Closing the metrology/process loop in CNC polishing

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ABSTRACT

This paper builds on previous reported work describing the marriage of robots and CNC polishing machines, both for the pre-processing of parts, and to automate operations hitherto manually conducted on the CNC platforms. This paper reviews strategies for metrology, then takes the work a stage forward by reporting the use of a robot to automate the exchange of a part between CNC machine and metrology station, the probing of the part, and the capture of interferometer data. This constitutes an important step towards realization of an automated manufacturing cell.

Keywords: Robot, automation, interferometer, metrology, manufacturing, surface

1. INTRODUCTION

We have previously described [1,2,3,4] our work combining industrial robots and CNC polishing machines in a Manufacturing Cell for functional surfaces, where a robot can play the dual roles of automating manual operations on the CNC platform(s), and provide an effective surface-smoothing capability in its own right. We have drawn attention to the complementary properties of standard CNC machines and robot platforms, in regard to their comparative speeds and accelerations, precisions of motion, and first resonant frequencies.

In this paper, we report on new work extending the scope of a Cell to incorporate a metrology station, and demonstrate how the transfer and alignment of the part, and acquisition of metrology data, can be very effectively automated. We have also demonstrated an automated ability to probe the part on-machine and then incorporate the probing data in the CNC control file. The purpose of this is to assure true registration of the CNC coordinate frame with that of the part. These advances constitute key developments towards our ultimate vision of a fully autonomous manufacturing cell. The distinguishing features are

i) The iterative nature of the processes deployed, where details of each process-step depend on analysis of the output of the preceding step
ii) the flexibility in manufacturing parts which are each of customized design (i.e. different in detail), or parts which are of completely distinct geometry, size or material.

The first point above means that it is impossible to define *a-priori* the detailed sequence of operations to be performed. Repeated metrology and feedback into the process is fundamental, and therefore it is very relevant to consider how the metrology is conducted. The second point is in direct contrast to mass-production lines as currently implemented.

Our philosophy of an autonomous manufacturing cell for customized precision and ultra-precision surfaces has been developing over several years, and has converged with the German concept of the *Fourth Industrial Revolution* – ‘Industry 4.0’ for short, part of the high-tech strategy of the German Government. The term was first used at the Hanover Fair in 2011 [5], where the final report of the Working Group Industry 4.0 was presented [6]. In this world-view, the four industrial revolutions comprise:-

- First industrial revolution – mechanization, water and steam power
- Second industrial revolution – mass-production, assembly-line, electricity
- Third industrial revolution – computer and automation

- Fourth industrial revolution – cyber physical systems

In this view, the advent of cyber and interconnected systems will revolutionize mass production, because it will lead not only to truly-autonomous manufacturing cells, but also the seamless linking to a design-optimization function. It will then no longer be necessary for mass-produced items to be identical; each may be automatically customized for its specific end-use or user:- hence the term, 'bespoke mass production'. This was further discussed at the Royal Society and Fraunhofer Joint Symposium on Innovation, 'Mind to Market' in London, May 2014.

2. ON-MACHINE VERSUS OFF-MACHINE METROLOGY

In the case of standard optical shop practice, large optics are often left on the CNC polishing machine turntable for the entire process/metrology sequences. The machine is then typically located under an optical test tower for full-aperture interferometric metrology. An example of this is shown in Figure 1, where fringe-finding has been automated (Figure 2) by feeding back the phase-maps from a 4D Technologies simultaneous phase interferometer on the test tower, to an automated motion stage incorporated in the test tower. Smaller specialized metrology instrumentation (e.g. for texture, sub-aperture interferometry etc) may also be deployed on the machine, or positioned directly on the surface of the part.

Figure 1. CNC polishing machine integrated with optical test tower for on-machine interferometry

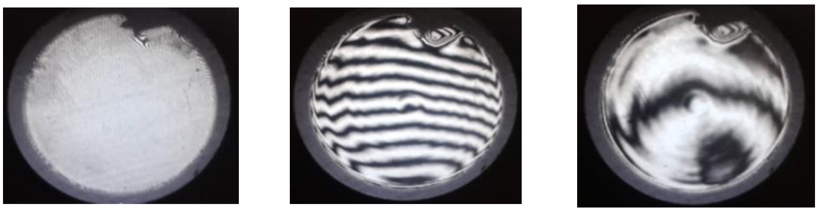

Figure 2. Sequence of interferograms demonstrating automated fringe-nulling on the test tower

When considering on-machine metrology, the balance of advantages and disadvantages is shown below in Table 1.

