First results on free-form polishing using the *Precessions* process

David Walker[1,2], Anthony Beaucamp[1], Christina Dunn[2], Richard Freeman[1], Andreas Marek[1], Gerry McCavana[1], Roger Morton[1], David Riley[1]

[1]Zeeko Ltd, The Precise Group, The Stables, East Lockinge, Wantage, Oxfordshire, OX12 8QJ

[2]Optical Science Laboratory, Dept of Physics and Astronomy, University College, Gower St, London WC1E 6BT

1. Introduction

In the context of this paper, we conveniently define a *freeform* surface as one that deviates significantly from a rotationally-symmetric form. We therefore include parts that are off-axis sections of rotationally-symmetric aspheric parents, such as off-axis paraboloids, hyperboloids, etc. We adopt this definition because the challenges of producing off-axis and generalized free-form parts are basically the same.

Free-form surfaces introduce additional degrees of freedom into an optical system compared with all axially-symmetric solutions. In general, this implies that a superior optical performance can be achieved by including free-form surfaces, or a given performance can be obtained with fewer surfaces in the system. Off-axis sections in particular can efficiently fold an optical system into a compact package without introducing additional elements and obstructions. *Conformal* optics, on the other hand, achieve a form that is required for non-optical functionality; such as for aerodynamic properties.

Fig. 1 Typical prosthetic knee joint component

The need to control form and texture on a complex surface is not limited to optics. We are involved in precision metal surfaces, including prosthetic knee and hip joints. In these prostheses, it is believed that the typical lifetime of 10-15 years is limited by the form-control in the craft polishing processes commonly used – achieving some 10-30 microns of form-error, with Ra ~ 3 to 5 nm texture. The form-tolerance required for optimum life is expected to be particularly demanding for the new 'hard-on-hard' joints, where even micron-level high spots may cause significant pressure concentrations and premature failure. Whilst the quantitative form accuracy required for extended lifetime is currently unknown, it is likely to be within the domain previously considered to be 'optical'.

2. Summary of the *Precessions* process

The tooling for the *Precessions* process[1,2,3] is a sub-diameter physical tool operating in the presence of a polishing slurry. The tool comprises an inflated, bulged, rubber membrane of spherical form (the 'bonnet'), covered with one of the usual proprietary non-pitch flexible polishing surfaces familiar to opticians. The polishing pressure (tool hardness) and the contact area (polishing spot size) can be modulated independently by varying:

1. the internal pressure
2. the axial position of the tool with respect to the local surface of the part, and therefore the degree by which the membrane is compressed against the part

The tooling is hosted by a seven-axis CNC custom-designed machine tool that provides the following degrees of freedom:

- H axis: rotation of the bonnet about its axis of symmetry

- X,Y Z: positioning of the bonnet with respect to the part
- A,B: orientation of the bonnet's axis in the coordinate frame of the machine
- C axis: rotation of the part

In a pass across the part, the tool attacks the local surface at a pre-defined offset angle between the tool's H axis and the local normal to the surface. In 'pre-polishing' (achieving a fine optical finish from a ground part whilst preserving form), the offset is zero and so the tool operates pole-down. In form-correction polishing, the polishing run is divided into (typically) four passes. Each has the same offset, typically in the range 5-20 degrees, but a different precession position-angle (direction in space of the H axis with respect to the local normal to the part). For four passes, the precession angles would be 0, 90, 180, 270 degrees. The influence function integrated over the four passes is then symmetrical and near-Gaussian.

3. Machine architecture and kinematics

In traditional polishing machines, the tool floats on the surface of the part. The tool therefore exerts a pressure that is constant, other than the gravity cosine effect which comes into play when the peripheral slope of the part becomes significant. The concept of constant or controlled pressure is also fundamental to some automated techniques. In contrast, the Zeeko machine tool and its control system are *position*-based, and bear strong similarities both in this respect and in construction to diamond turning and grinding machines. In use, the tool is first advanced towards the surface of the part until a sensor detects first contact (to a few microns). This provides the zero point for the Z position in the machine coordinate system.

