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An Investigation into Enabling Industrial Machine Tools as Traceable Measurement Systems

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AN INVESTIGATION INTO ENABLING INDUSTRIAL MACHINE TOOLS AS TRACEABLE MEASUREMENT SYSTEMS

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An investigation into enabling industrial machine tools as traceable measurement systems

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Abstract

On-machine inspection (OMI) via on-machine probing (OMP) is a technology that has the potential to provide a step change in the manufacturing of high precision products. Bringing product inspection closer to the machining process is very attractive proposition for many manufacturers who demand ever better quality, process control and efficiency from their manufacturing systems. However, there is a shortness of understanding, experience, and knowledge with regards to efficiently implementing OMI on industrially-based multi-axis machine tools. Coupled with the risks associated to this disruptive technology, these are major obstacles preventing OMI from being confidently adopted in many high precision manufacturing environments.

The research pursued in this thesis investigates the concept of enabling high precision machine tools as measurement devices and focuses upon the question of: *“How can traceable on-machine inspection be enabled and sustained in an industrial environment?”*

As highlighted by the literature and state-of-the-art review, much research and development focuses on the technology surrounding particular aspects of machine tool metrology and measurement whether this is theory, hardware, software, or simulation. Little research has been performed in terms of confirming the viability of industrial OMI and the systematic and holistic application of existing and new technology to enable optimal intervention.

This EngD research has contributed towards the use of industrial machine tools as traceable measurement systems. Through the test cases performed, the novel concepts proposed, and solutions tested, a series of fundamental questions have been addressed. Thus, providing new knowledge and use to future researchers, engineers, consultants and manufacturing professionals.

Nomenclature

Abbreviations, Acronyms

6σ	Six Sigma
ASME	American Society of Mechanical Engineers
ATSU	Automatic Tool Setting Unit
BMS	Bounding Measurements Set
BSI	British Standards Institution
CA	Capability Acquisition
CAx	Computer Aided ....
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAQ	Computer Aided Quality control
CAM	Computer Aided Manufacture
CAP	Computer Aided Planning
CAIP	Computer Aided Inspection Planning
CNC	Computer Numerical Control
CoNQ	Cost of Non-Quality
CFD	Computational Fluid Dynamics
CMM	Coordinate Measuring Machine
CMS	Coordinate Measuring System
CT	Computed Tomography
CTE	Coefficient of Thermal Expansion

CVE	Computer-aided Verification and Evaluation
DIN	German institute for standardization *(De.: Deutsches Institut für Normung)*
DFT	Discreet Fourier Transform
DfM	Design for Manufacture
DFSS	Design for Six Sigma
DOE	Design of Experiments
DMAC	Direct Machining and Control
DMIS	Dimensional Measuring Interface Standard
EDM	Electrical Discharge Machine
ERP	Enterprise Resource Planning
FEA	Finite Element Analysis
FEM	Finite Element Model
FFT	Fast Fourier Transform
FPS	Full Parametric Simulation
GPS	Geometrical Product Specification
GUM	Guide to the Expression of Uncertainty in Measurement
HTM	Homogenous Transformation Matrix
ISO	International Organization for Standardization
KPI	Key Performance Indicator
KPV	Key Performance Variable
JIS	Japanese Industrial Standards
LAN	Local Area Network
LCL	Lower Confidence Limit
LE	Leading Edge
LIMA	Laboratory for Integrated Metrology Applications
LLS	Linear Least-Squares
LSL	Lower Specification Limit
LSQ	Least Squares
MANOVA	Multivariate Analysis of Variance
MC	Minimum Circumscribed
MCM	Monte Carlo Method

MDI	Manual Data Input
MI	Minimum Inscribed
MPE	Maximum Permissible Error
MPEOM	Machine Performance Evaluate Optimise Monitor
MVA	Multivariate Analysis
MZ	Minimum Zone
NC	Numerical Control
NIST	National Institute of Standards and Technology (US)
NPL	National Physical Laboratory (UK)
NURBS	Non-Uniform Rational Basis Spline
OVCMM	Offline Virtual CMM
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OMI	On-Machine Inspection
OMM	On-Machine Measurement
OMP	On-machine probe/probing
OOP	Object Oriented Programming
PC	Personal Computer
PCS	Part Coordinate System
PDF	Probability Density Function
PDM	Product Data Management
PFMEA	Process Failure Mode Effect Analysis
PLM	Product Lifecycle Management
PMA	Production engineering, Machine design and Automation
PMI	Product Manufacturing Information
R-R	Rolls-Royce plc.
RFT	Right-First-Time
SAMULET	Strategic Affordable Manufacturing in the UK with Leading Environmental Technologies
SAP	A German multinational software corporation
SBC	Simulation By Constraints
SCU	Supply Chain Unit

SI	International System of units *(Fr.: Système International d'unités)*
SOMMACT	Self Optimising Measuring MAChine Tools
SPC	Statistical Process Control
STEP	Standard for the Exchange of Product model data
SWOT	Strengths Weakness Opportunity Threat
TCP	Tool Centre Point
UCL	Upper Confidence Limit
UES	Uncertainty Evaluation Software
USL	Upper Specification Limit
VDI	Association of German Engineers *(Ger.: Verein Deutscher Ingenieure)*
VIM	International Vocabulary of Metrology *(Fr.: Vocabulaire International de Métrologie)*
VCMM	Virtual CMM
VTL	Vertical Turning Lathe
XML	Extensible Markup Language

