Institution: University of Huddersfield

Unit of Assessment: 12 (Engineering)

Title of case study: Improving Machine-Tool Accuracy and Productivity

Period when the underpinning research was undertaken: 2010–2018

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Prof. Andrew Longstaff	Professor	2001–present
Dr Simon Fletcher	Principal Enterprise Fellow	2000–present

Period when the claimed impact occurred: 2014 – 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

Machine tools are used widely in manufacturing across many sectors (aerospace, automotive, automation, green energy, consumer goods, etc.). Poor machine accuracy leads to waste in production time and energy, and scrapped components.

Research by the University of Huddersfield created new ways to measure and interpret errors, thus enabling the elimination of predictable failures. The research led to the development of new measurement products and the opening of new markets for machine tools. The processes developed were embedded in blue-chip companies, such as aerospace manufacturers. Two SMEs commercialized elements of the research, which are now sold globally. Further benefits, to second and third-tier users, are estimated to exceed £90m.

2. Underpinning research

CNC precision machine tools are used for cutting materials such as metal or carbon fibre for use in precision-engineering industries, such as automotive and aerospace, and consumer goods such as mobile phones. The components are manufactured to extremely high tolerances. This degree of precision can extend the life of a component (by reducing friction), increase the fuel efficiency of an engine or make components simpler to assemble.

A key challenge was maintaining the accuracy and repeatability of the machine tools that produced components to micron-level accuracy. It should be possible to manufacture a new piece within specification simply by using the nominal values indicated on the CNC control panel, but systematic errors often meant the first piece produced was out of tolerance and had to be discarded. This “sacrificial part” informed adjustments that were then made to the machine program. As a result, manufacture became relatively cheaper if many copies of a component were made (assuming that the machine tool maintained its accuracy in use), but “batch-size-one” was very costly.

Best practice was to calibrate regularly, by checking the alignment and accuracy of the machine using a laser interferometer and adjusting to correct any errors. This was a complex and time-consuming process that could take a machine out of production for several days. As a result, very few machines were regularly calibrated, with businesses having to correct when things went wrong.

The traditional calibration technique used a laser or other device to check the errors of each of the machine axes individually (at least 21 errors on a 3-axis milling machine, rising to 36 on a 5-axis machine). This was a long process because the machine had to stop at several points along the axis for each error measurement, which usually meant that the bare minimum (often only three of the 21 errors) were checked. Therefore, machine-tool users rarely knew the true accuracy of their machines. Further variability was introduced due to thermal effects during machining. These caused expansion and bending that are not normally detected during calibration (where the machine is not under thermal load).

As a result, machines either produced components outside specification, or productive time was lost while performing remedial calibration. “Work-around” solutions that helped maintain quality (e.g. manual offsets and “warm-up” cycles), reduced productivity and only delayed the onset of quality issues. Even machine-tool suppliers only specified performance tolerances using a small number of calibration points. Hence manufacturers, using a machine to make a product for their customer, could purchase one that did not perform at the level of precision required, or lost sales because they could not guarantee the precision needed by their customers. This case study describes how these challenges were tackled.

The research was carried out at the University of Huddersfield (UoH) by Prof. Andrew Longstaff (Professor of Machine Tool Technology, at UoH since 2001) and Dr Simon Fletcher (Principal Enterprise Fellow, at UoH since 2000). There were four key industrial partners: Rolls-Royce (aerospace engine manufacturer), Renishaw (manufacturer of machine-tool calibration equipment and software), MTT (provider of services to the users of machine tools) and Dapatech (which commercially exploits new machine-tool technologies).

