connected everything.

industrial systems in the digital age

Feasibility of capturing crafts-based knowledge in an AI System for future autonomous precision surface manufacturing

Professor David Walker
University of Huddersfield

EPSRC
Engineering and Physical Sciences Research Council

Executive Summary

Our ultimate objective is to automate manufacture of ultra-precision surfaces, as used in optics, medical implants, moulds and dies, turbine blades etc. Even using advanced CNC grinding and polishing machines, expert operators are required:

i) to define *ab-initio* process-chains for specific materials, geometries and tolerances, then
ii) at different stages of processing to interpret measurement data and make appropriate decisions, and finally,
iii) to decide when to terminate processing. These experts are in short supply and retiring.

The project has assessed feasibility of capturing their craft-skills in a digital manufacturing system deploying AI techniques. The obtained results will serve as a foundation for the AI autonomous manufacturing cell that we plan to develop.

1. Research challenge

The project has investigated the challenge of determining which specific craft-based knowledge could reasonably be captured, what sorts of information can be secured directly from machinists, how to do so when faced with possessiveness of knowhow, and what types of interview are most effective to facilitate extraction of knowledge/expertise. It has also proposed how to represent that knowledge, and use it for processing a new part. Finally, it addresses where crafts-knowledge might more effectively be captured indirectly.

2. Context

Science, industry, space, defence, consumer products and healthcare all demand functional surfaces with increased complexity, tighter tolerances, in less time with lower cost. Material-types run into hundreds, with different physical, chemical and thermal properties. Ultraprecision polishing in particular is some way from deterministic, requiring operator monitoring or intervention at every step. Skilled know-how is the foundation for future autonomous manufacturing, but will be irrecoverably lost if steps are not taken to capture it.

3. Approach

A psychologist on the project was involved in knowledge elicitation. Project members with manufacturing expertise created a Scenario/Case-Study, in which three skilled machinists participated. The task was reasonably challenging, but of manageable complexity. The machinists were provided with a glass part with defined characteristics. Think-aloud verbal protocol was used to elicit machinists' knowledge. During the polishing task, the machinists were asked to 'think aloud' by verbally expressing their internal thoughts, whilst wearing a portable camera and lapel microphone. From analysis of this information, flow charts were constructed which showed the sequence of process-steps performed by the three machinists.

A key question arose – in which steps of corrective polishing do the machinists particularly use their skills/knowledge? We assigned a Case-Based Reasoning (CBR) system to each of the process steps. CBR enables the re-use of concrete relevant experience from the past, when dealing with a new task. As a brief idea of CBR, each case contains specific knowledge/expertise applied in a specific context in order to decide on the next step. Some of the attributes of a Case concern characteristics of the part: diameter, thickness, radius-of-curvature, material (which implies chemical, thermal and mechanical properties), description of the surface error-map, etc.

In a full implementation, the Case-Base would communicate with data-bases which contain relevant data about materials. Each Case suggests the values of the parameters that the machinist (or the automated equivalent) sets in the particular step, which serves as input to the tool-path generator software (TPG) on the CNC polishing machine.

It was necessary to define a similarity measure to determine which Case from the Case-base was the most useful for polishing a new part. For example, the material is critical because it determines the removal rate and the optimum conditions to achieve texture. As another example, the radius of curvature affects the process angle-of-attack. The standard simple similarity-measure is the k-neighbour similarity, which measures the weighted difference between feature-values of the new Case, and Cases from the Case-base. However, the project has shown that we need a better similarity measure to take into consideration how specific or general are some values of Case attributes. For that reason, we plan to define ontology of concepts in ultra-high precision manufacturing, which will enable the system to infer the level of similarity between two concepts, how specific are the concepts/values, or what is the level of commonality between two compared concepts. A pair of specific values should be more important in the definition of similarity, than two concepts that may have the same value, but are rather general.

As regards novelty, we are not aware of any previous attempts to capture crafts knowledge in a high-tech. manufacturing context by applying psychological techniques as above, or indeed by indirect data-capture as below.

4. Implementation

The experimental work was implemented on a Zeeko IRP1200 CNC polishing material, using a 110mm dimeter glass sample, which had previously been pre-machined to a concave spherical surface. Metrology was conducted using a 4D Inc. interferometer, providing topological maps of the surface-errors with respect to a perfect sphere. Implementing the interviewing and monitoring of the three crafts operators required considerable prior negotiation with their commercial employer, reinforcing our view that we were treading on very sensitive ground. Personal privacy issues were particularly pressing with one of the interviewees, and all were clearly possessive of their knowledge. We were required to edit video footage, deleting any record of human faces, bespoke tooling or anything else sensitive in the workshop. We were asked to edit the audio, to mute secondary background conversations, but this proved impractical and was not conducted.