Symbols

μ	Micron ($1x10^{-6}$)
μm	Micrometer (0.001mm)
P	Position of a feature
O	Orientation of a feature
σ	True standard deviation
s	Estimated standard deviation
s	Size of a feature
f	Form deviation value of a feature
M	Number of Monte Carlo runs
n	Number of points
N,m	Number of sampling points
l	Array containing the probing
${}^{meas}x$	Measured value of parameter x
${}^{true}x$	True value of parameter x
${}^{err}x$	Error value of parameter x
u, u_c	Standard uncertainty, combined standard uncertainty
U	Expanded uncertainty
k,k_x	Coverage factor
Y	Measurand
y	Measurement result, estimate of the measurand
y'	Measurement result, with expanded uncertainty
X_i	Input quantity
x_i	Estimate of input quantity X_i
$x_{i,k}$	k^{th} observation of input quantity X_i
P	Level of confidence
T	Target value
V	Variation
C_m, Cm	Machine capability index
C_p, Cp	Process capability index
C_g, Cg	Gauge capability index

C_{mK},C_{mk},Cmk	Machine capability index, when USL and LSL are relevant
C_{pK},C_{pk},Cpk	Process capability index, when USL and LSL are relevant
C_{gK},C_{gk},Cgk	Capability of gauge, when USL and LSL are relevant
X_m	Reference measurement

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Chapter 1

Introduction

This thesis deals with the goal of re-purposing high precision multi-axis machine tools as capable and traceable dimensional measurement systems. This chapter describes the background, opportunity, and challenges associated with this goal. The chapter also presents the overall aim, core research question, and scope of the research contained in this thesis. An outline of the thesis is presented at the end of the chapter.

1.1 Background – Industrial need

As organisations operate in more and more globally competitive markets, their competitors are becoming equivalently funded, ambitious and resourceful as emerging markets become ever more entrepreneurial and ambitious. Typically, such organisations realise this and often create strategies to enable competitive advantage under these circumstances. These such strategies will centre on the 'voice of the customer', where such a voice often speaks of quality, lead-time, cost and safety requirements, as illustrated in Figure 1-1.

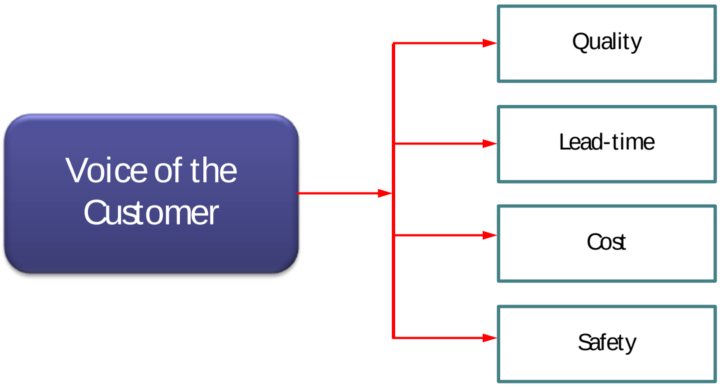


Figure 1-1: The 'voice of the customer'

For manufacturing based organisations this is no different. In a fiercely challenging marketplace, manufacturing is expected to make a significant long-term contribution to competiveness and business strength [1]. For manufacturing organisations to establish and sustain competiveness there is a need to continuously focus on customers' needs. This involves consistently applying: capable, standard processes; making the most effective and efficient use of new and existing assets; constantly looking for ways to improve productivity and reduce waste; and pushing this ambition through the supply-chain.

1.1.1 Host company - Rolls-Royce plc.

This research was carried out on live manufacturing equipment made available by Rolls-Royce plc. (UK). Rolls-Royce plc. is a power systems company which designs, develops, manufactures and services integrated power systems for use on land, sea, and in the air. The organisation is built up of a worldwide network of offices, manufacturing, research and service facilities and is set-up to operate in multiple global markets, including: civil aerospace, defence aerospace, power systems, marine and energy. In 2014 these markets contained a total business opportunity worth of US$3 trillion over the next 20 years [2]. The order book currently stands at £73.7 billion (Table 1-1).

Table 1-1: Rolls-Royce plc. Group financial data 2014 [2]

	2013	2014	% Change
Order book- firm and announced	£71,612m	£73,674m	+3%
Underlying revenue	£15,505m	£14,588m	-6%
Underlying profit before tax	£1,759m	£1,617m	-8%

Rolls-Royce plc. invested in this research as it believed that maximum profitability can be achieved by the improvement, optimisation and sustainment of its manufacturing systems, in particular its machine tool assets.

1.1.2 High Value Products

Rolls-Royce plc. akin to other major aerospace companies is considered a high value business [1]. A characteristic of a high value business is its ability to deliver high performing products. The core product produced by Rolls-Royce is the gas turbine (Figure 1-2). A typical gas turbine, consisting of +18,000 components, is capable of withstanding incredible operational demands under extraordinary operating conditions [3]. Gas turbine technology, most often observed as a jet engine, is designed and produced to transport huge volumes of air in order to create enough force to push the aircraft through the atmosphere. Although originally produced and optimised for the aerospace industry, 80% of the technology contained within aero engines is the same as found within gas turbines which are utilised within the energy and marine sectors.