Research (with MTT) to characterize the accuracy and maintenance process, showed how the calibration and control problem can be broken down using a lean manufacturing approach [R1] (2010). It established accuracy as a key performance indicator in the regular machine maintenance schedule. New simulations of the effects of errors [R2] (2014) were created to determine their impact on the final accuracy of a machine tool when producing a part. It was clearly demonstrated that existing practices omitted too many factors and were not fit for purpose. The limiting factors were shown to be the complexity of measurement (it was perceived as too specialist) and the machine downtime required to gather sufficiently comprehensive data. The engineers who performed the calibrations chose the order in which the measurements were taken almost at random – convenience was the overwhelming factor. Later research [R3] (2015) showed that the order in which measurements are taken affects the uncertainty of the calibration. A software solution was developed using artificial-intelligence (AI) planning to balance quality with the time needed for calibration.

Using these findings the UoH team worked with industrial partners to develop new hardware and processes to enable comprehensive data to be captured more rapidly. UoH was a key contributor to Rolls-Royce’s SAMULET (Strategic Affordable Manufacturing in the UK with Leading Environmental Technology) project (2011–2013). Rapid calibration strategies using new instrumentation for machine tools were first developed and tested in laboratory settings. They dramatically reduced the average calibration time (from several days to a few hours). Rigorous validation showed that the errors of each linear axis could be measured (i) more rapidly, (ii) while the machine was in motion and (iii) with improved accuracy [R4] (2016).

Next the team investigated the approach in several different industrial settings. Specialist knowledge transfer then enabled the industry partners to implement it independently. This demonstrated that it could be applied successfully across multiple types of machine tool, across many sites with differing ways of working. The team then focused on minimizing the machine downtime. They designed new hardware and refined the algorithms. This enabled engineers to balance the level of precision of the calibration (number of errors calibrated and level of accuracy obtained) against the downtime (cost).

The team then created a comprehensive cost model. It demonstrated the balance between measurement cost and the consequential cost of non-conforming machines and let users calculate the financial benefit of adopting the techniques. Data collected from the industrial partners provided the knowledge base for a new AI decision support system [R5] (2018). This characterized the impact of machine accuracy on productivity, to determine where regular calibration has a positive impact and where “run to failure” is more economical.

Temperature effects were a limiting factor. Even a well-calibrated machine is susceptible to variation from machine warm-up, coolant, draughts, etc. The new calibration methods allowed rapid measurement of thermal errors, but the time to create models remained long. AI was used to optimize sensor location and model the effect of thermal changes in the machine on the accuracy of the manufactured parts. Using an ANFIS (adaptive neuro-fuzzy inference systems) technique, multiple error sources were simulated (including thermal effects). This speeded up prediction of the final accuracy of manufactured components [R6] (2015). Manufacturers do not often provide a detailed model of thermal behaviour of their machines. The UoH-developed approach is a reliable method of predicting thermal effects within a reasonable time. The team then worked with DAPATECH to develop the intelligent thermal error compensation (iTEC) system to reduce the errors.

3. References to the research

These references are considered to be 2* or higher. [1] is from the MATADOR conference (double peer-reviewed, running since 1959). [2–6] are from prestigious journals, with [3, 4, 6] Q1 and [5] Q2 in this field (source: Scimago).

1. Willoughby, P., Verma, M., Longstaff, Andrew P. and Fletcher, Simon (2010) “A Holistic Approach to Quantifying and Controlling the Accuracy, Performance and Availability of Machine Tools” Proceedings of the 36th International MATADOR Conference. Springer, London, UK, pp. 313–316. ISBN 978-1-84996-431-9 https://doi.org/10.1007/978-1-84996-432-6_71 [can be supplied on request]
2. Longstaff, A., Fletcher, S., Parkinson, S. and Myers, A. (2014) “The Role of Measurement and Modelling of Machine Tools in Improving Product Quality” *International Journal of Metrology and Quality Engineering*, 4 (03), pp. 177–184. ISSN 2107-6839 https://doi.org/10.1051/ijmqe/2013054
3. Parkinson, S. and Longstaff, A. (2015) “Multi-objective optimization of machine tool error mapping using automated planning” *Expert Systems With Applications*, 42 (6), pp. 3005–3015. ISSN 0957-4174 https://doi.org/10.1016/j.eswa.2014.11.066
4. Miller, J.E., Longstaff, A.P., Parkinson, S. and Fletcher, S. (2016) “Improved machine tool linear axis calibration through continuous motion data capture” Precision Engineering, vol. 47, pp. 249–260 https://doi.org/10.1016/j.precisioneng.2016.08.010
5. Shagluf, A., Parkinson, S., Longstaff, A. & Fletcher, S. (2018) “Adaptive Decision Support for Suggesting a Machine Tool Maintenance Strategy: From Reactive to Preventative” *Journal of Quality in Maintenance Engineering.* 24, 3, p. 376–399 https://doi.org/10.1108/JQME-02-2017-0008
6. Abdulshahed, A.M., Longstaff, A.P., Fletcher, S. and Myers, A. (2015) “Thermal error modelling of machine tools based on ANFIS with fuzzy c-means clustering using a thermal imaging camera” *Applied Mathematical Modelling*, 39(7):1837–1852. https://doi.org/10.1016/j.apm.2014.10.016

