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The role of robotics in computer controlled polishing of large and small optics

David Walker*[a,b,c], Christina Dunn[b], Guoyu Yu[a], Matt Bibby[c], Xiao Zheng[a], Hsing Yu Wu[a,b], Hongyu Li[a], Chunlian Lu[d]

[a]National Facility for Ultra Precision Surfaces, OpTIC-Glyndwr, St Asaph, N. Wales, LL17 0JD, UK; [b]University College London, Dpt Physics and Astronomy, Gower St, London, WC1E 6BT, UK; [c]Zeeko Ltd, Coalville, Leicestershire, LE67 3FW, UK; [d] Key Lab in In-Fiber Integrated Optics, Ministry Education of China, College of Science, Harbin Engineering University, 150001 Harbin, PR China

ABSTRACT

Following formal acceptance by ESO of three 1.4m hexagonal off-axis prototype mirror segments, one circular segment, and certification of our optical test facility, we turn our attention to the challenge of segment mass-production. In this paper, we focus on the role of industrial robots, highlighting complementarity with Zeeko CNC polishing machines, and presenting results using robots to provide intermediate processing between CNC grinding and polishing. We also describe the marriage of robots and Zeeko machines to automate currently manual operations; steps towards our ultimate vision of fully autonomous manufacturing cells, with impact throughout the optical manufacturing community and beyond.

Keywords: polish, robot, automation, grolish, smooth, segment, asphere

1 INTRODUCTION

The European Extremely Large Telescope ('E-ELT') [1] will be a 39m aperture segmented mirror telescope for the optical and near-IR wavebands, under construction managed by the European Southern Observatory (ESO). One of the challenges is that the number of mirror segments for this project is nearly *thirty times* the number for each of the two Keck 10m telescopes [2], yet the project time is not dissimilar. This means that a step change is required in the philosophy of manufacturing 1-2m class optics in order to meet delivery schedules:- "multiple prototype manufacture" is no longer appropriate. Additional issues arise from the tight specification on the smoothness of the mirror surfaces as in the original specification [3]. This is compounded by the very long base radius of curvature of the segments (84m for the original 42m aperture design, reduced to 69m for the approved 39m aperture design), and the matching of base radius and conic constant between segments over several years of production.

At the National Facility for Ultra Precision Surfaces, hosted by OpTIC in North Wales, we have previously reported [4] on the successful completion of a 1.4m Master Spherical Segment (R=84m) which is used as a comparator to assert segment matching. We have also successfully completed three 1.4m across-corners, hexagonal, off-axis aspheric mirror segments as prototype for the R=84m E-ELT design, and received formal acceptance [5]. CNC grinding was performed using the BOX™ machine [6] at Cranfield University, and pre and corrective polishing using the 1.6m Zeeko CNC polishing machine at OpTIC, the segments being in the hexagonal state throughout.

A fourth, circular segment has also been completed to a more stringent mid-spatial specification, and passed acceptance. The optical test facility has also been certified as compliant, comprising a 10m high Optical Test Tower, 1.5m Master Spherical Segment, scanning pentaprism profilometer, stitching interferometer, and white light texture interferometer. All metrology throughout the pre- and corrective polishing cycles was conducted with the segment mounted on its hydrostatic whiffle tree support system on the turntable of the CNC polishing machine. More details of the challenges of developing effective metrology for segments may be found in the parallel papers [7,8]

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2 SEGMENTS – THE LANDSCAPE POST-PROTOTYPES

Pre-polishing of the CNC-ground segments (ie to deliver a specular surface amenable to interferometry) proved unexpectedly slow, due to the time required to remove the depths and spatial frequencies of local grinding defects, and to correct the global form errors from grinding. Whilst more aggressive abrasives (e.g. aluminum oxide, loose and bound diamond) have been implemented on other Zeeko machine, this route was not pursued due to the danger of contaminating the fine polishing process. This decision was indeed right in retrospect, as the surfaces produced have been remarkably clean. Therefore, there is a compelling reason to implement a fast intermediate smoothing process on another platform; preferably removing the dominant grinding form-errors in the same operation. This paper reports on an on-going development in this area.

The other key issue is the time and level-of-risk associated with several manual interventions required in the prototype manufacturing, even using CNC machines throughout, such as:-

- Changing tooling
- Deploying sub-aperture on-machine metrology instrumentation
- Mounting the part on the machine
- Aligning the part on the machine
- Washing down the part
- Aligning the full-aperture optical test (Optical Test Tower)
- Analysing metrology data
- Computing corrective tool paths
- Initiating the next polishing run in an iterative and convergent process

We have been alerted to similar issues in other sectors, particularly involving mass-production of smaller optics, where auto mounting/demounting of parts is required.