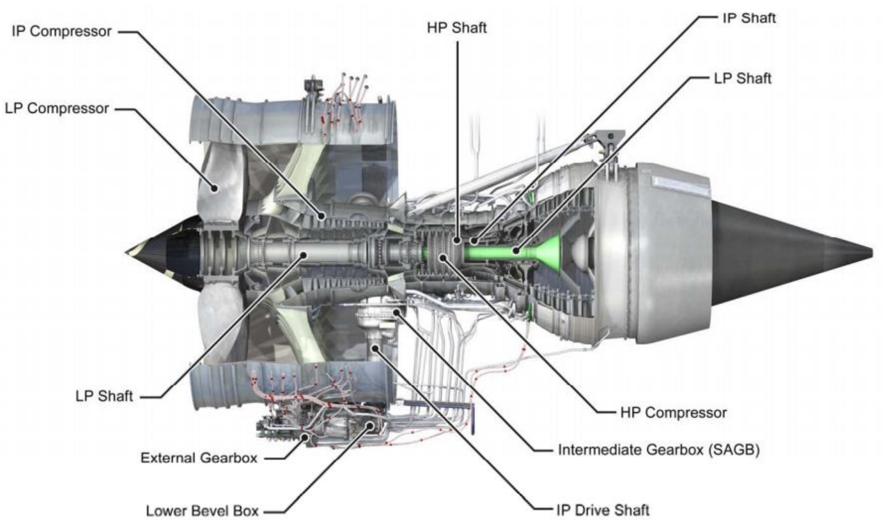


Figure 1-2: Rolls-Royce Trent 1000 aero gas turbine (Source: Rolls-Royce plc.)

With all components produced, continuous research and development has required significant changes in terms of product design and manufacture. This includes the advancement of materials, technologies, design methods, product geometries and manufacturing requirements [4]. This often has to be achieved on an established manufacturing supply-chain with a fixed or limited capacity. Therefore, there is a constant challenge for manufacturing engineering departments to drive the maximum from their current asset base and infrastructure.

"In the global aerospace market, competitiveness is delivering an engine that is lighter than the competition's, burns less fuel, has lower emissions, and can remain on wing for longer, so that the cost of ownership of the engine over the long-term is less"

Production Leader, Trent Engines [5]

1.2 The manufacturing challenge

Today, high precision manufacturers operate within global markets which demand high performance products for the lowest cost. As such, these organisations will constantly strive for the highest levels of manufacturing capability. Typically, where manufacturing implies the interaction between product and process, capability implies the efficiency of this interaction. Manufacturing process capability is integral to overall business performance, in that, it dictates product quality, delivery, and cost of the entire organisational system in operation. Process capability is crucial to overall manufacturing capability, however, a typical process can by compromised by a huge range of factors, indicted by Figure 1-3.

Figure 1-3: Factors influencing manufacturing capability

When a product is defined at a design stage, decisions are made that have a consequential effect on future manufacturing capability. The role of managing compromises which deliver the optimum business results subsequently fall to manufacturing system designers. It is rare, due to inherent systems complexity, that one process or product change can be made without affecting the entire manufacturing system [6].

To take processes beyond their inherent capability, engineers are continuously challenged to simultaneously manage and drive innovation through newer and ever-evolving high performance products, component and assembly complexity. In parallel to this, special care must be taken to manage process flexibility, material variation, machine-to-machine variation and specialist and non-specialist human interventions, all of which can have profound effects on process capability.

1.3 Opportunity for on-machine inspection to improve manufacturing capability

Figure 1-4 illustrates the existing manufacturing paradigm with regards to the production of high precision products. In essence this represents the classic manufacturing process. In this situation the machine tool, a primary workhorse of industry, is utilised to perform the task of producing components to the specified shape and size. Typical for the manufacture of tight tolerance components, such as those used in the aerospace industry, is a need for final product inspection systems to qualify and certify product quality to required local and international standards.

