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**Abstract.** An IRB6620 industrial robot from ABB Co. Ltd. (Zurich, Switzerland) is used as a processing platform for optical processing, and computer-controlled optical surfacing is applied as a key technology. The function of each coordinate system of the robot in processing is reviewed, as well as the relationship of each coordinate system and coordinate transformation. An algorithm governing coordinate transformations is provided. In order to assess the functionality of the robot as a polishing instrument, experiments have been designed so that the removal rate and surface form error correction of the robot facility have been compared with those from established computer numerical control polishing. The importance for the application of industrial robot in optical processing is also presented. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.53.5.055102](https://doi.org/10.1117/1.OE.53.5.055102)]

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## 1 Introduction

With the advance of modern technology like computer numerical-controlled (CNC) machining, much more complicated systems can be fabricated, although new process technologies are still under intensive research. Some of these new optical systems are very large in size. Some of them have thousands of optical elements, such as the National Ignition Facility (NIF) introduced by Campbell et al.,<sup>1</sup> and a ground-based telescope (European-Extremely Large Telescope, E-ELT) with a diameter of 39.3 m, which is being built by European Southern Observatory, mentioned by Gilmozzi and Spyromilio.<sup>2</sup> These two are examples of modern, complex optical systems. These optical systems have some common properties such as large aperture and many optical elements (e.g., segments). So, the modern optical manufacturing technology has to meet the requirements of fabrication of big aperture, high-precision optics with fast speed and a cost-effective process.

Computer-controlled optical surfacing (CCOS) is a technology of optical manufacturing, first developed by Itek in 1970s. Jones and Rupp<sup>3-10</sup> and some other researchers have reported some research works about it. The CCOS has been developed rapidly thanks to the development of the computer technology from the late 1980s. Deterministic control for removal is the most important feature of CCOS technology different from that of traditional optical processing. This technology is now a major method for optical manufacturing and has a very important role in processing of large-diameter, high-precision aspherics (especially off-axis aspherics). In this process, a wheel head that is much smaller than the aperture of the work-piece is used. The wheel head works on the

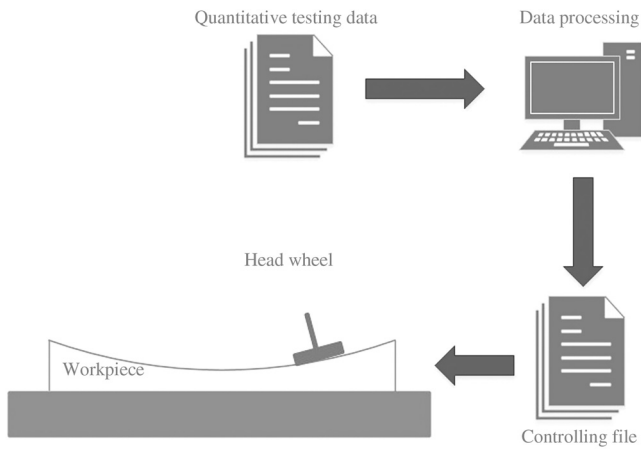
surface of the work-piece following certain paths under the control of the computer. Figure 1 shows the basic diagram of CCOS technology.

The theoretical foundation of CCOS is the Preston equation. The core of this technology is that the computer controls the polishing tool's dwell time, rotating speed, or pressure on the surface, aiming at different removal amounts at different points, according to the measurement results. Generally, the surface error will continue to converge after each correction run until specifications are met. Many kinds of surfaces could be polished by CCOS technology such as plano, spherical, cylindrical, aspherical, and even freeform surfaces. In fact, in many application areas, computer-controlled polishing and figuring equipment have already been widely accepted. Examples are the Zeeko Ltd IRP (Leicester, United Kingdom) corrective polishing machines reported by Walker,<sup>11-13</sup> QED Q-series magnetorheological finishing (MRF) figuring machine discussed by Golini,<sup>14-16</sup> and ion beam figuring (IBF)-series machines from NTG Co. (Gelnhausen, Hessen, Germany) discussed by Franz and Hänsel.<sup>17,18</sup> Although the tooling is different, and MRF and IBF require polished surfaces as input, the error correction principles are similar to those described above. However, these devices are all expensive and this has prevented them from being even more widely used.

