

# Novel CNC polishing process for control of form and texture on aspheric surfaces

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## ABSTRACT

We first consider the potential impact of a technology that could deliver polished, accurate aspheric surfaces in a routine and automated manner. We then summarise the technical challenge, and present an appraisal of the performance of the novel '*Precessions*' process, which is a major advance in this direction. We outline the design concepts behind the productionized CNC polishing machines which executes the process, and then describe the progress developing strategies to preserve form when polishing ground surfaces, and to correct form on both pre-ground and polished surfaces. Particular consideration is given to resolving the inherent difficulties of control of centres on rotationally-symmetric parts. We then report on experimental results achieved with the machines. Finally, we present our programme to extend the control-algorithms to handle fully free-form surfaces, and draw conclusions about the effectiveness and generality of the '*Precessions*' technique.

## 1. Introduction

The '*Precessions*' polishing process has already been described at earlier stages in its development<sup>1,2,3</sup>. At the time of the present paper, two IRP200 (200mm capacity) CNC machine-tools have been produced, and the emphasis of the development programme has changed from machine development to process development. In this paper we describe the results of the more recent work, which has been conducted as a collaborative programme between Zeeko, UCL and Loh Optikmaschinen. The first IRP600 machine is under commissioning at UCL, and design of a 1m machine will commence shortly.

From the process development to date, it is clear that *Precessions* polishing will provide dramatic reductions in production time, compared with craft processes. This is partly due to enhanced removal rates, and partly due to the high level of repeatability we have observed with *Precessions* polishing. As a result, we anticipate that aspherics will become routine in many areas of optical instrumentation, where cost, schedule and technical risk have precluded them to date. The impact will be reduced size and mass of instrumentation, increased imaging performance and, hence, enhanced commercial competitiveness.

The emphasis in this paper is on process repeatability in single-pass polishing. This is the bed-rock for removal of stock-material both to polish and preserve existing form, and to rectify form-errors. Results of multi-pass polishing will be presented separately.

## 2. The technical challenge of aspherics

The principal challenge of polishing aspherics is the mis-match between tool and part, as the tool traverses the asphere's varying radius of curvature. This tends to drive the classical optician to very small tools for severe aspherics, resulting in surface defects and low removal-rates.

The Steward Observatory<sup>4</sup> has addressed the challenge with the 'stressed lap'. The tool is about 1/3<sup>rd</sup> the size of the part, and actively deformed by on-board actuators to conform to the local target asphere. The tool is loaded against the part by gravity, and moved across the surface in X and Y by motorised slide-ways. The tool is complex, and essentially has

to be re-built for each new job, but this can be warranted for high capital-value jobs. It has been used for several notable astronomical mirrors, for example, the 6.5m single mirror retrofit to the Multiple Mirror Telescope<sup>5</sup>.

In contrast, the *Precessions* process has taken the opposite approach, using passive tooling which is effectively 'universal', and whose absolute motion and orientation in space is orchestrated by an active 7-axis CNC system. In this respect, tool simplicity has been traded for machine complexity, but the end result is a highly versatile system.

As we have described elsewhere<sup>2</sup> the tooling is an inflated spherical membrane tool, which naturally moulds itself to the local aspheric surface everywhere. We call this the 'bonnet', and it is covered with a standard detachable polishing surface such as polyurethane. The method gives independently variable contact-area and contact-pressure, as the machine varies both the position of the bonnet in the direction normal to the surface of the part, and the inflation pressure.

The bonnet is rotated about its axis to increase surface speed and hence removal-rate. The machine motions can be configured so that the rotation axis is inclined to the local normal to the part, which avoids the centre-zero of removal observed with a pole-down rotating tool. In this case, the tool's axis of rotation is precessed about the local normal, in order to improve texture and achieve a well-behaved-influence function (IF). Currently, precession is performed in discrete steps (typically four); it is planned to implement continuous precession later in the development programme.

We identify three principal modes of operation of the machine: i) form-preserving ('onion skin') pre-polishing, ii) form-correction polishing and iii) finishing (achieving the ultimate surface texture). We consider i) and ii) in this paper; texture results have previously been described<sup>1,2</sup>.