In order to address these emerging requirements in terms of both speeding up the overall process-chain through an intermediate process-step, and automation of manual interventions, we have focused on the potential role of *industrial robots*. Indeed, robots and Zeeko machines are proving highly complementary (described further in Section 4), presenting the opportunity to combine them in an integrated cell. We ultimately see this as including a CNC grinding machine. This theme is the essence of current work-in-progress, as reported in this paper.

3 NEW ROBOT LABORATORY AT THE NATIONAL FACILITY

With these objectives in view, a new robot facility has been established by Glyndwr University, UCL and Zeeko Ltd at the National Facility for Ultra Precision Surfaces, with three complementary robots:-

- Fanuc 1.8m-reach, 20Kg-payload
- ABB 2.55m-reach, 40Kg-payload
- Fanuc 3.05m-reach, 125Kg-payload.

Currently, the 1.8m robot is located between a Zeeko IRP600 machine (seen in the background of Fig. 2, right) and a prototype computer-controlled XYZ metrology station (in the foreground). This is located in the mezzanine upper of the Robot Lab., and is being used for process-automation, particularly in the context of smaller commercial parts.

In the main lower level of the Robot Lab (Fig. 2, left) , a massive 1.2m Zeiss air-bearing turntable (kindly provided by Brera Observatory, Italy) is available to rotate parts. The two larger robots are clustered around this turntable, so that each can reach the turntable, but also reach its own auxiliary fixed work-station. This gives flexibility both for process-development, and for robot-automation development when this is ported onto the larger robots addressing metre-scale parts. The robots are enclosed with physical partitions, light-curtain and Fortress Locks for safety interlocking.

Two customservo motor spindles, each with its own gearbox, are available to drive tooling in rotation for processing parts (Table 1). The higher power unit is configured to enable the motor alone, or motor+gearbox, to be used, giving a wide range of speeds and torques. Tooling effectively 'floats' in Z on the surface of the part under gravity, and is driven in the X-Y plane by the robot gimbal-type coupling.

Table 1 Spindle and motor gearbox continuous ratings

Spindle	Motor max. torque	Motor max. speed	Gearbox reduction ratio	Gearbox + motor max torque	Gearbox + motor max speed
Low power	2.4Nm	3000 rpm	3:1	6.8Nm	1000
High power	10Nm	4000 rpm	10:1	90Nm	400

Fig 2. The 3.05m and 2.55m robots (left), and the 1.8m robot and Zeeko IRP600 machine in Automation Cell (right)

4. INTEGRATING ROBOTS AND ZEEKO MACHINES

4.1 Comparison of robots and Zeeko machines

Both the Fanuc and ABB robots have been integrated within the standard Zeeko software suite and, in particular, the Tool Path Generator software (*Zeeko-TPG*). This enables any tool-path to be designed in TPG and output to a Zeeko machine, or to either type of robot. Additional robot types will be integrated according to Zeeko's commercial requirements as they arise. Standard toolpaths comprise raster, spiral and adaptive-spiral (morphing from a true spiral at the centre of the part, progressively out to follow the edge of a non-circular part), and zero-crossing random tool-paths [9]. None of these paths cross themselves (which would create local doubling of removal), and are therefore ideal for a high-precision CNC machine, such as a Zeeko machine, delivering relatively slow feed-rates. The Zeeko machine's principle mechanical roles can then be summarized as providing precise:-

i) Z-tracking of the local surface, so that bonnets can be deployed which adapt fully and effectively to the local aspheric or freeform profiles

ii) Local Z-offset as required to change the spot-size (bonnet contact area) 'on the fly', especially to control profiles at edges and perforations

iii) X-Y registration of the polishing spot on the surface, in order to target local surface features (e.g. attack mid spatial frequencies), and to control edges and perforations

iv) Motion-control for on-machine metrology instrumentation

In contrast, the equivalent robot provides positional *repeatability* an order-of-magnitude worse than the Zeeko's positional *accuracy*. However, the robot may deliver some twenty times the feed-rate. The mechanical role of the robot is in exploiting the high speeds and agile articulation available. The lack of precise positioning is mitigated by using larger tool contact-areas, which deliver efficient surface-averaging (although at the expense of lack of *finesse* in addressing local features). In view of this, TPG has been extended beyond the standard toolpaths, to include orbital toolpaths (more akin to the craft processes), as these satisfy the many-crossing criterion. Kim and Burge have adopted such tool-paths for their visco-elastic tools [12].