The CNC then translates the tool in X, Y & Z with respect to the part as it traverses over the part's surface. Simultaneously, it can continuously rotate the orientation of the tool's spin-axis (H) about a virtual pivot located at the centre-of-curvature of the bonnet. Any arbitrary angle in Cartesian space can be achieved, within the limits of the mechanical system. The angular limits on the A and B axes are +/- 180 deg in both cases. In practice this means that the H axis can move between the vertical and horizontal positions and rotate around the C axis by +/- 180 deg.

The above design provides the capability to follow a free-form surface, and to attack all points on such a surface with a constant geometric relationship between the tool and the surface's local normal. This applies equally to pole-down operation, or to a precession angle of variable orientation and amplitude. Furthermore, any tool-path can be implemented, within the acceleration and speed limitations of the machine. The ability to rotate the part (C axis) gives an additional degree of freedom in defining tool-paths if required. The only significant limitation is on parts that are short-radius concave, or with local areas of such concavity in some direction (including a saddle). As a general rule, the radius of the bonnet should be a factor of at least ~ 2 less than that of the part, as otherwise they 'nest'. With the current shortest radius bonnet of R=20mm, R~40mm concave parts or regions can therefore be handled.

4. The 2D case, and descriptions of the surface in 2D and 3D

In the 2D *Precessions* optimization code for form-control, it is assumed that the surface is polished in concentric rings (although these are re-formatted to a spiral for actual polishing). The process variables are the ring-spacings, the polishing spot-size, and dwell-time for each ring. The code takes as input a family of experimentally-produced influence functions of different spot-sizes, together with an error-map of the surface. Numerical optimization is then used to determine the optimum set of variables to minimize the form error (as defined by the combination of height and slope errors, according to user-defined numerical weights). In the 3D case, we also use numerical optimization. However, as well as allowing the import of a height map, the code also supports import of a NURBS file (in Rhinoceros and IGES formats for instance), which gives a smooth description of a complex surface using control points. This offers considerable advantages from the viewpoint of the CNC controller because the continuity of the derivatives allows smooth tool paths. An example of a NURBS surface is given in Figure 2.

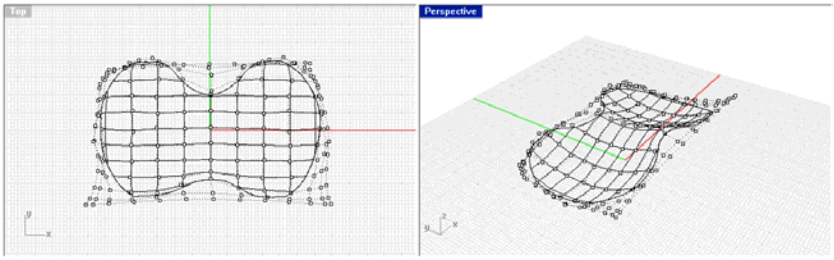

Fig. 2. NURBS description of a prosthetic joint surface, showing the control points

5. Preliminary results

The first practical experiment to validate the form-control algorithms was conducted by polishing a complex feature into a flat surface by rastering, using a Zeeko 200mm machine.

1. An influence function was polished into the centre of a flat piece of glass to calibrate the process. The same side of the glass was used for the subsequent experiment below.
2. The influence function was measured on a Form Talysurf and azimuthally averaged.
3. A target surface was defined in a CAD package comprising:
   a) a rectangular depression 0.5µm deep, with rounded corners and sloping edges
   b) within this rectangle, a feature a further 0.5µm deep comprising part of the Zeeko logo
4. The corresponding error map was produced, i.e. (target-profile - initial-profile)
5. The 3D optimisation code was run with the influence function and error-map to create an optimal crossed raster tool-path.
6. The tool-path data were input to the machine
7. The part was polished as an integral 3D surface, not as separate features.
6. Four passes over the part were made: ‘up’, ‘down’, ‘left’ and ‘right’, corresponding to the four precess positions.
7. Form was measured on a Zygo interferometer.