### **3. The design concepts of the productionized machines**

The first key requirement of the machine is that it must place the contact-area of the bonnet (the polishing 'spot') at the correct position with respect to the part, in all three coordinates X,Y,Z. The precision required is on the order of 10 microns for the IRP200, in order to give the correct compression of the polishing membrane and achieve stable influence functions (IFs). The second main requirement of the machine is to orientate the bonnet with respect to the local surface-normal, allowing both for the surface-slope and the precession angles. This is accomplished using CNC machine tool technology as commonly applied to diamond turning and grinding machines. This may be contrasted to the more traditional polishing machines, where the tool effectively floats on the surface of the part.

Starting from the bonnet and working downwards, the Tool-Head contains an integral motor for rotating the tool at up to a nominal 1500 rpm ('H' axis), and a load cell assembly to measure contact force. The membrane is pressurized from an external air supply. Different radii membranes can be interchanged to give different ranges of contact spot diameter. On the IRP200, for example, a 40mm radius bonnet is suitable for ~20-100mm diameter parts, and an 80mm bonnet up to 200mm diameter.

The Tool-Head is mounted in a virtual pivot assembly that rotates in two axes ('A' and 'B') about a common point in space – the centre of curvature of the membrane. Rotations then cause negligible translations of the contact-spot on the part surface, thereby requiring no XYZ offsets. One of the rotation axes is limited to  $\pm 45^\circ$ ; the other can describe a full semicircle. With a typical precession angle of  $\pm 15^\circ$ , the maximum surface slope on the part is then  $30^\circ$  for four-way precession. Larger slopes can be accommodated with only two precession positions, but at the expense of degraded texture.

The part can also be rotated ('C' axis). The main X,Y,Z,A,B,C mechanical subsystems of the machine are mounted off a cast polyquartzite base (a composite material superior to granite). This gives a very stable platform. The base also contains screw fixtures for the attachment of user-supplied metrology devices. The base is mounted on a fabricated frame with vibration-isolation mounts, and the entire machine is supplied with an enclosure with the statutory interlocks. The CNC uses a Fanuc 16i system, housed in an electronics enclosure.

### **4. Form-preserving ('onion skin') pre-polishing**

#### **4.1 Basic philosophy of operation**

The purpose of this is to take a precision-ground lens or mirror with, say, 5-20 microns of surface and sub-surface damage, and pre-polish it without a requirement for active control of form.

If a Gaussian tool describes a spiral from edge to centre of the part, the tendency is to dig a hole in the centre. This is because, near centre, a tool of finite size overlaps the centre and cuts on both sides, locally increasing the removal. For form-preserving pre-polishing, two methods are under development to overcome the centre problem: - raster and diametric spiral. In both cases, the tool is first advanced towards the part until the load cell establishes contact, then advanced further by a pre-calculated distance to give the required spot-size. In form-preserving polishing, the spot-size is then maintained constant. The tool then tracks the aspheric form in either a raster on a stationary part, or an oscillating diameter on a rotating part.

An essential pre-requisite is that both the bonnet itself and the polishing surface on the bonnet are trued-in to spherical forms concentric with the intersection of the rotation axes A,B (the virtual pivot). Otherwise, different areas of the part are subject to different spot-sizes and hence (through the area relationship) to different removal rates. Truing-in is achieved by spinning the bonnet and cycling the A,B axes, with the polishing surface working against a rotating bound-abrasive wheel.

#### 4.2 Raster tool-path

Rastering with a stationary part avoids at source the problem of controlling centre, as the process then has no circular symmetry. Figure 1 shows a rastering result on BK7. The part was machined on a diamond grinding machine to a nominally spherical form of 50mm radius of curvature, but with some 0.9 microns peak-to-valley of form-error. On the IRP200 it was mounted in a stainless steel holder with the front face machined to follow the same (nominally) spherical profile as the part. This gave a 'waster' – a surface to support the overhang of the tool as it approached the periphery of the part.