The bridge-type IRP machines suffer a singularity (gimbal lock type condition), which requires high velocity reversal of one or more axes in order to maintain the tool orientation relative to the part surface. This is analogous to the zenith singularity with an alt-az telescope. In the case of the IRP machine, this condition occurs when the tool axis passes through a local surface normal vector of [0,0,1]. In order to maintain the precess angle, the machine A-axis must reverse rapidly. Depending upon part geometry and precess angle, this reversal can exceed the machine axis velocity-limit. If not correctly handled this can leave a witness on the surface. Several strategies are available to avoid or mitigate this effect, for example adjusting the precess angle, or inclining the part.

The equivalent singularity occurs on robotic arms such as the Fanuc, when joint 5 is rotated to place the axis of the polishing spindle parallel to the joint 4 arm. The control system of the Fanuc robotic arm prevents the system being configured at the singularity by producing an “axis configuration” error. If a tool path is running which passes through this configuration, execution is terminated. Our use of a tool floating on the surface, removes the requirement that the spindle-axis must be maintained at a precise relationship to the local surface normal. Therefore, TPG can modify the toolpath to ensure that the robot avoids the singularity.

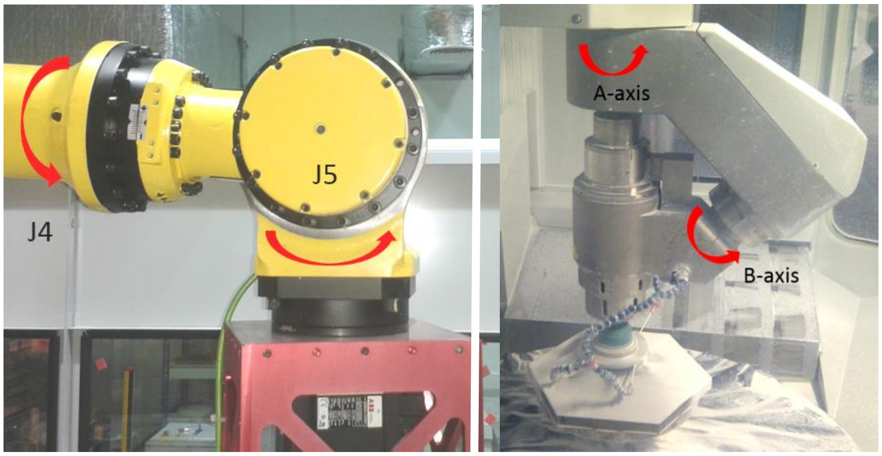


Fig 3. Comparison of the relevant Fanuc R2000 robot and IRP machine axes

4.2 Software implementation

For both ABB and Fanuc robots, MATLAB functions were added *to Zeeko-TPG* to allow for the testing of generalized tool paths. These functions take the Cartesian coordinates as generated by *Zeeko-TPG* and format them into the correct syntax for each robot.

For the case of the Fanuc robot, the tool path is output as an LS file; a readable text file which is converted to a binary TP file readable by the robot. LS files consist of definitions of positions and motions. The position definitions are given in six axes*:* x, y, z, w, p, and r. The angles w, p, and r are computed with respect to the surface normal of the workpiece, which is obtained from *Zeeko-TPG*. The position definition also includes information about the frame-of-reference of the coordinates. The motion definitions specify the robot's progress between these defined positions and also specifies the speed at which the motions will be carried out.

The Fanuc robot has limited memory for holding programs, which restricts the length of the LS files that can be generated. Unfortunately, this limit is smaller than most required tool paths. To circumvent this problem, tool paths can be broken into segments and generated as a series of LS files that do not exceed this limit. A Karel program was written which loads an LS file, converts it to a TP binary file, runs the program, clears it from robot memory on completion, and then loads the next file until the entire series has been run.

The process for the ABB robot is similar. Output coordinates from *Zeeko-TPG* are written into the correct syntax for ABB robots, resulting in a series of files. A calibration file contains robot parameters, such as the mass of the tool used by the robot and reference frame used for coordinates. Another file called a module file contains a list of the coordinates and velocities for each motion. A third file called the PGF file tells the robot the order in which to load this files - the calibration file following by the motion module file. The ABB robot has the same memory issue as the Fanuc robot. For the ABB, the tool path is divided into a series of motion module files and these multiple module files are included in the PGF file in the order to be run.