As the demands of producing large and increasingly complex aspheric optics become higher, the need of a new polishing system that can meet up to these new challenges has motivated us to develop a new polishing system. Also, we hope that the new polishing systems could have large processing ranges, high-machining quality, and most important, is that they are cost-effective.

After years of development, industrial robots have been widely used in many fields, such as welding, painting,

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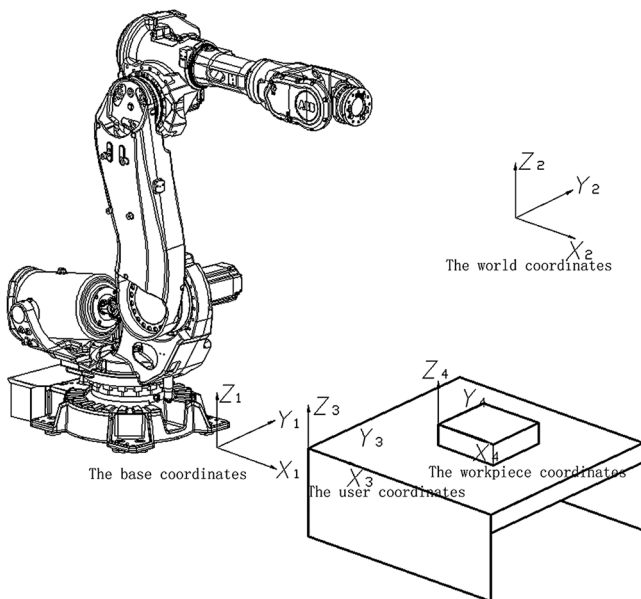


**Fig. 1** Schematic diagram of a generic computer controlled optical surfacing technology.

assembly, handling, palletizing, and so on. They are being used in polishing applications more and more often, but mostly for polishing ceramic sanitary products. The function is mainly to improve the surface roughness rather than control the surface's form error accurately. The industrial robot has good mechanical characteristics like large range of space motion, strict six-axis synchronization, and relatively low price, so that they could be used in modern optical polishing as a processing platform carrying a wide range of tooling.

## 2 Coordinate Systems of the Industrial Robot

Although the robots have very good mechanical characteristics, their internal coordinate systems are complex. Therefore, the conversion of the internal coordinate systems of the robot, the coordinate system for optical design, and the coordinate system for actual processing are very important. It is also one of the key factors for industrial robots to be used in high-precision optical polishing. An algorithm for coordinate transform is reported in this article.



**Fig. 2** The base-coordinate, world-coordinate, work-piece coordinate, and user-coordinate systems of the robot polishing configuration.

For an industrial robot, its internal coordinate systems include the base coordinates, the world coordinates, the user coordinates, the work-piece coordinates, and the tool coordinates. All these coordinate systems follow the right-hand law, as shown in the Fig. 2.

The base coordinates are defined on the main robot mounting-flange. Its origin  $O$  is the projection of the axis of rotation of the first axis onto the plane of the robot base, which defined as  $XOY$ .

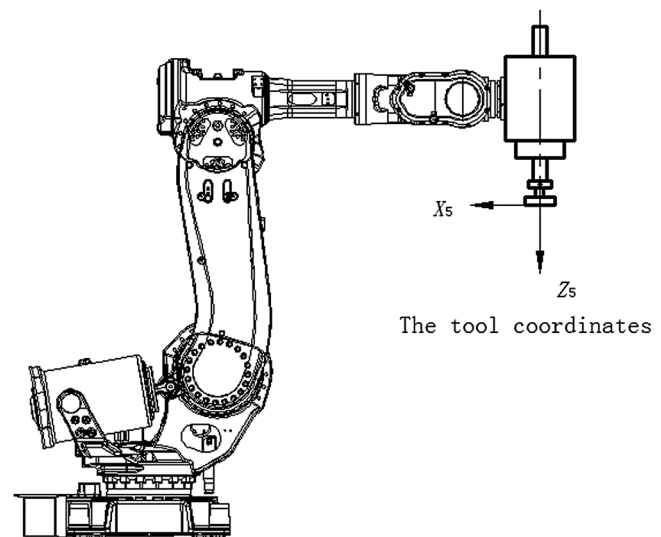
For process-users, the coordinates of the worktable are used as a reference for programming. The coordinates of the worktable are named as the user coordinates. When the table is displaced or rotated, a corresponding change of the user coordinates would be sufficient, instead of reprogramming. This is the benefit of using the user coordinates.