The machine was programmed to perform 'Precession' polishing, and perform parallel linear tracks following the best-fit (spherical) radius of curvature. The four precession positions of 0°, 90°, 180°, 270° were performed by repeating the entire process four times. Form Talysurf scans before and after removing 5 microns depth in a single pass are shown superimposed. The original form is well preserved and the texture improved. Figure 2 shows the process continuing on the same part removing the next 5 microns of material (10 microns in total). The sharp cusp is starting to be rounded in the second pass, as expected for the tool spot-size used (nominally 7mm full-size), and when tracking the nominal sphere. This shows the power of the technique in passively removing medium spatial-frequency errors.

The main disadvantage of raster polishing is the need to accelerate and decelerate the machine traverse at rates within the machine capacity, which costs process time. Moreover, if the accelerations/decelerations are on the part, it can cause local enhanced removal due to the longer dwell times implied. This was another reason for mounting the part in the stainless steel holder as described above, so that the accelerations/decelerations could be localised to the metal surface.

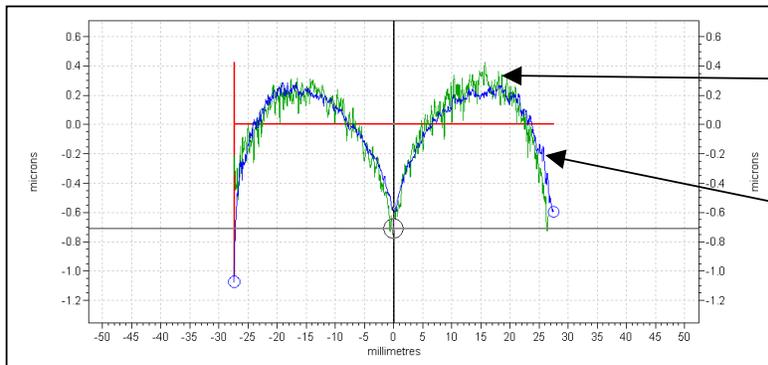


Figure 1. Cross-section through lens before rastering...  
...and after removing 5 microns of bulk material

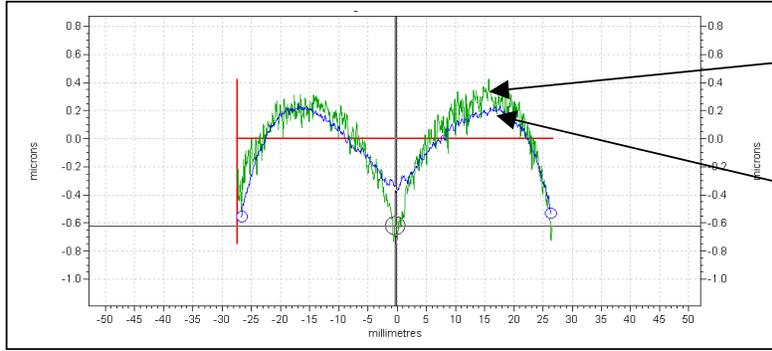


Figure 2. Cross-section through lens before rastering...  
...and after removing 10 microns of bulk material

### 4.3 Spiral Pre-polishing

In this method, the tool is rotated 'pole down', rather than cantered-over as for 'Precession' polishing. The influence function then exhibits a 'centre zero' of removal. The rotating tool performs spiral paths by traversing the diameter of the part many times, as the part is rotated at the same speed and in the same direction. The overall effect is to give a uniform removal across the part including centre.