4. Summary of Results

It is well known that elicitation of knowledge is not easy. After troublesome negotiations with management as above, we demonstrated that relevant aspects of the knowledge of three skilled operators could be encoded in Cases, in a way that would underpin future autonomous manufacturing. Considering how this might be rolled-out in a commercial environment points to a hybrid solution. Where practical, automated digital data-logging of process-variables should be implemented, before and after every process step, and in real-time during processing. This should include unique identification of each piece of hardware deployed on the machine (fixtures, tooling etc.), using QR codes or equivalent. In particular, user-selected process-parameters should be comprehensively auto-data-logged, and operators prompted to enter manually the parameters difficult to auto-log (e.g. slurry-composition/additives).This philosophy will moderate the task of direct elicitation of knowledge, which can then focus on key aspects such as the logic behind decision made, 'tricks of the trade', and strategies for recovering from unexpected process-errors. One practical scenario in an industrial context, would be for digitally-recorded operator-decisions (e.g. select tool X, head-speed Y etc.), to prompt questions as to the logic behind the decisions, which the operator would answer verbally before the next step could be executed.

6. Wider Applications

The techniques for which feasibility has been explored are relevant in other domains. These concentrate in areas where crafts expertise is important to achieve optimum results, but are challenged by skills' shortages. This is amplified where automation is needed to reduce costs and delivery times. Candidate areas range from gastronomy at one extreme, to robotic surgery at the other.

7. Future Plans

We already undertake basic data-logging of key process variables defined prior to a polishing run. We plan to secure funding to implement comprehensive pre/post-run and in-process monitoring. The question then arises, 'How can data mining help?' We can use these records to define new Cases. We plan to investigate to what extent we can automate the extraction of knowledge from these records to define Cases. In addition, data mining can be used to reveal some patterns, for example to detect cause-and-effect relationships between process variables and outputs. These can inform the design of the components of CBR, e.g. it may lead to revised weights in the similarity measure between Cases, and assist in the adaptation phase of the CBR as required to address the differences between a new Case and the retrieved Case.

Our ultimate aim is to create an automated manufacturing cell which will have characteristics of Autonomous Intelligent Systems. This would receive as input a requirements-specification for the finished part and a blank of a specified material, and will produce as output a finished product to meet the specification. Intelligent characteristics will include the capability of the Cell to synthesize descriptions of chains of operations to meet the specification ability, to explain its behaviour and the rationale for its construction, increasing the confidence of the decisions made; ability to perform diagnostic reasoning on any failures and avoid repeating the same mistakes in the future; ability to perform automated acquisition of causal operators, and adapt and improve itself through experience.

In order to progress this ambitions objective, we are currently looking to submit a proposal to Innovate UK which will build on the results on this feasibility study and develop an AI architecture for the autonomous manufacturing cell. In addition, we are considering parallel proposals to address other aspects, including under EPSRC's *Instrument Development*, and STFC's *Innovation Partnership Scheme*.

8. Conclusions

This study proved invaluable in providing first insights into some of the decisions, procedural or operational, that machinists make and the reasons underlying their choices of certain actions over other possible actions. It was also very useful in identifying, and overcoming, some of the (commonly experienced) difficulties in eliciting knowledge from expert crafts people. It has also focused our minds on the balance between direct and indirect elicitation of knowledge, where the former should ideally be reserved for specialist information which is difficult to capture through digital data logging alone. In these ways, the project has proved an important step towards the development of an autonomous manufacturing cell.

9. Presentations and Papers

EOSAM Conference, Delft, Oct. 2018, invited paper, D. Walker, "*Fully automating fine optics manufacture - why so tough, and what are we doing?"*

Industrie 4.0 Summit, Manchester, March 2018, D. Walker et. al., "*Autonomous Manufacture of Ultra-Precision Surfaces – its Potential Realisation and Impact"*

Innovations in Ultra Precision Engineering Conference, Cambridge, May 2018, D. Walker et. al., Headline talk, "*The Road Towards Autonomous Manufacture of Ultra-precision Surfaces"*

Connected Everything Conference, Newcastle, June 2018, D. Walker and S. Petrovic, *"Feasibility of Capturing Crafts-based Knowledge in an AI System, for Future Autonomous Precision-surface Manufacturing"*

Connected Everything Conference, Glasgow, 2017, "*Feasibility of Capturing Crafts-based Knowledge in an AI System for Future Autonomous Precision-Surface Manufacturing*", D. Walker, A. P. Longstaff, S. Parkinson, W. Pan, S. Petrovic, P. Ward, K. Wilson

Walker, D.; Yu, G.; Beaucamp A.; Bibby,M.; Li, H.; McCluskey, L.; Petrovic, S.; Reynolds, C. 2017, "More steps towards process automation for optical fabrication", in *Fourth European Seminar on Precision Optics Manufacturing,* Proceedings of SPIE.

10. Feasibility study team members

The study was conducted by a team of researchers from the University of Huddersfield and the University of Nottingham:

University of Huddersfield
Professor David Walker, Ultra-Precision Surfaces
Dr Andrew Longstaff, AI for Manufacturing
Dr Simon Parkinson, Informatics and Manufacturing
Dr Wencheng Pan, Stability and System Dynamics
Dr Kyle Wilson, Psychology
Gouyu Yu, CNC Polishing and Metrology
Hongyu Li, CNC Polishing and Metrology

University of Nottingham
Professor Sanja Petrovic, Operational Research

connected everything.

industrial systems in the digital age

Connected Everything
Faculty of Engineering
University of Nottingham
University Park
Nottingham
NG7 7RD
UK.

www.connectedeverything.ac.uk