If there are several work-pieces on the worktable in-process, individual coordinates for each work-piece maybe defined. The benefit for using individual coordinate system is that the controlling program could be modified easily if any work-piece needs to be relocated. The separate coordinates for each work-piece are named as work-piece coordinates. In the process, the user needs to define a coordinate that would be convenient toolpath according the placement and shape of the work-piece. Besides, the work-piece coordinates are useful when the robot is in "teach-mode."

When the machining tool is mounted onto the end-flange of the robot, it is necessary to define its own coordinate system. Its origin coincides with the center of the tool [tool centre point (TCP)]. TCP describes the relationship of displacement and rotation between the machining point of the tool (it is assumed to be the geometric center of the polishing head in this article) and the center position of the robot end-flange. When a new tool is installed, a revised tool coordinate-system is needed, instead of reprogramming. Figure 3 shows the tool coordinates when the polishing tool is mounted on the robot.

## 3 Coordinates Selection and Conversion Algorithm in the Process

According to the laboratory arrangement, the robot is mounted on the ground so that the base coordinates coincide



**Fig. 3** The tool coordinate system when the polishing head is mounted onto the robot end-flange.

with the world coordinates. During the process, the work-piece is fixed onto the work-table so that the relative position of the work-piece and the table remain unchanged. Therefore, only one work-piece coordinate-system needs to be defined.

After defining the work-piece coordinates and the tool coordinates, the process operates in the reference of the work-piece coordinates, so that the tool always points to the surface normal direction.

The design coordinates of the work-piece are normally provided by the designers, in the drawings adopting a simple form. Therefore, a special method is needed to achieve the transformation from the design coordinates to the coordinates of the robot. Figure 4 shows all the transformations needed in the entire process.

Three variables are in general needed when motion of a datum on the end flange of a six-axis robot is commanded, namely position variables (pos), rotation variables (orient), and posture variables (confdata).

Position variables (pos) could be expressed as  $(x, y, z)$ , indicating the  $x, y, z$  position of the point in the reference coordinates. Also, it means the projection of a machining point on the work-piece on the  $x$ -,  $y$ -, and  $z$ -axes in the process. Rotation variables are expressed as  $(q1, q2, q3, q4)$ . In the process, the position of the tool is determined by pos, and the direction of rotation is determined by orient. Tools need to have the direction perpendicular to the work-piece surface, so if the surface processed is flat, orient can kept as a constant, however, if the surface is a spherical surface or free-form surfaces, rotate variables must keep changing with the processing paths.

Generally,  $(\alpha, \beta, \gamma)$  is used to indicate the rotation angles, along with the  $X, Y,$  and  $Z$  axes, respectively, and they are replaced by variables as  $(q1, q2, q3, q4)$  in the robot system.

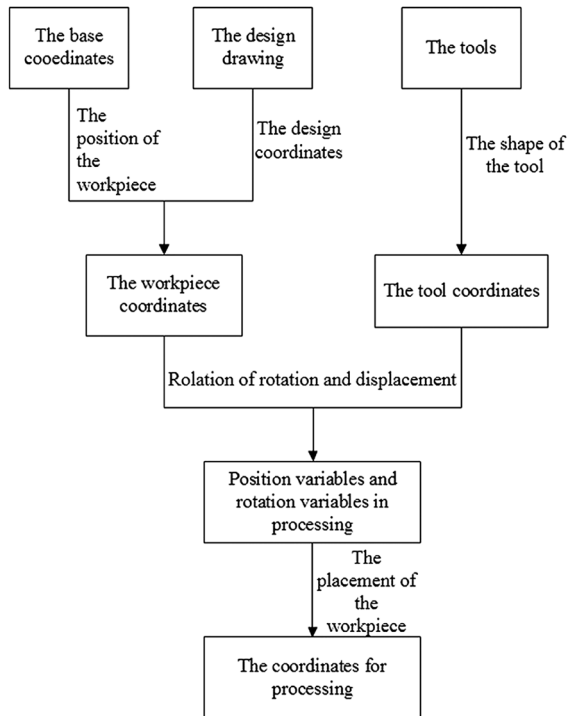


Fig. 4 The complete set of transformations needed for the entire process.