With these new additions to *Zeeko-TPG*, tool path files can now be generated in the appropriate file format for Zeeko CNC machines, and Fanuc and ABB industrial robots.

4.3 Automation of Zeeko machines using robots

One of the aims of the new robotics laboratory is automation of currently manual IRP machine operations. Tasks such as loading and unloading of parts and tooling are currently carried out by the machine operator. The use of a robotic arm and tooling such as grippers allows the development of a manufacturing cell, in which multiple CNC systems such as grinders, polishing machines and metrology systems may be tended by a robot. The current prototype system allows the IRP600 machine, shown in Fig. 2 (right), to be loaded and unloaded from a single user interface, rather than working with individual machines within the cell. By the end of August 2015, we expect that this interface will be further developed for remote command of pre-polishing setup tasks, such as surface-probing for polishing-path tilt-correction, and to execute polishing. This system is well suited to manufacturers who operate a controlled manufacturing environment, in which human ingress for direct interaction with machines is undesirable.

Zeeko has separately demonstrated the use of automatic sub-aperture metrology and texture metrology as methods of increasing both throughput and quality of measurement data [10,11]. The incorporation of such a metrology system into the existing prototype robot cell is providing an ideal environment for developing the basis of a fully-automated closed-loop manufacturing system.

5. ROBOT PROCESSING

We are examining two modalities – loose abrasives and bound diamond abrasives. A subset of results is presented in this paper. From empirical evidence, it is possible to smooth aspheres using hard tools and loose abrasives, providing that the abrasive grit size delivers an effective layer to bridge the aspheric misfit. Building on this, our first experiments have involved porting such processes onto the robot platforms, using solid brass tooling and aqueous aluminum oxide abrasive slurries.

5.1 Tool-wear with loose abrasive processing and hard tools

One important factor affecting efficiency of the grolishing process, particularly in regard to potential introduction of new mid spatial frequencies, is uniformity of pad wear. This is dependent on the operating conditions. Two different 280mm diameter pads has been used to investigate this. The original pad was a flat brass disk with no perforations or grooves, pre-lapped into intimate contact. In use, slurry was injected at the periphery. The modified grooved pad has a 20mm diameter central hole, and radial grooves spreading radially to the edge. Slurry was injected through the central hole and centrifugally dispersed by tool-rotation.

The part used was assembled of 5-off 1m a/c hexagonal float-glass sheets epoxied together, giving a total thickness of 75mm. Experimental parameters are shown in Table 2. A 6000 mm/min feed-rate gave a total process-time of 9 min 27s, which is considered short for a 1m part. Spindle speed constituted the process-variable.

Table 2 Experimental parameters

Traverse Speed	6000 mm/min	Tool Path	Raster
Part geometry	1 m hexagon	Tool	280mm dia. brass
Tool load	13.5 kg	Part material	Float glass
Abrasive	C20 aluminum oxide	Abrasive size	20 µm
Time	9 min 27s	Slurry Density by weight	1 abrasive: 3 water
Spindle Speed	20 ~ 120 rpm	Raster track Spacing	10 mm

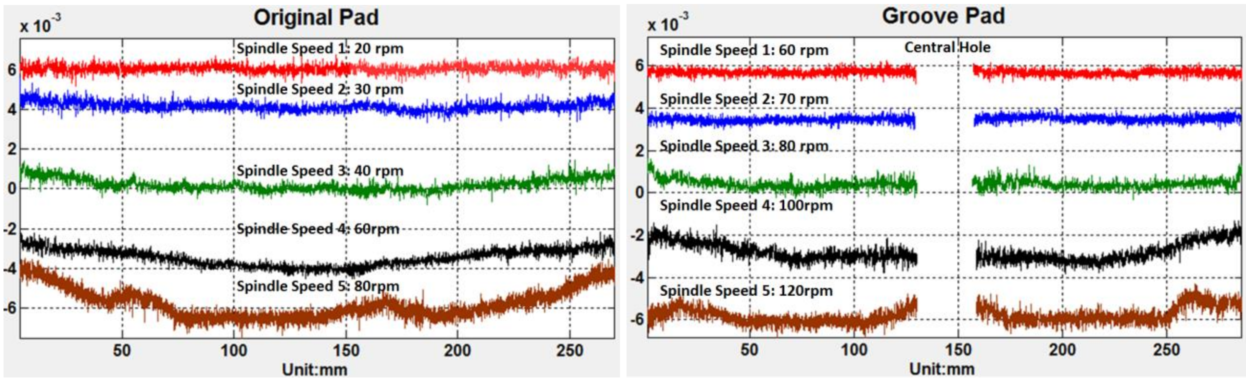


Fig. 4 Pad wear experimental results

For the original pad, 20 rpm was the maximum spindle speed for uniform pad-wear during the run. When the spindle speed was increased, so was pad irregularity, and at 80 rpm the wear showed sharp features. In contrast, the grooved pad showed uniform wear up to 70rpm, and this is attributed to superior slurry-mobility.