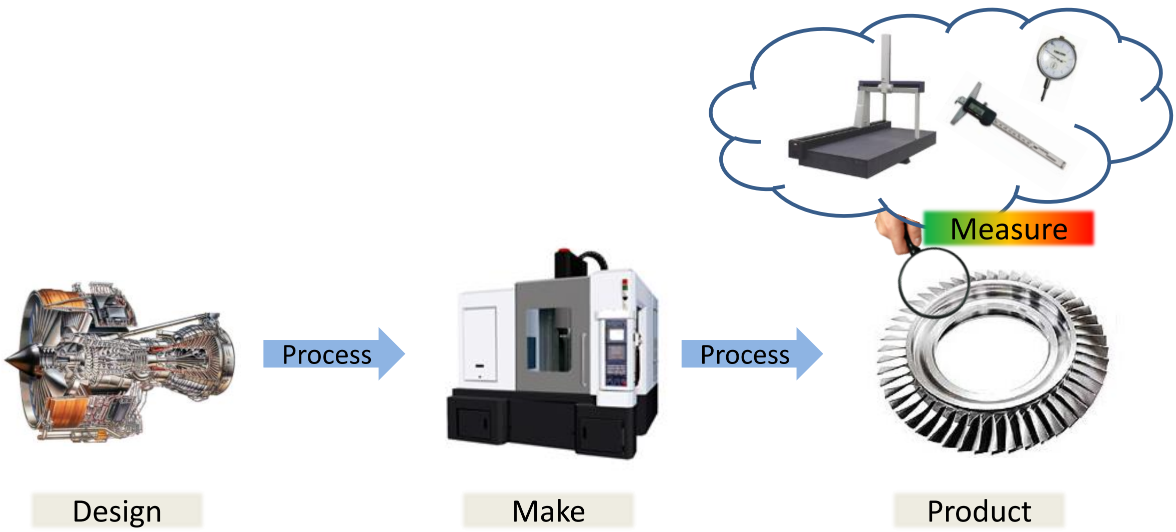


Figure 1-4: Current manufacturing paradigm

With this paradigm the manufacturing process follows a philosophy weighted on post-process dimensional inspection. Here independent measurement systems, such as coordinate-measurement machines (CMMs), are used to qualify manufactured products.

These systems are primarily used to confirm and maintain quality as well as generate manufacturing knowledge through data creation. This manufacturing approach is seen to be most powerful for smaller lower value products manufactured in high volume and on a transfer line. The reason being that statistical process control (SPC) data can be used with a high level of confidence. However, for medium-large high value components (i.e. those larger than $0.3m^2$) produced in smaller batches this manufacturing approach is less effective and less efficient. The reason being that there is low statistical significance (i.e. few components produced) and there is a higher cost per component.

1.3.1 Issues with the current manufacturing paradigm

A manufacturer machining larger volume high precision products, utilising expensive materials and resources, whilst striving for economic competitiveness on relatively small batch size, can seldom afford to operate in a manner where they are reactive to change. In these cases, should the post-process inspection system highlight a manufacturing defect, it is not often the case that the system will be able to pin-point the exact source of variation i.e. is it material, machine variation, tooling variation, an extrinsic factor etc. The reason being the product will likely pass through a number of operations and states before it arrives at a measurement system. This often leads to the scenario indicated by Figure 1-5, whereby the process is known to be at fault but the source of fault is unknown. The manufacturer is therefore forced to make the decision of creating a concession, scrapping or re-cycling the component back through the system. Cost associated to this process is inferred, through scrap, rework, cost-concessions, investigative costs and unplanned expenditures.

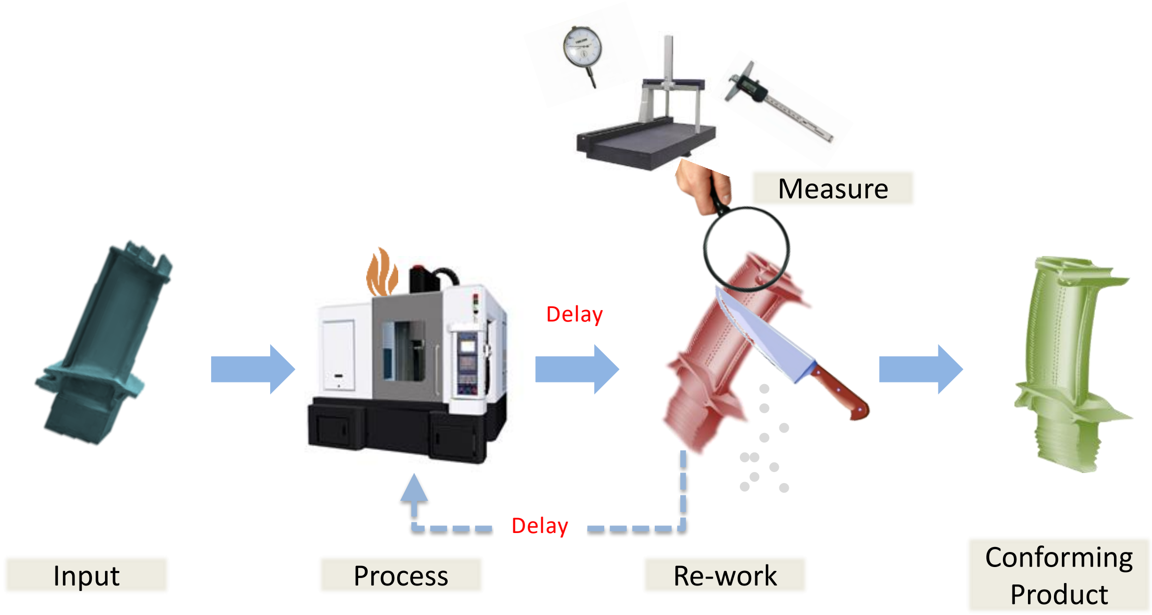


Figure 1-5: Issues with current manufacturing paradigm

Also indicated by Figure 1-5, irrespective of the machining process being used there is usually a significant delay between product/feature creation and its realisation/validation. Typically the longer the delay between the measurement and the machining process the more difficult it is to react to change and the less relevant is the measurement data.