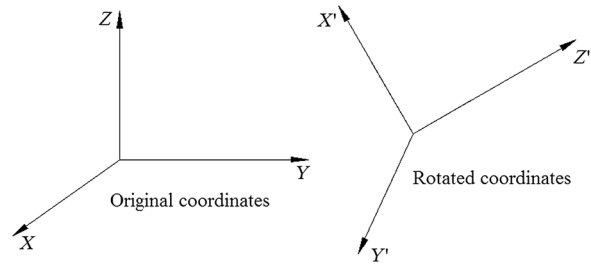


Fig. 5 The rotated coordinates in the original coordinate frame.

A rotated coordinates  $(x', y', z')$  in the original coordinates is shown in Fig. 5.

It could be expressed as

$$\vec{n}_x = (x_1, x_2, x_3), \quad \vec{n}_y = (y_1, y_2, y_3), \quad \vec{n}_z = (z_1, z_2, z_3).$$

So, the orient  $(q1, q2, q3, q4)$  can be expressed as

$$\begin{aligned} q_1 &= \frac{\sqrt{x_1 - y_2 + z_3 + 1}}{2}, \\ q_2 &= \frac{\sqrt{x_1 - y_2 - z_3 + 1}}{2} \quad \text{sign } q_2 = \text{sign}(y_3 - z_2), \\ q_3 &= \frac{\sqrt{y_2 - x_1 - z_3 + 1}}{2} \quad \text{sign } q_3 = \text{sign}(z_1 - x_3), \\ q_4 &= \frac{\sqrt{z_3 - x_1 - y_2 + 1}}{2} \quad \text{sign } q_4 = \text{sign}(x_2 - y_1). \end{aligned} \quad (1)$$

Also, the orient should meet the requirement that  $q_1^2 + q_2^2 + q_3^2 + q_4^2 = 1$ .

Because of the special structure of the six axis robot, it may be that different postures can deliver the same tool position and angle, as shown in Fig. 6. It means that there are different solutions for a fixed pos value and a fixed orient value. Thus, a posture variable, confata, is needed to determine the position of the axes.

The confata variable could be expressed as  $(cf1, cf4, cf6, cfx)$ , which  $cf1, cf4, cf6$  denote the angular position of axis one, four, and six, respectively. For the robot IRB6620,  $cfx$  is default.

Assuming the equation of the optical surface processed can be expressed as

$$F(x, y, z) = 0,$$

and normal vector for an any point  $M(x_0, y_0, z_0)$  on this surface is

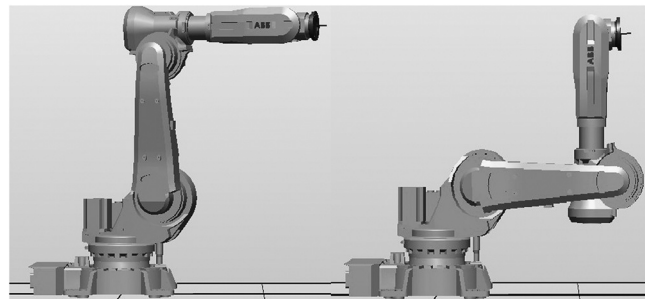


Fig. 6 The same tool positions and angles, but with different robot postures.