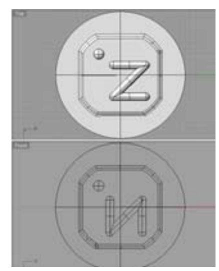

Figure 3 CAD design of 3D feature

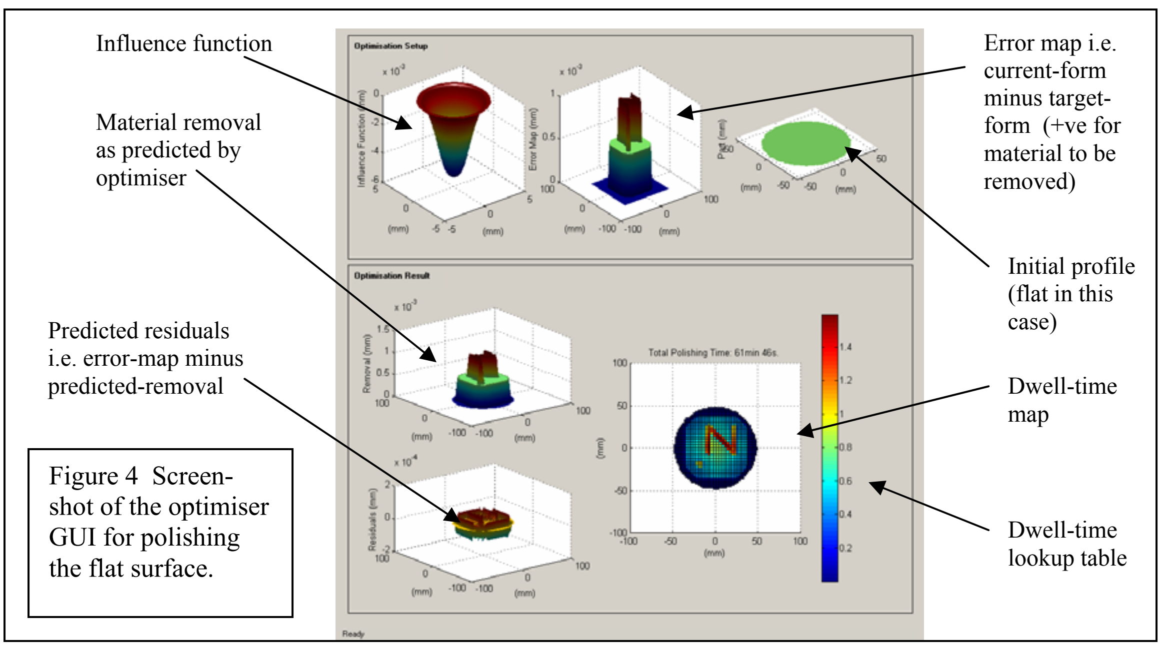

Figure 4 Screen-shot of the optimiser GUI for polishing the flat surface.

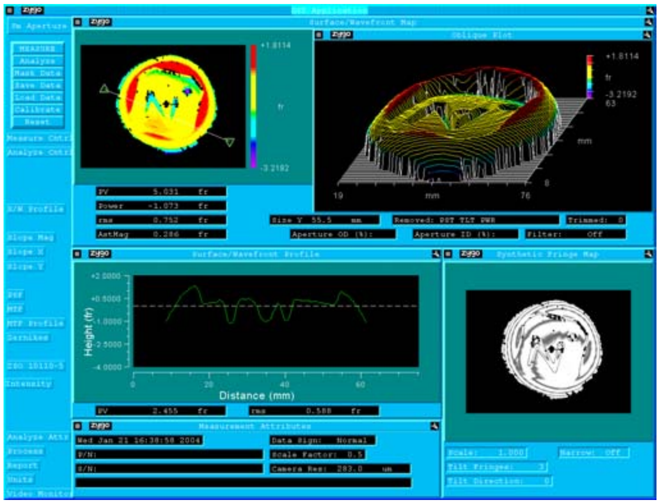

Figure 5 Zygo result polishing feature in flat part

The experiment was successful, showing the correct geometry and absolute depth of the features as per the design. Note the central superimposed depression which is the initial influence function, as expected.

However, there was a residual slope term visible in the Zygo data, corresponding to a slope of the polished feature with respect to the surrounding glass. This was traced to a tilt in the part on the machine, for which compensation had not been correctly made.

Nevertheless, the result on the flat surface confirmed the operation of the optimiser, including the correct computation of dwell-times. It also confirmed the correct XY trajectory of the tool path and the velocities and accelerations within it.