This delay causes two distinct problems. Firstly, the logistics in relocating large components from the machining centre to a measurement device, and vice versa, is difficult and often accounts for a significant amount of overall manufacturing time. Secondly, the longer the delay the more difficult it is to identify the source of error. Re-processing a component through the same system without confidently knowing the root cause of the initial fault increases risk that an incorrect intervention is made, therefore errors are just as likely to be induced as removed.

Generally, with smaller products the feedback delay is often short (i.e. in the region of minutes) whereas with medium-large (>0.3m) components the feedback delay is significant (i.e. in the region of hours-days). Therefore, reducing or eliminating this delay is becoming of utmost importance to manufacturing organisations.

1.4 Value lost due to post-process measurement

Figure 1-6 illustrates the work content involved in the set-up and post inspection of a typical aerospace component. As indicated by the diagram a majority of the work content can be considered non-value adding, despite being enabling.

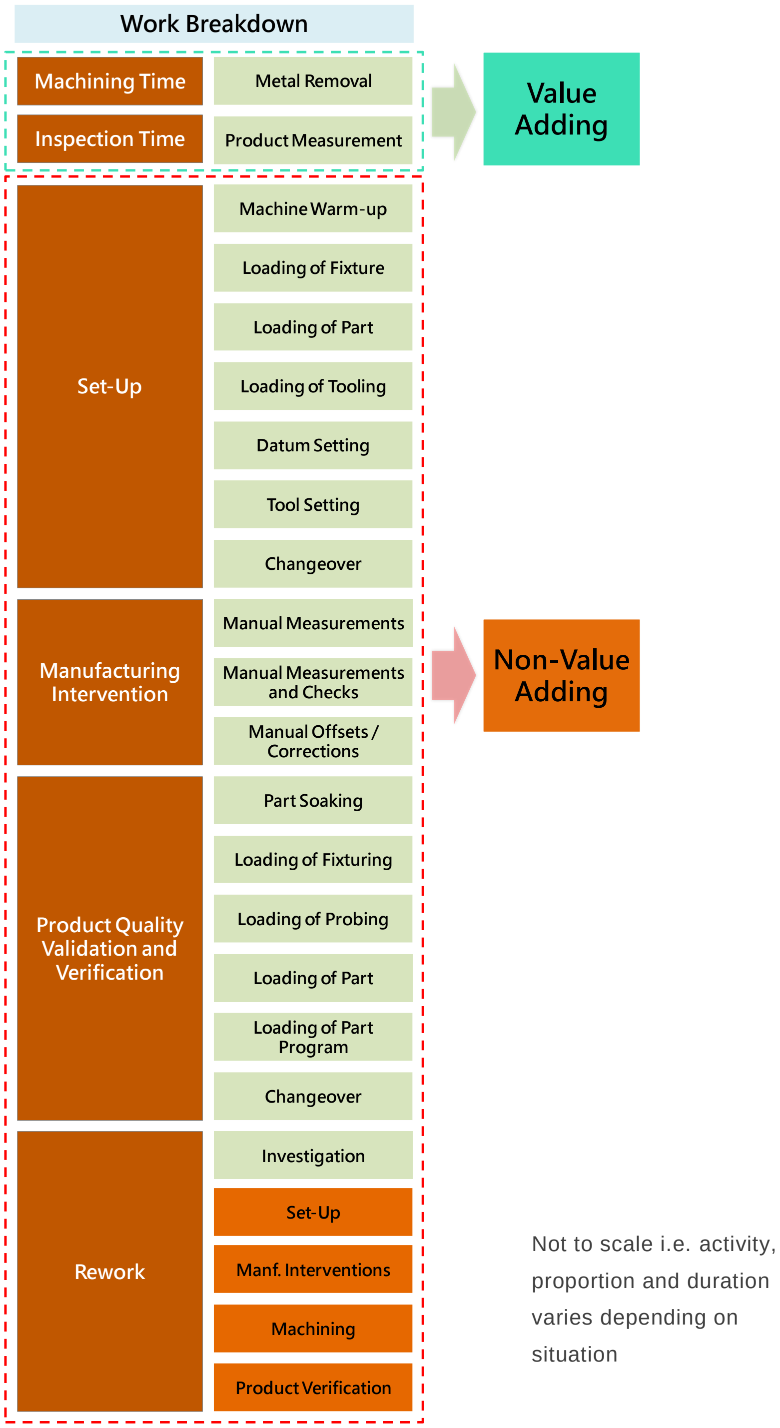


Figure 1-6: Value adding and non-value adding manufacturing activities

Even a slight reduction in any of these activities is likely to reduce component cost, only if any such intervention does not affect product quality output.

If manufacturing engineers could reduce or eliminate one-or more of these 'non-value adding' activities without compromising high product quality, then significant efficiency gains can potentially be achieved. Figure 1-6 illustrates why one would look to the machine tool as the solution to eliminate many of these non-value adding activities.

1.5 Ensuring machine tool capability for on-machine inspection

A strategy to ensure that the machine tool produces parts to specification every time would be to apply a purely deterministic approach i.e. measure and control all process variables in order to control output [7]. Figure 1-7 illustrates this vision of refocusing measurement on the machine rather than the product i.e. the effort and capital investment which is typically applied to provide efficient handling and measurement equipment for measuring the product could be spent on increased measurement, and validation, of the manufacturing process. Here the machine is checked and calibrated to be as correct as possible before anything is produced by it.