5.2 Mid spatial frequency reduction with hard tools

In the context of delivering an intermediate process-step to attenuate mid spatial frequencies from a previous process-step (e.g. CNC grinding of the base asphere), we are investigating the efficiency of different grolishing tools for use with the robots. An illustration of results using hard tools is shown in Figures 5, 6. Prior preparation of the part used a D20 unconditioned bound-diamond pad cemented directly to a 100mm diameter flat brass tool, in order to introduce mid spatial frequencies of approximately half a micron PV. The experimental run parameters were the same as Table 2 above, except that the grooved tool was used at a single speed – the optimum of 70rpm.

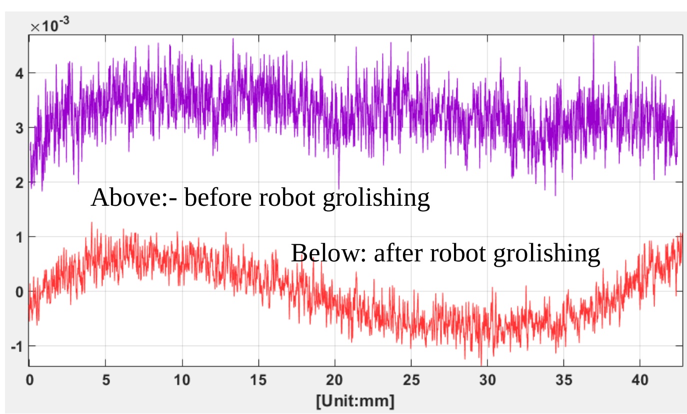


Fig. 5 Form Talysurf Intra profiles (50mm range) before and after grolishing, measured across the raster

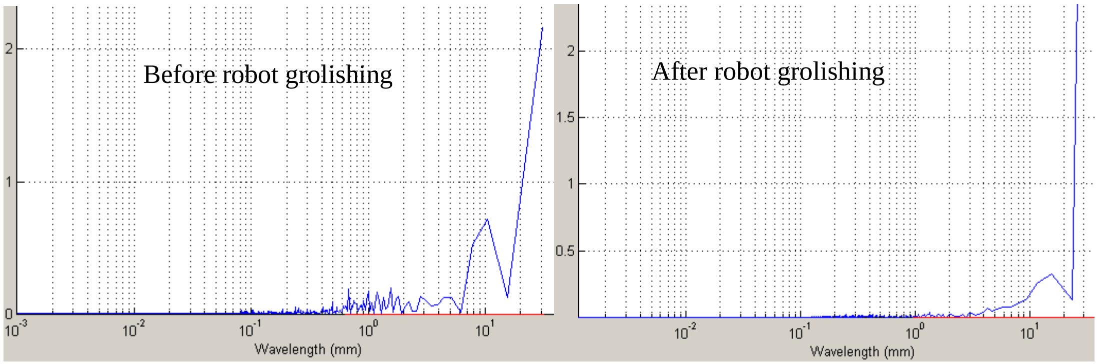


Fig. 6 Power Spectral Density plots before and after hard-tool grolishing

5.2 Bound diamond abrasive tools

We also report on bound diamond pads cemented to brass tooling, again used on the robot platform. As these pads can't be directly lapped into intimate contact with the work-piece, a compliant layer was provided between pad and brass.

Witness samples of borosilicate glass were first prepared by classical lapping on an orbital machine. Measured volumetric removal rates and textures are given in Table 3.