The experiment was then repeated according to the above protocol, but on a concave spherical part of radius 300.99 mm. The first stage once again was to polish an influence function on the same piece of glass, in order to calibrate the process.

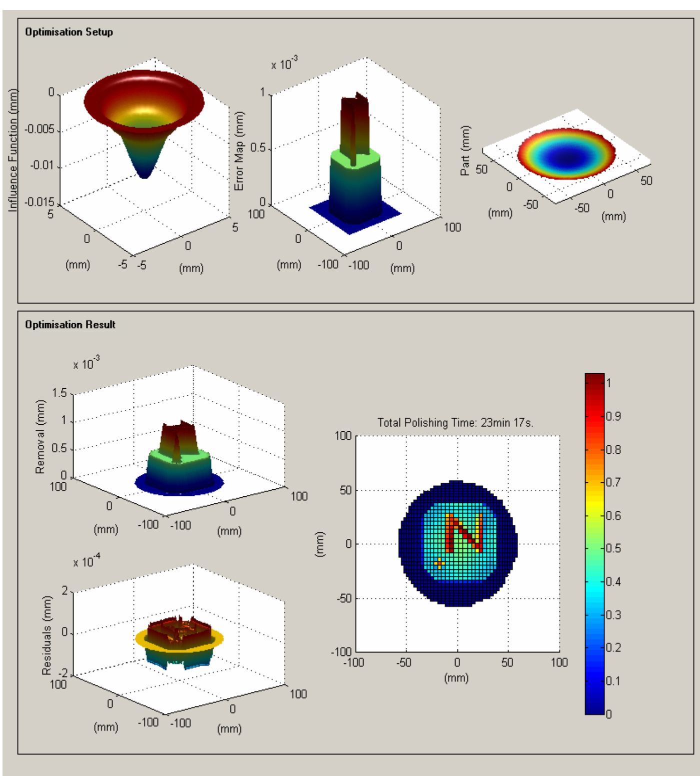

Figure 6 Optimiser GUI for the spherical part

Then, after generation of the error-map and subsequent 3D optimisation, the target was again to polish a rectangular region 0.5 µm deep with the superimposed logo an additional 0.5 µm deep. In this run, care was taken to avoid the tilt problem experienced previously with the flat part. The optimiser GUI is shown in Fig. 6, and these images follow the convention defined in Fig. 4.

Maps of the machine feed rates and crossed-raster tool-paths are shown in Figure 7, and the Zygo result in Figure 8. This experiment was also quantitatively successful, demonstrating that the kinematics of the machine and CNC correctly followed the curved surface whilst rastering. The tool-path was correct in three dimensions, as were the dwell times, as required to give the predicted depths and positions of removal.

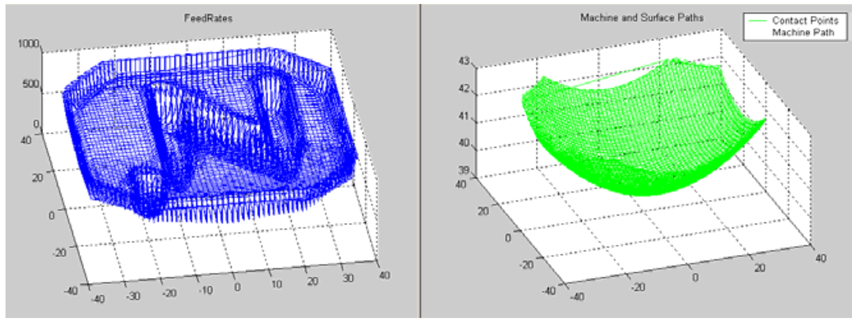

Figure 7 Maps of feed-rates (left) and tool-paths (right) for polishing the spherical part