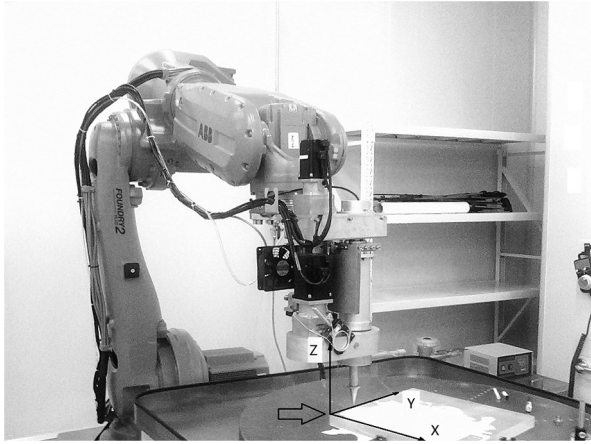


Fig. 7 The experimental setup for robot polishing trials.

$$\vec{n} = \{F'_x(x_0, y_0, z_0), F'_y(x_0, y_0, z_0), F'_z(x_0, y_0, z_0)\}$$

The following calculations determine the vectors of  $nx$ ,  $ny$ , and  $nz$ , which are the unit vectors for  $X$ ,  $Y$ , and  $Z$  axes of the tool coordinates in the reference coordinates. First of all,  $nz$  can be determined. Its direction is reverse with the normal vector of the surface according to the definition. It is

$$n_z = \left[ \frac{-F'_x(x_0, y_0, z_0)}{c_1}, \frac{-F'_y(x_0, y_0, z_0)}{c_1}, \frac{-F'_z(x_0, y_0, z_0)}{c_1} \right], \tag{2}$$

where  $c_1 = \sqrt{F'^2_x(x_0, y_0, z_0) + F'^2_y(x_0, y_0, z_0) + F'^2_z(x_0, y_0, z_0)}$ .

According to the calculations,

$$n_x = \left\{ \frac{x_0}{\sqrt{x_0^2 + \left[ \frac{-x_0 \cdot F'_x(x_0, y_0, z_0)}{F'_z(x_0, y_0, z_0)} \right]^2}}, 0, \frac{\frac{-x_0 \cdot F'_x(x_0, y_0, z_0)}{F'_z(x_0, y_0, z_0)}}{\sqrt{x_0^2 + \left[ \frac{-x_0 \cdot F'_x(x_0, y_0, z_0)}{F'_z(x_0, y_0, z_0)} \right]^2}} \right\}, \tag{3}$$

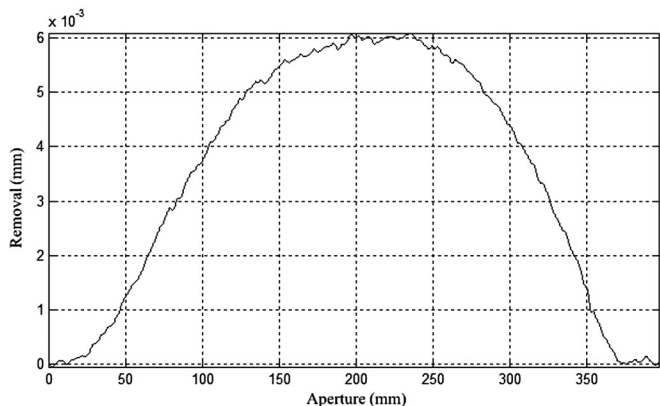
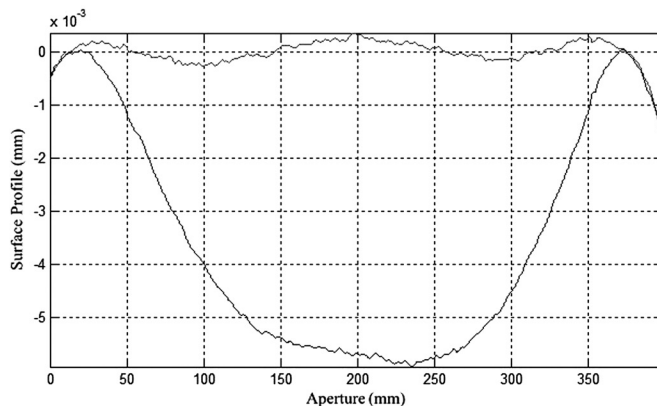


Fig. 8 Removal test results from the robot facility.