Figure 1-7: Paradigm shift associated to EngD research

In this scenario if the machine tool is measured as incorrect, e.g. it is out of geometric specification, it can be rectified beforehand and thus prevent non-conformance in the product.

It is widely acknowledged that until this ‘measure twice-cut once’ approach is implemented the machine tool cannot be expected to consistently make good parts [7]–[9]. However, such an approach is often not adopted by most manufacturers as time spent on measurement, whether on the product or process, is accounted and perceived as non-value adding [10]. This is because material manipulation is not occurring i.e. no material is being removed or it slows down the rate of removal.

The case of a deterministic predictive approach is also undermined by the existence of random errors. Such errors often emerge from the material being machined or the operating environment. As a result of these random errors, many will argue that due to the nature of high-precision manufacturing post-process inspection will always be necessary.

One way to solve both problems, of guaranteeing machine tool capability as well as reducing inspection delay, is to integrate an on-machine probing (OMP) device (Figure 1-8). Such a device can be used to measure raw material before machining and apply corrections to the machining program where necessary. This device could also be used to apply corrections on an adaptive basis, where measurements and compensations are made prior to final cuts.

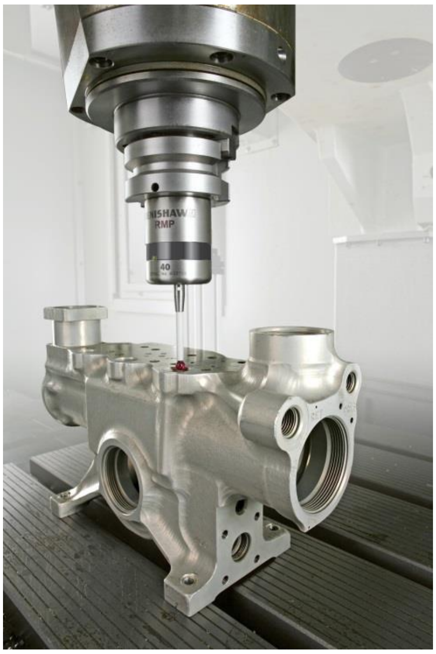


Figure 1-8: On-machine probing device [Image Source: Renishaw plc.]

1.6 On-machine probing systems

On-machine probing systems (OMPs) have been present on the shop floor since the 1980's [11]. Today, on purchase of a new high precision multi-axis machine tool an OMP system will often be delivered with it. Depending on usage, such devices can be utilised to perform the following functions:

1. Datum (zero) the tool spindle
2. Datum the part
3. Set tooling offsets
4. Set rotation points (for multi-axis machining)
5. Set fixture offsets
6. Inspect features after semi-finish machining to set process offsets
7. Inspect features after final machining

Where these essential processes would normally be very labour intensive, slow and prone to human error, OMP devices in conjunction with the machine tool controller system can automate and de-skill such tasks. However, as indicated by Figure 1-9, the inclusion of probing on machines can involve considerable labour, knowledge, and understanding with regards to set-up and sustainment of such a capability.