Table 3 Removal rate and surface texture with different bound diamond abrasives grit sizes

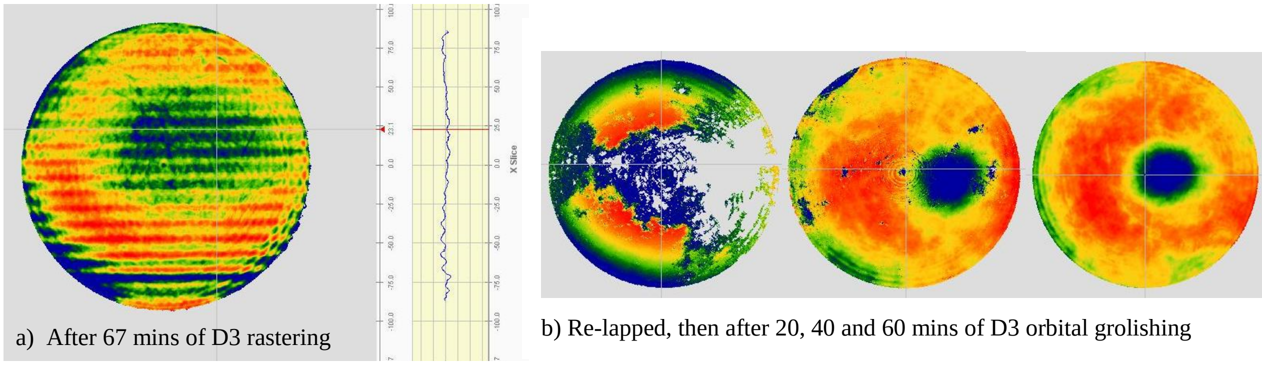
Diamond grit size	D20	D9	D3
Removal rate (mm^3/min)	38.56	2.69	0.68
Surface texture (Sa)	392 nm	138 nm	52 nm

A 400mm hexagonal flat borosilicate glass part was pre-lapped with C9 abrasive on a cast iron lapping plate, using a traditional orbital machine. The entire part was then raster-grolished for 68 mins on the robot platform using 3 micron bound-diamond abrasive ('D3'). The surface was immediately measurable using a 186mm diameter beam-expander and 4D technologies simultaneous phase interferometer (Fig. 7a), revealing 60nm PV raster features, but no data drop-outs.

The part was then re-lapped as before, and the entire surface grolished using twelve successive 5 min runs with an orbital tool-path (implemented within Zeeko TPG software). Fig. 7b shows four intermediate measurements of the surface as it evolved.

Table 4 Experimental parameters for 400mm hexagonal part

Traverse Speed	1500 mm/min	Robot Tool Path	Raster or orbital
Part geometry	400 mm hexagon	Tool	100 mm dia. tool with diamond pad
Tool load	8.7 kg	Part material	Borosilicate
Abrasive type	Bound diamond	Abrasive size	3µm (D3)
Spindle Speed	300 rpm	Track Spacing for raster	10 mm



a) After 67 mins of D3 rastering

b) Re-lapped, then after 20, 40 and 60 mins of D3 orbital grolishing

Fig. 7 Comparison of interferograms after D3 grolishing of pre-lapped parts with a) raster and b) orbital tool-paths

6. CONCLUSION

We have successfully integrated the control of Fanuc and ABB robots within the Zeeko tool path generator software, providing control of robot systems with access to the comprehensive suite of Zeeko algorithms and utilities.

Robot mounting and demounting of parts on an IRP600 CNC polishing machine, and an adjacent auxiliary metrology station, has been implemented. This has provide the first fully-operational demonstration of a robot automating the currently manual operations on the Zeeko machine, and provides a sound basis for expanding the range of operations that can be automated.

Tool spindles have been implemented on two robots, enabling direct pre-processing of surfaces using robots. Loose-abrasive grolishing, operated under Zeeko TPG control, has been demonstrated using the ABB and large Fanuc robot, establishing the ability to attenuate deliberately-introduced mid-spatial frequencies. This work has also investigated tool-wear and optimum spindle speed. D20, D9 and D3 bound-diamond pads mounted on a compliant layer have also been characterized for volumetric removal rates and delivered texture, using the large Fanuc robot. D3 in particular has shown ability to produce surfaces which are directly measureable with an interferometer without data drop-outs, and well-matched to corrective polishing. This establishes the ‘missing link’ between i) smoothing processes that leave non-specular (grey) surfaces, and ii) metrology-dependent post-processing to refine form and texture using a Zeeko machine.

Planned future work includes demonstration of the techniques (especially compliant tooling) on aspheres. The work is intended to progress to the development of an optimized process-chain, bridging the gap between CNC grinding and CNC pre- and corrective polishing, in order to minimize total process-time. This will then be melded with the robot automation work to provide the core of a fully functioning manufacturing cell with dual-purpose robot and Zeeko machine.

We are optimistic that these developments will have a significant impact on reducing manufacturing times and risk for producing small and large optics, including mirror segments for extremely large telescopes.

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