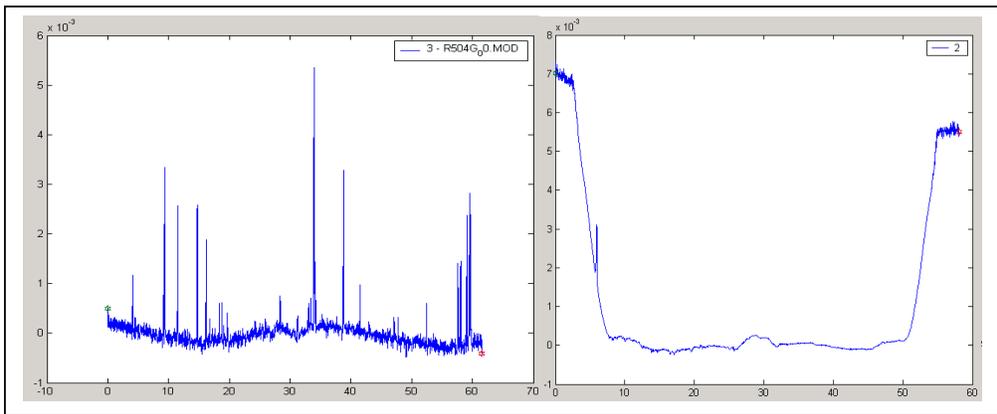


Figure 3 Form before spiral polishing

Figure 4 ... after one pass of spiral polishing

Figure 3 shows a nominally-spherical part of 50mm radius of curvature taken off the diamond grinding machine, and Figure 4 the same part after polishing the central ~40mm on the IRP200 in a single pass. The reason for restricting the polishing to the central zone in this experiment was to leave a peripheral land of unpolished material, in order to define the depth of material removed. Some 7.5 microns was removed in polishing, and the difference between the initial and final forms was approximately 0.3 microns, implying a process uniformity of some 96%.

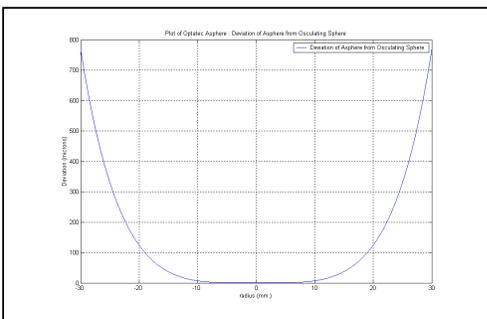


Figure 5 Aspheric departure (125 microns in polished zone) c.f. sphere osculating about vertex

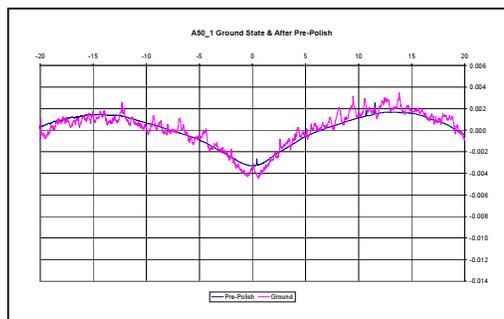


Figure 6 Form-error of 40mm diameter polished zone before and after pre-polishing

This pre-polish process is also used on aspheres. Figure 5 shows the aspheric departure over the 60mm diameter lens, which had the following form parameters:

$$\begin{array}{lll}
 R = 47.80 & K = -1.746886432 & A4 = -1.3212887e-6 \\
 A6 = 1.03734945e-10 & A8 = -2.75918694e-14 & A10 = 3.90291578e-18
 \end{array}$$

The lens was spiral polished over an area of approximately 40mm diameter, again leaving a peripheral land to define absolute depth of removal. The aspheric departure from the sphere that osculates about the vertex, over the 40mm diameter area polished, was 125 microns. Figure 6 shows the *error* in the surface-form, both before pre-polishing and after about 7 microns depth of removal. The aspheric form is preserved to approximately half a micron indicating a uniformity of removal of ~93%. Once again, the ability to remove mid spatial frequencies is demonstrated.

## 5. Form-Control

### 5.1 Basis of Form Control

The purpose of this mode is to correct surface-form, after establishing the form-error by surface metrology. The numerical optimisation method using the *Precessions* code (rather than de-convolution) has already been described<sup>4</sup>. In summary, a family of experimental influence functions is imported for different spot sizes, together with target and measured profiles. The tool-path is assumed to be concentric rings, where ring-spacing, spot-size and dwell-time are the variables. The optimiser maximises a merit function derived from a weighted combination of height and slope errors, and process-time. Tool spot-size as a function of radius on the part can be constrained by the user through a GUI. The predicted result is displayed, and if satisfactory, may be output as a file to the CNC controller. If further improvements are required, the optimisation can be re-run with different constraints and/or weights before polishing commences. The algorithms handle simple folding errors in axially-symmetric forms<sup>4</sup> by cyclically modulating the speed of rotation of the part during each rotation.