4. Details of the impact

The research findings benefited businesses and users across the machine-tool supply chain. They enabled the introduction of new products and services and changed professional practice through better and cheaper calibration methodologies. They delivered over £90m of benefit to industry.

The impacts can be summarized under three headings:
1. Influence on new product development
2. New revenue streams for providers of services to machine-tool users
3. Changing professional practice for users of machine tools

Influence on New Product Development

Renishaw is a manufacturer of products for the calibration and regular checking of machine tools, enabling users to establish and maintain their performance. The research [R1] proved that a laser system, developed as a Quality Assurance device for internal use, would work as part of a new solution for the calibration of machine tools. An understanding of the benefits of rapid calibration [R 2,3] led the company to commercialize it as the XM60 multi-axis calibrator.

UoH research strongly influenced the development of the product. The Business Manager in the Laser and Calibration Products Division wrote, "You [..] show[ed] that a three-axis machine tool can have all its linear axes calibrated within one hour, highlighting a competitive edge of our new product. You also devised scientific methods [..] in order to help our own exploitation plan". The product was launched in 2016 and in 2020 he confirmed that: "Global sales of the XM60 now make up a significant proportion of the revenue generated from calibration product range" [a].

Dapatech Systems was established in 2011 to commercialize new technologies for machine-tool accuracy, compensation and monitoring. It used the research findings to develop a low-cost, mass-producible thermal compensation product (the iTEC). UoH researchers identified where to locate the temperature sensors and how to connect them to the machine tools [R6]. By using iTEC to remove the need for machine warm-up cycles (that can "cost" 30 mins to two hours of productive machining time per day), customers could save significant costs. The MD of Dapatech wrote, "For customers with many hundreds (or even thousands) of machines, using iTEC in this way will save tens of thousands of machining hours each year" [c] (2020). The company has demonstrated the product to customers in the UK, North America, South America and South East Asia and has generated interest from large volume manufacturers of consumer electronics and for high-precision applications in the aerospace sector. The MD added, "This opens up a huge market opportunity for the company" [c]. Although the Covid-19 pandemic slowed progress, he reported, "In 2019 we had negotiated an initial order with one partner for the first 1,000 systems, with the potential for this to rapidly grow to orders of tens of thousands of systems over a 2-3 year period [..] Currently we are negotiating a contract for the delivery of 1500 iTEC Systems to an OEM" [c].

New Revenue Streams for Providers of Services to Machine-Tool Users
MTT (Machine Tool Technologies) is a high-end provider of calibration and other services to users of precision machine tools. It worked closely with the UoH team to develop the early research [R1] into a high-end maintenance offering. MTT used the measurement toolkit created during the SAMULET project, including the Renishaw XM60 and the error modelling methods [R2, 4, 6], to provide rapid calibration services (2014–20). The MD of MTT stated, "[..] in the period 2014–2020 our relationship has facilitated an additional £7m of sales for MTT, as well as creating four directly related jobs". MTT created training courses in collaboration with the researchers. These were delivered to 12 of their engineers and 30 of their customers. The MD added, "This [..] led to these "intelligent customers" improving their processes, which generated revenue [..] of another £1.5m" [b] (2020).