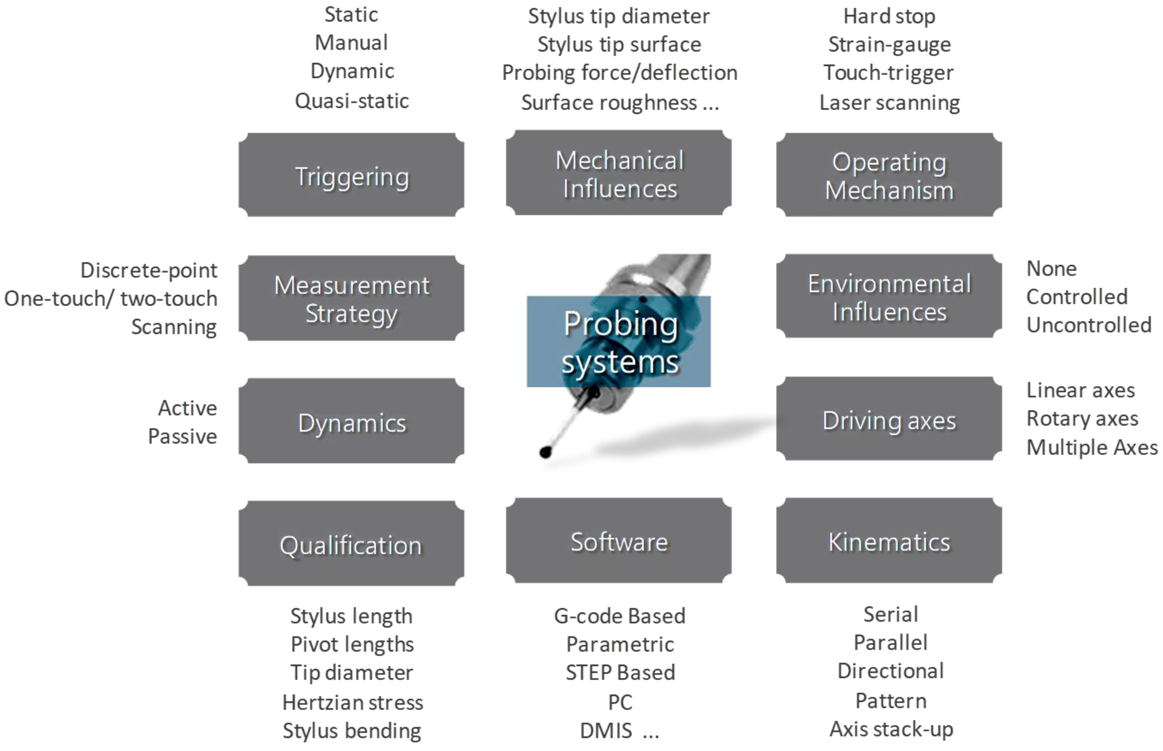


Figure 1-9: On-machine tool probing (OMP) set-up considerations

Despite all such considerations being manageable, machine tool users will still often only utilise their on-machine probing devices for purposes of product-fixture alignment and tool datum setting. This is as the return on investment is straightforward and achievable. Should such users wish to extend the use of their probing devices to perform on-machine inspection for:

1. Confirming the correct machine geometry and condition before the machine is used
2. Using on-machine probing to adjust the machining process so that it avoids making erroneous cuts before they are made
3. Using on-machine probing after machining is finished to confirm that the product is accurate before it leaves the machine

This often does not happen in an industrial environment. Hence, this initially asks the question of *“Why are on-machine probe devices on high precision machine tools not being more frequently utilised for product inspection as well as machine setting?”*

1.7 On-machine inspection challenges

Typically, industrial manufacturing systems are highly varied, integrated and dynamic; this makes the process of achieving and sustaining on-machine inspection tasks far from trivial. There are numerous barriers preventing the re-purposing of machine tools as measurement devices, which include:

1.7.1 The wide variety of machining systems in use

Machine tools can be broadly classified as cutting, non-cutting, and non-conventional type. A cutting machine performs a material removal process using a defined cutting edge to modify a material i.e. milling, drilling. A non-cutting machine utilises an undefined cutting edge i.e. grinding, honing. A non-conventional machine which utilises erosion techniques to remove material i.e. Electro-discharge (EDM), Laser, Water-jet [12].

Depending only on the material removal method, configuration, capability of driving systems, feedback and controller system all such machine tools will operate and perform differently. In combination with the variability of sizes and configurations this presents significant technical challenges should a generic solution for on-machine inspection be sought. The challenge is therefore to provide a solution that can manage this variability as much as possible.

1.7.2 Small incremental measurements vs. larger measurements

One aspect that is working in ones favour is that all machine tools operate under the same feedback loop, often containing the machine tool structure and axes, tooling, material manipulation process, workpiece and fixturing, as indicated by Figure 5-1.

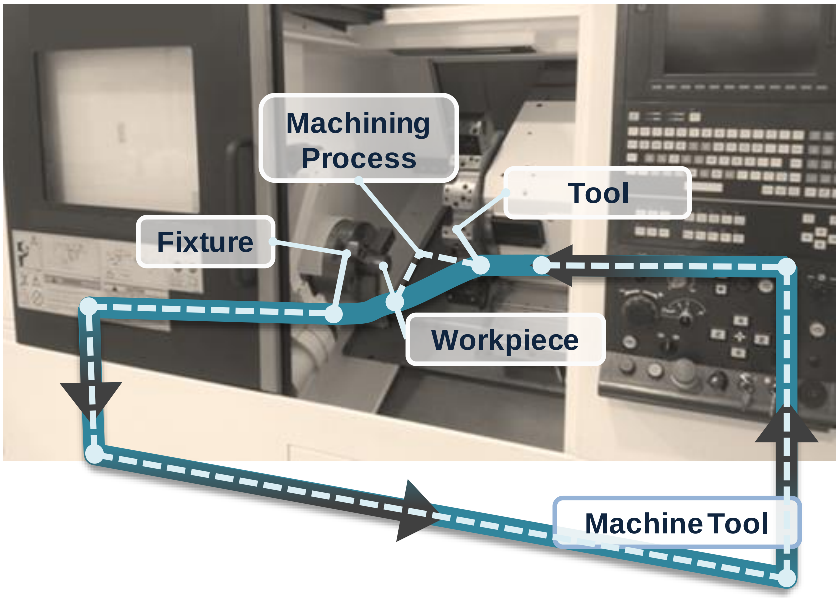


Figure 1-10: Machine tool kinematic chain

However, machine tools are in fact open-loop systems until a measuring device is used to measure the product and provide feedback for adjustment. Machine tool users are often more comfortable making in-process small incremental 'measure-cut' functions sometimes using an on-machine probing device. This is because that if in-process measurements are small and/or incremental, then the accuracy of the machine is likely to be adequate. If larger scale measurements are made, that use a significant proportion of the travel of one or more axes, the risk of inaccurate measurements rises. Subsequently, there is a view that larger-volume measurements are not possible or reliable due to ever changing geometric and kinematic errors within the machine tool. Thus, if the researcher could implement a solution for measuring and tracking such errors then these could be better managed and compensated for.