$$n_y = \left[ \frac{x_0 \cdot F'_x(x_0, y_0, z_0) \cdot F'_x(x_0, y_0, z_0)}{F'_z(x_0, y_0, z_0)}, \frac{-x_0 \cdot F'_z(x_0, y_0, z_0) - \frac{x_0 \cdot F'_x(x_0, y_0, z_0)}{F'_z(x_0, y_0, z_0)}}{c_1 \cdot c_2}, \right. \\ \left. \times \frac{x_0 \cdot F'_y(x_0, y_0, z_0)}{c_1 \cdot c_2} \right], \tag{4}$$

where  $c_2 = \sqrt{x_0^2 + \left[ -x_0 \cdot F'_x(x_0, y_0, z_0) / F'_z(x_0, y_0, z_0) \right]^2}$ .

So, the orient could be obtained by substituting Eqs. (2)–(4) into Eq. (1). With this calculation result, the processing coordinates could be determined after determining the placement of the work-piece, as shown in Fig. 4.

## 4 Experiments

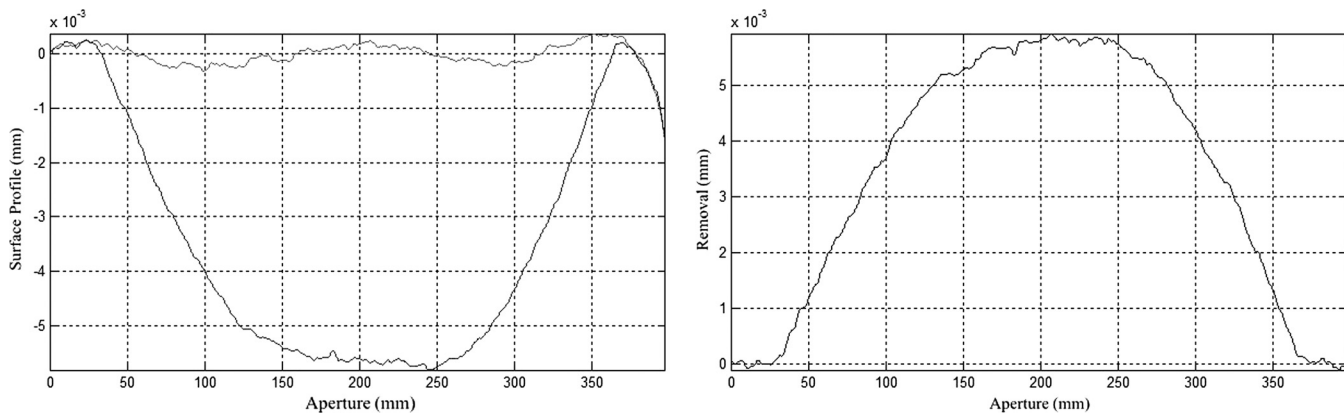
The experimental setup is shown in Fig. 7. The user coordinates are determined after the part is fixed onto the worktop. The origin of the user system is shown by the arrow. To compare the quality of the polishing results, the same work-piece has been used on this robot and on an IRP600 polishing machine from Zeeko. With the identical polishing parameters, the material removal rate and interferometer data of the surface form have been compared.