Accudyne Europe Ltd, in conjunction with their USA based parent company, Accudyne Systems, Inc.is a manufacturer of Automated Fibre Placement (AFP) heads that are used to lay composite materials, such as carbon fibre. The head must be mounted on a carrier machine which, for challenging applications where materials are laid with extreme curvature, had to be extremely rigid, and was consequently expensive to buy and run. Working with MTT (2016) on instruments and processes developed using the research [R1,2], the company was able to move to a lightweight and cost-effective carrier. Crucially, the new measurement methods let Accudyne prove to potential customers that their new machine was fit for purpose. The methods also provided a reliable solution for regular machine maintenance with reduced downtime. This led to "a new product line, which has already realized turnover of £7.5M and cemented [Accudyne's] competitive foothold in a strategically important customer base" [d]. It estimated that customers are saving £250k on every machine by using their more cost-effective solution and £50k pa from additional uptime [d] (2020).

Changing Professional Practice for Users of Machine-Tools

The SAMULET program targeted the development of a high-speed machine-tool calibration and verification system. Rolls-Royce (RR) commissioned UoH to define requirements in terms of measurement accuracy, data quality, protocol optimization and evaluation of uncertainty. This led to an anticipated downtime reduction from 2.5 days to a single eight-hour shift, is estimated to save £150k per annum at one site [e], and verifiably improved quality. One RR site adopted the method on 100 machines and the Process Owner at RR confirmed that related "[..] operations implemented to date, demonstrated 100% conforming parts. Thus we have had zero rework and salvages" [e] (2020).

The impact has extended to users of the Renishaw XM60 product, who have been able to reduce the costs of their calibration activities. Renishaw's Business Manager stated, "Users [..] can also perform full 3D characterisation of the linear axes in one fifth of the time previously required. This significantly reduces the machine downtime and increases the capability of maintenance programs. Combined, this allows the equipment to pay for itself in under 12 months when compared with traditional systems" [a] (2020). This is in line with UoH research [R5].

MTT estimated that the improved calibration services they now deliver have provided significant benefits to their customers, including lower machine-tool downtime and more products manufactured within specification. MTT's MD wrote that its customers have enjoyed benefits amounting to "c. £70m in the period 2014-2020" in sectors such as aerospace, Formula 1 racing and manufacturing for the MoD [b] (2020).

Since 2013, the UoH team have shared the nature of the research findings and best practice for their application with companies across precision engineering. MTT, Rolls Royce, Dapatech and the Manufacturing Technologies Association (MTA) all cite the knowledge transfer as a key enabler of improvements in professional practice.

The CEO of the MTA commented that the "upskilling employees and improving the quality of the high precision end of machine tools" that has been made possible by the UoH research has been vital to the development of the UK precision-engineering sector and his own organization. He added: "Your work also led to advanced training courses, which two members of our technical team undertook in early 2019. This was invaluable in upskilling our employees, who have as a result been able to offer a more in-depth [..] service to our members" [f] (2020).

The MTA noted that the impact of the research has led to the UoH team being instrumental in the UK's contribution to international standards in machine-tool accuracy. In its 2018 report on the impact of manufacturing, authored by Oxford Economics, it estimated that GVA per job is £65,000 in the engineering subsector, which is 15% higher than the UK average. It added, "Your research has directly led to more efficient working in this high-value sector" [f].

5. Sources to corroborate the impact

a. Testimonial from Business Manager (Laser & Calibration Products Manager) Renishaw Plc.
b. Testimonial from Managing Director, MTT Ltd.
c. Testimonial from Managing Director, Dapatech SARL.
d. Testimonial from Technical Director, Accudyne Europe Ltd.
e. Testimonial from Process Owner for Rolls-Royce.
f. Testimonial from CEO of the Manufacturing Technologies Association (MTA).