Table 1 Comparison of on- and off- machine metrology for conventional handling

On-machine metrology		**Off-machine metrology**	
Advantages	Disadvantages	Advantages	Disadvantages
Reduced part-handling			Risk in handling part
Alignments maintained			Re-align at each cycle
Process-contamination minimised			Risk of process contamination
	Machine unavailable for metrology during polishing	Machine available all the time	

	Metrology unavailable during setup, polishing and wash-down	Metrology infrastructure shared between parts	
	Possible danger to part deploying some metrology	Deploying metrology does not risk part	
Minimal human intervention required			Maximum human intervention

Now, consider the case of CNC polishing of modest-sized parts, but with the addition of:-

1. A robot to load/unload parts at the CNC polishing machine
2. A separate metrology station
3. Precision fixturing for the part both at the polishing machine and the metrology station
4. A robot gripper compatible with the fixturing
5. Automated wash-down between polishing and metrology

The balance of advantages and disadvantages is then changed, as shown in Table 2

Table 2 Comparison of on- and off- machine metrology with robotic automation

On-machine metrology		**Off-machine metrology**	
Advantages	Disadvantages	Advantages	Disadvantages
Minimal part-handling		Minimal part-handling	
Alignments maintained		Alignments maintained	
Process-contamination minimised		Process-contamination minimised	
	Machine unavailable for metrology during polishing	Machine available all the time	
	Metrology unavailable during setup, polishing and wash-down	Metrology infrastructure shared between parts	
	Possible danger to part deploying some metrology	Deploying metrology does not risk part	
Minimal human intervention required		No human intervention	

3. EXPERIMENTAL TEST BED FOR DEVELOPMENT OF AN AUTOMATED CELL

We have taken significant steps towards implementing a practical automated polishing cell using a robot, through our new Test Bed (Figure 3). This positions a robot between a Zeeko IRP600 machine and a metrology station incorporating a Fisba interferometer on a precision XYZ motion-stage. The software has been developed to enable the successful demonstration of the following automated sequence of operations:-

1. Load the fixtured part onto the metrology station using the robot
2. Align the interferometer in X,Y,Z to find and fluff-out the fringes
3. Capture interferometer data
4. Load the fixtured part onto the IRP600 CNC polishing machine using the robot
5. Probe the part at several locations over its surface using touch-on of the polishing bonnet
6. Compute a non-liner fit to the probing data over the part's surface
7. Correct the CNC file using the probing data to correct the position of the part in the machine coordinate frame
8. Initiate a polishing run

Figure 4 shows screen-shots of Fisba interferograms before and after auto-fringe nulling.

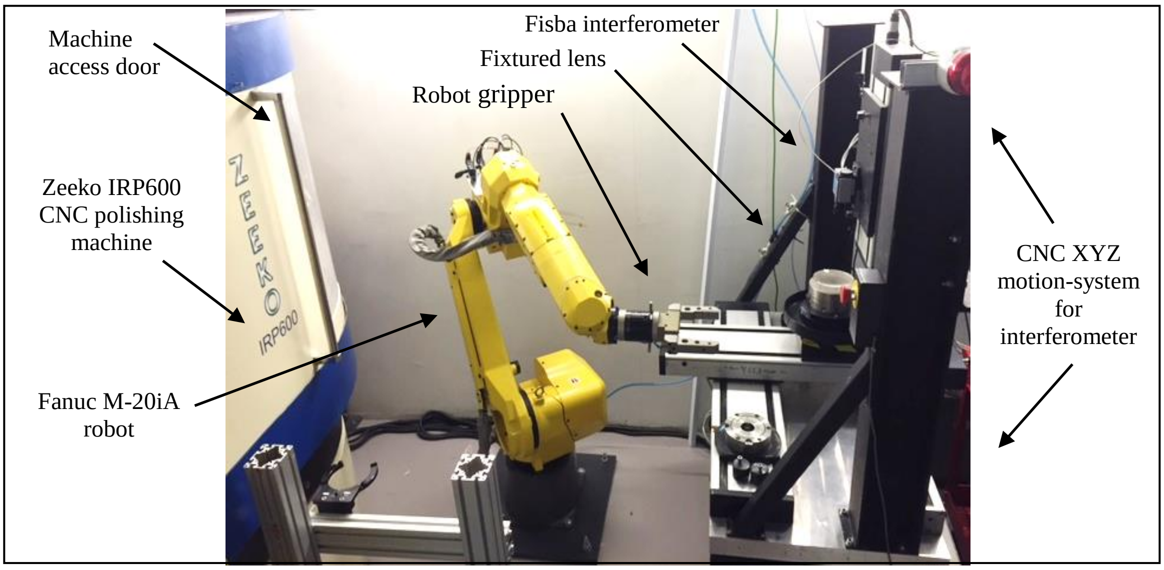

Figure 3. Robot-cell Test Bed for automation development

Figure 4. Screen shots of Fisba fringes before and after auto-nulling, and the resulting phase map

The next stage in this development will be to install an automated wash-down facility, to be performed by the robot arm. This will enable the loop Step 8 => Step 1 to be completed

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