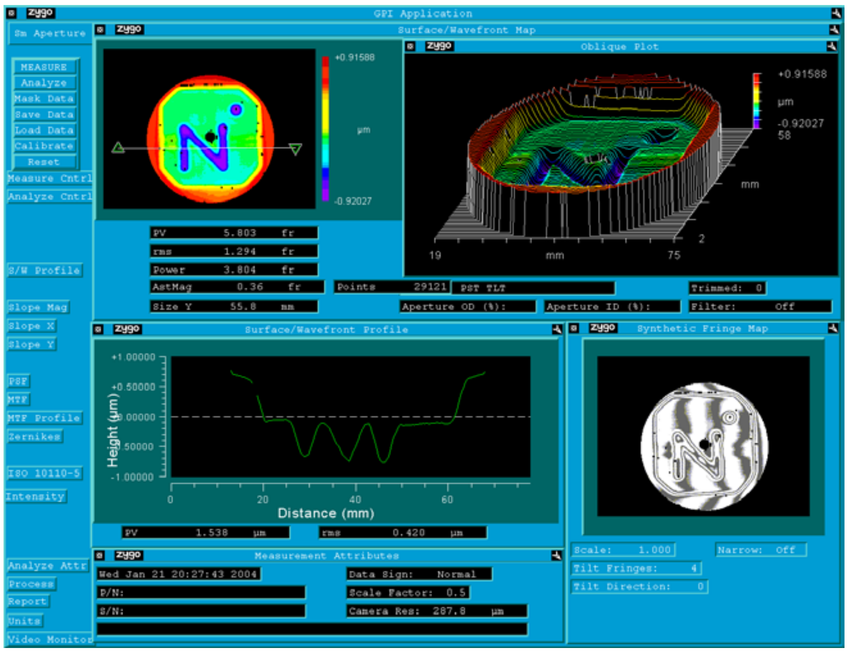

Figure 8 Zygo result of polishing the feature into into the concave spherical part

6. First Polishing trials on true free-form surfaces

In addition to the results reported above, we have been commissioned to conduct polishing trials on truly free-form precision metal engineering surfaces (actually, complex curved lugs). The objective was to improve texture, to preserve edges, but not to correct form. This work has also been highly successful, confirming once again the correct operation of the machine-kinematics, the CNC software and the tool-path generator. Form Talysurf scans before and after polishing are shown in Figures 9 and 10 respectively.

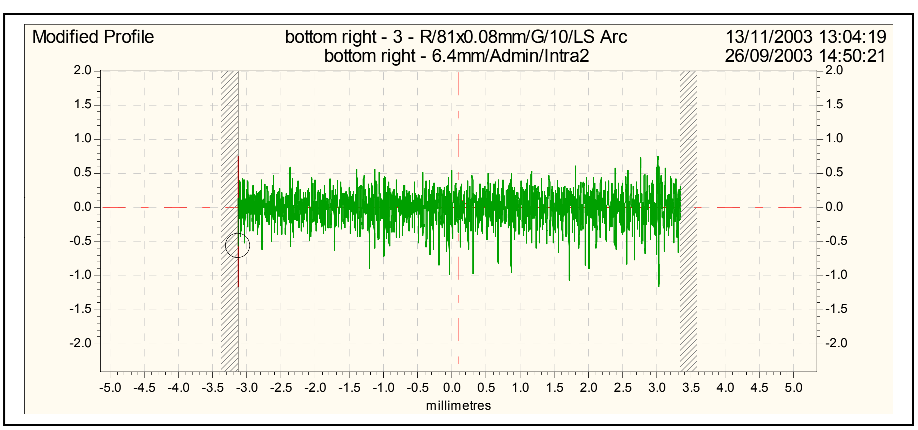

Figure 9 Polishing free-form metal lug.

Before polishing Ra = 170nm

Figure 10
Polishing free-form metal lug

After polishing
Ra = 18 nm

7. Conclusion

The Zeeko family of machines provides all the degrees of freedom to polish free-form surfaces. As a first demonstration of the ability to control form in three dimensions, we have polished a complex 3D feature into both a flat and a concave part. The results confirmed the correct operation of the form-optimisation code, the tool-path generator, and the machine's ability to follow the prescribed too-path and velocity-map. Considering our previous work on severe axially-symmetric aspherics that exhibit substantial curvature changes across the diameter, we assert that we have demonstrated a process able to handle free-form surfaces. The rider is that the surfaces are within the mechanical limits of the machine and within the concavity limits imposed by physical bonnets. Our confidence is reinforced by successful polishing trials improving texture on truly free-form mechanical surfaces. The next stage in the work will be to polish a truly free-form lens or mirror to optical tolerances, controlling form. Hardware and software is already in place to support this next step.

8. References

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