronagraph, as the telescope has already contaminated the light of the extra-solar planet. In this regard, the innate quality of the telescope optics becomes paramount, in terms of the point-spread-function and near-field and far-field stray light.

Two major projects worldwide exemplify opposing views of how to build an extremely large telescope. The European Southern Observatory (ESO)[12] is currently designing the 'Overwhelmingly Large Telescope' (OWL). This is designed to be diffraction limited in the near-IR to visible, using multi-conjugate adaptive optics. The 100-m primary mirror will be made of 3048 hexagonal, identical segments, each 1.6-m in size and of spherical form. A 25.6-m secondary mirror is required to fold the beam back on itself and so shorten the telescope tube length. This flat will comprise 216 flat segments, also of 1.6m. The segments will be made of low expansion glass-ceramics or silicon carbide. The spherical form of the primary was chosen because all the segments can be made identical, and they can be mass-produced by a planetary polisher.

The opposing view is held by the Thirty Metre Telescope (TMT) project, 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].

The advantage of ESO's spherical primary is simplicity both in manufacture and subsequent operations. The latter aspect arises because, with identical segments, only a few spares are required to permit all the segments to be cycled through a re-aluminsing plant on an on-going basis. The main penalty is the complexity of the remainder of the optical system, needed to correct the spherical aberration. After the 25.6m folding flat, the design includes two deformable eight-meter class active mirrors, a 4.2-m focusing and a 2.35 flat fast steering adaptive mirror for first stage adaptive correction. The 4.2-m mirror will eventually be replaced by an adaptive one, in order to compensate for atmospheric turbulence over larger fields. The consequence of a six-mirror system with two segmented mirrors is inevitably a degradation of stray-light and infrared-emissivity, which are key aspects of performance needed for sensitive science objectives such as extras solar planet detection.

Project cost is sensitive to the length of the telescope tube, and so a faster primary could have a significant positive impact, if only faster primary segments could be manufactured economically and reliably. It is interesting in this respect that the 50m Euro50 telescope concept[15] also adopts a classical Ritchey Chretien 2-mirror configuration (with an adaptive Gregorian secondary), but the primary is a remarkably fast f/0.85 in order to achieve a compact telescope tube and enclosure. The assumption in this project is that high-precision grinding followed by small-tool polishing will be used.

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. This consortium is building a pilot segment fabrication plant with nominal 1m size capability. 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 is building a 1m-class ultra-precision grinder and a Reactive Atomic Plasma Technology machine. These will be used in a programme of “total process optimization”. The results presented in this paper (that is, selective polishing, free-form polishing, and sub-micron removal), provide important steps to the full implementation of segment fabrication at the 1-2m scale.

7. CONCLUSION

This paper has shown the ability of the *Precessions* process to remove tens of nanometers of material in a highly controlled manner, to perform selective polishing of limited regions of a part, to raster-polish a toroidal ring which is not rotated in the process, and to imprint a pre-defined arbitrary free-form profile into a lens surface. Substrate materials used in the experiments reported here comprise steel, platinum, silicon and glass, and different data-input methods have been demonstrated. The unprecedented level of versatility of the process should stimulate optical designers to explore new design concepts.

We have shown the process-flow for machine-preparation and for processing a part. The need has been highlighted to maintain a consistent coordinate frame between the metrology data-set and the CNC positioning of 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.

Finally, we have summarized the European and US perspectives on Extremely Large Telescopes, as exemplified by the ESO-OWL project, the American TMT project and the Euro50 concept. Clearly, a technical approach that can provide controlled local removal of material in a predictable manner even over severe and non-uniform aspheric departures could swing the debate towards an aspheric design with a fast primary f/ratio.

8. ACKNOWLEDGEMENTS

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