In early work, the machine polished in concentric overlapping rings, based on a direct interpretation of the output of the optimiser. However, errors were introduced when placing and lifting the tool at the start and end of each ring. This was due to a combination of small timing errors, and the inevitable overlap (or gap) when a ring wraps around on itself, leading to a depression (or hill) localised in azimuth. Therefore, the output of the optimiser, still in the form of concentric rings, is now transformed into a continuous edge-to-centre spiral for execution on the machine. The (typically) four precess positions of the tool are accommodated by executing the spiral four times in succession.

The optimiser inherently handles the problem of tool-overlap at centre. This is accomplished by adding contributions both sides of centre into the prediction of instantaneous removal over the surface of the part. However, the resulting dwell times near centre become extremely short. For this reason, the tool rotation-speed is decreased near centre. For this to be effective, there must be a predictable relationship between removal-rate and rotation-speed. Figures 7,8 show the results of an experiment.

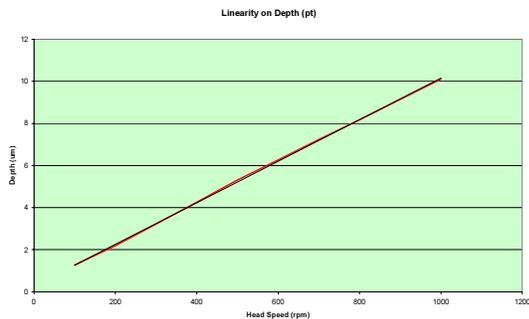


Figure 7 IF depth v. tool rpm (100-1000)

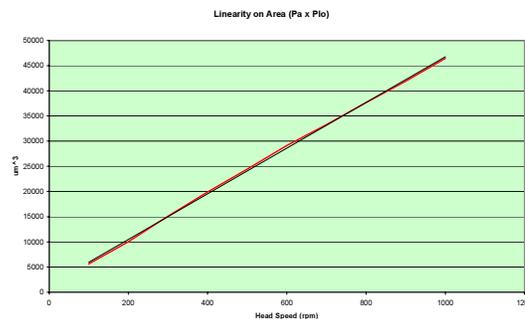


Figure 8 IF area versus tool rpm (100-1000)

Influence functions (Ifs) were produced in a BK7 flat sample at a range of tool-speeds from 100 rpm to 1000rpm. The depths and the areas of the influence functions were measured. The plots are highly linear over a decade in speed. Therefore, tool-speeds near centre can be moderated, and the dwell-times as predicted by the optimiser increased in direct proportion.

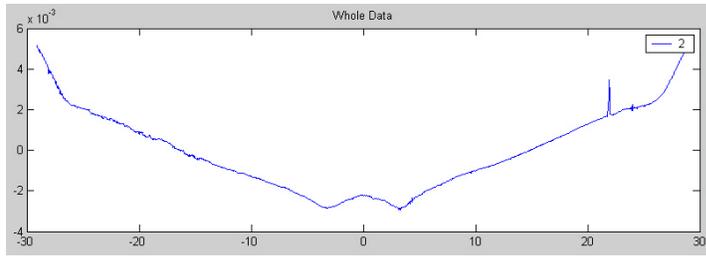


Figure 9 Error profile of nominally spherical part

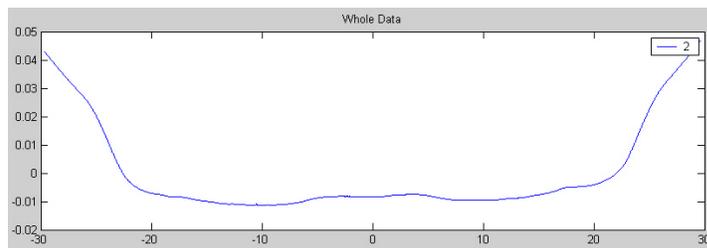


Figure 10 Profile after removing 45 microns from central zone

The end-to-end form-correction process is illustrated in Figures 9, 10. The lens had a form-error of  $\sim 8$  microns as shown in Figure 9. This was input to the *Precessions* optimiser, and the IRP200 machine was run both to remove bulk material and correct form. A peripheral land was left as a reference.