### 4.1 Removal Rate

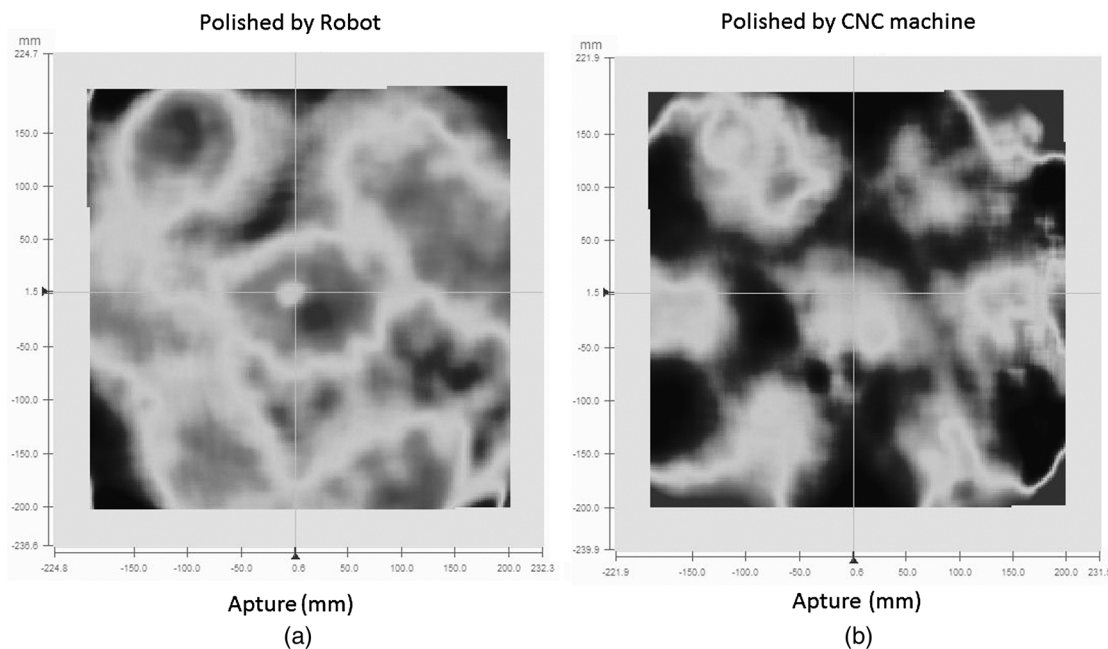
The work-piece used is a 400 × 400-fused silica part with a plano surface. The polishing tool has been conditioned so that its surface matches well with the work-piece. The processed area is designed so that there is an untouched area on the surface, to be used as fiducial for surface profile measurement. A Taylor Hobson Form Talysurf profilometer has been used. Data stitching has been applied using bespoke software. The surface is measured before and after polishing. The subtraction of these two curves represents absolute surface removal across the full aperture. Very similar removal characteristics have been achieved by these two machines, as can be seen in Figs. 8 and 9.

### 4.2 Surface Form

Another experiment has been carried out to inspect if the machines will leave characteristic signatures. The surface was first prepared by traditional lapping and prepolishing. The surface was then measured using an interferometer



**Fig. 9** Comparative removal test results from the Zeeko computer numerical control (CNC) polishing machine.



**Fig. 10** Interferometry results from (a) the robot facility and (b) the Zeeko CNC polishing machine.

and the data has been used for surface form correction. After the seventh correction, the surface forms can be seen in Fig. 10. The RMS error has achieved 9.83 and 7.26 nm, respectively, (tilt and power terms removed) from the robot and the CNC polishing machine. There are no significant mid-spatial errors left by any of these two machines.

## 5 Conclusions

In this article, an IRB6620 industrial robot from ABB Co. is used in the process of optical polishing, because of its mechanical characteristics, such as large range of motions, strict six-axis synchronization and relatively low price. The CCOS technology is adopted as the core technology. It is a deterministic polishing technology in which all tool parameters are precisely controlled with a subaperture tool, to achieve deterministic control of material removal. This technology is widely used as the principle method for optical processing and

has a very important role in the processing of large-diameter, high-precision aspheric surfaces.

Coordinate systems of the robot and their functions in optical processing are introduced in this article, as well as the relationship of each coordinate system. The conversion of the internal coordinate systems of the robot, the coordinate system for optical design, and the coordinate system for actual processing is researched in this article. An algorithm for coordinate transformation is obtained. We can obtain the coordinates for processing when the placement of the work-piece is determined. It is an important foundation for subsequent processing steps.

Removal-rate and surface-form correction tests have been carried out, to test the quality and efficiency of the robot process. The results from this facility have been compared with equivalent process results from a polishing machine of an established manufacturer. The aim is to verify the accuracy of these derived equations and user coordinates. The test

results have shown very similar quality both in removal-rate and quality of surface-form, under identical process parameters. Within the limits of the preliminary experiments reported, the potential has been demonstrated for the industrial robot to be developed as a cost-effective complement or alternative to CNC polishing machines. In general, robots deliver higher surface-speeds and accelerations, but with significantly lower stiffness and positioning accuracy. Therefore, a likely result is that the two methods will eventually demonstrate distinct (but overlapping) applications where their individual performances are optimum.

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