Figure 10 shows the resulting profile. Some 45 microns depth of material has been removed. The form error was about halved, indicating  $\sim 90\%$  convergence with respect to the total depth of material removed.

## 6. Handling edges

When a compliant tool passes over the edge of a part, the tendency is to turn down the edge. Some preliminary work has been undertaken to address this by using a brass waster ring around the part as already mentioned. The ring was machined with a profile that is an extension of that on the part, and mounted in a fine screwed fixture to bring it to the correct level, as measured using a Form Talysurf profilometer. This has established the principle of the method in removing turned-down edges, but also revealed the sensitivity of the adjustment required to avoid instead turning edges up at the few-micron level. In practice it would be preferable to machine the waster assembled on the part, to ensure heights matched to optical tolerances. By this means it should be possible to eliminate edge-defects.

## 7. The future – free-form surfaces

The IRP series of machines provides the mechanical and control functionality for polishing fully free-form and conformal surfaces. These will be polished by rastering, and the machine provides the flexibility for parallel straight rasters, crossed rasters, etc. The tool-path generator for rastering has been experimentally demonstrated, as shown by the form-preserving results.

The optimisation to control 3D form is in principle an extension of the axially-symmetric case. Indeed, in one important respect it is simpler:- there is no problem of control of centre as there is no rotational symmetry in the rastering process. The intention is to freeze the raster spacing on the surface to remove one dimension from the optimisation. The variables would then be spot-size and dwell-times; the latter varied by modulating the local traverse speed. The challenge arises in achieving tolerable execution times for the 3D optimisation. This is work at the planning stage, and we expect to report in due course.

## 8. Conclusions

The *Precessions* process is highly versatile in the forms that it can handle, limited by the maximum surface-slope on the part that the specific mechanical system can address (making allowance for the additional tool-inclination required to establish the precession angles). In the current generation of machines, one of the tool inclination axes achieves  $\pm 45^\circ$  and the other  $> \pm 90^\circ$ . For a typical precession angle of  $\pm 15^\circ$ , the surface slope on the part must therefore be within  $\pm 30^\circ$ . However, restricting precession to only two positions enables the surface-slope to be increased. Note that the

slope restrictions are not fundamental. If required, a modified mechanical configuration could deliver more steeply inclined surfaces with four-way precession.

The next limitation occurs when polishing concave parts, due to the radius of curvature of the bonnet. 20, 40 and 80mm radius bonnets are readily achievable. The chosen bonnet must fit within the concavity of the part, leaving sufficient margin to create variable spot sizes. The bonnet radius is not, however, a free parameter because it defines the range of spot-sizes that can be produced without a tool-change. These spot-sizes need to be matched to the spatial frequencies in the aspheric profile to be polished. Therefore, minimum spot-size poses a limit both on the extremeness of the asphere and how small the part may be. A 20mm bonnet has been designed and it should readily deliver spots down to ~2mm full-diameter. 10mm diameter is therefore a realistic minimum part-size.

At the other end of the scale, there is no obvious upper-limit to tool size and part size. Under a commissioned design study<sup>6</sup>, a conceptual design has been developed for a 2m capacity machine for producing off-axis segments for extremely large telescopes.

The next stage of the development programme will be to iterate the form-control to establish the ultimate limit of precision of the surface that can be produced. As much smaller depths of material are removed in a pass, a limit will be set by the shortness of the dwell-times required (particularly near centre). To address this, the volumetric removal rate will be reduced, by moderating *all* machine speeds equally and scaling up dwell times in proportion. The demonstration of linear response to tool-rotation speed, as shown in Figures 7 and 8 above is particularly important in this respect.

## Acknowledgements

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