1.7.3 Machine tool capability assumption

It is often the case that machine tool users are misled by machine specifications that imply a much higher level of accuracy than may be achievable in practice. Machine tools will more often be accepted on their ability for producing the final product rather than their geometric and kinematic profile. Where this may not be an obvious issue with respect to a machines ability to produce, it becomes more significant when the machine is used as a measuring device. This is particularly the case when a machine has been wearing and aging over a period of time or where the level of sensitivity to change is much greater. The risk of not knowing the true capability of a machine is that there is always the danger that the machine will make an incorrect part but pass it off as good, because the same errors that caused the defect are also applied to the measurement.

Additionally, there is also a danger that when using adaptive machining when the machine is not measuring accurately this will in fact drive the machine to produce non-conforming parts, when it might have produced good parts if the feedback had not been applied to the nominal NC program. Therefore, a challenge to enable on-machine inspection is for machine tool users to have the ability to profile a machine not only on its ability to produce but geometrically and kinematically [13].

1.7.4 On-machine inspection is perceived as non-value adding

Despite measurement being an enabling function it is often perceived as non-value adding [10]. This is as it is considered too disruptive and time consuming relative to the benefit it can provide. This 'non-value adding' connotation may arise from the fact, that unless predictive, any measurement on a final workpiece is considered as too late. It can also be argued that predictive measurement does not have strong enough linkage to final product conformance due to the enormity of the number of variables which still may not be measured or controlled. The debate of whether or not measurement is accounted as a value-adding or non-value adding task is currently prevalent in the industry, especially when engineers contemplate the cost and need for increasing shop-floor inspection capacity. When suggesting using the machine tool, a clear value adding asset, as a measurement device this case becomes much more difficult and open to scrutiny. Therefore, unless the true economic value of on-machine measurement can be proved it is unlikely to be readily adopted.

1.7.5 Calibrating machine tools is technically challenging

To achieve stable and capable on-machine measurement the machine must firstly be measured and calibrated as if it were a measurement system. Following this the machines' calibration status must then be maintained via subsequent independent measurements by a process of regular re-verification. In theory, it is critical to understand the errors contained within a machine tool system as the configuration and variation of these have a direct impact on its underlying accuracy and repeatability and consequently its overall capability. In order to produce conforming products at a high level of process capability it is fundamental that a machine tool is demonstrably accurate. A simple 3-axis machine has 21 potential sources of geometric error – linearity, angularity, straightness, squareness [14]. Adding rotary axes increases the complexity further [15]. Each of these errors needs to be fully understood, in terms of impact on measurement task, and either corrected or compensated for, especially before machining parts.

There are a number of devices that have been used to calibrate machines for many years, but it typically takes up to five days fully to calibrate an industrially based machine. This amount of downtime is very expensive, resource intensive and not generally acceptable by industry. Thus, there is a need to cut the measurement time drastically and implement rapid/non-intrusive re-verification systems to confirm on-going equivalence and warn of catastrophic failures. This is no straightforward task for machine tool users due to: the variability of machine tools in terms of their control systems sizes and configurations; the plethora, limitations with, and technical complexity of available ‘off-the-shelf’ machine tool measurement equipment; the limited availability of skilled measurement equipment operators; the limitations of current standards and guidance in terms of assessing the uncertainty of measurements taken; as well as the limited tools and methods available for processing and analysing collected data in order to make decisions.

1.7.6 Process planning complexity

To produce products with multiple quality characteristics that must meet a set of predefined quality standards is the primary function of an advanced manufacturing system. To achieve this, such systems will employ a set of machining resources and inspection resources to fabricate quality characteristics and inspect them. Manufacturing operations already face the problem of allocating such resources to meet ever changing demand. This presents two distinct challenges: process planning and inspection planning. As mutually exclusive functions these are challenging functions, by bringing them together on the machine tool creates an added level of complexity in the production process. Thus, to mitigate this challenge one must look at novel solutions such as advanced product life-cycle management (PLM) and manufacturing execution systems (MES). This adds a further level of complexity which many companies may not be ready for.

1.7.7 On-machine inspection reporting

Currently there is a common misunderstanding with co-ordinate measurement machine (CMM) programmers about how they should be reporting the measurement results [16]. Often, many programmers become confused between measurements that reflect what the stage drawing or operation (Op) sheet shows, and measurements that reflect what the finished component drawing shows. The former is what you could probably measure usefully with on-machine probing as it shows how well the machined performed against the requirements of that operation. A CMM can provide a detailed report, which adheres to the required quality standards, if a component is acceptable to go on to the next manufacturing operation or to a finished parts store. The key debate is about whether you can actually do the CMM's job on the machine, especially if there is a need for 'CMM style' reporting and data analysis. As on-machine inspection is still at the beginning of early stage of adoption many industrially based machine tools are unlikely to have the necessary NC-interface or supporting software capable for carrying out, reporting and supporting it.

1.7.8 Tolerance specifications and measurement uncertainty

Many high precision manufacturers will refer to ISO 14253 standards with regards to the specification of tolerances for their products [17]. Typically, the specification of a dimension contains an upper specification limit (USL) and lower specification limit (LSL). When the measurand lies within specification (or tolerance) there is conformance to specification. When the measurand lies outside the specification limits there is non-conformance. The range of all measurements taken is divided into a conformance and non-conformance zone. When considering measurement uncertainty there is no such clear distinction between conformance and non-conformance and a zone of uncertainty (or doubt) arises. This is illustrated in Figure 1-11.

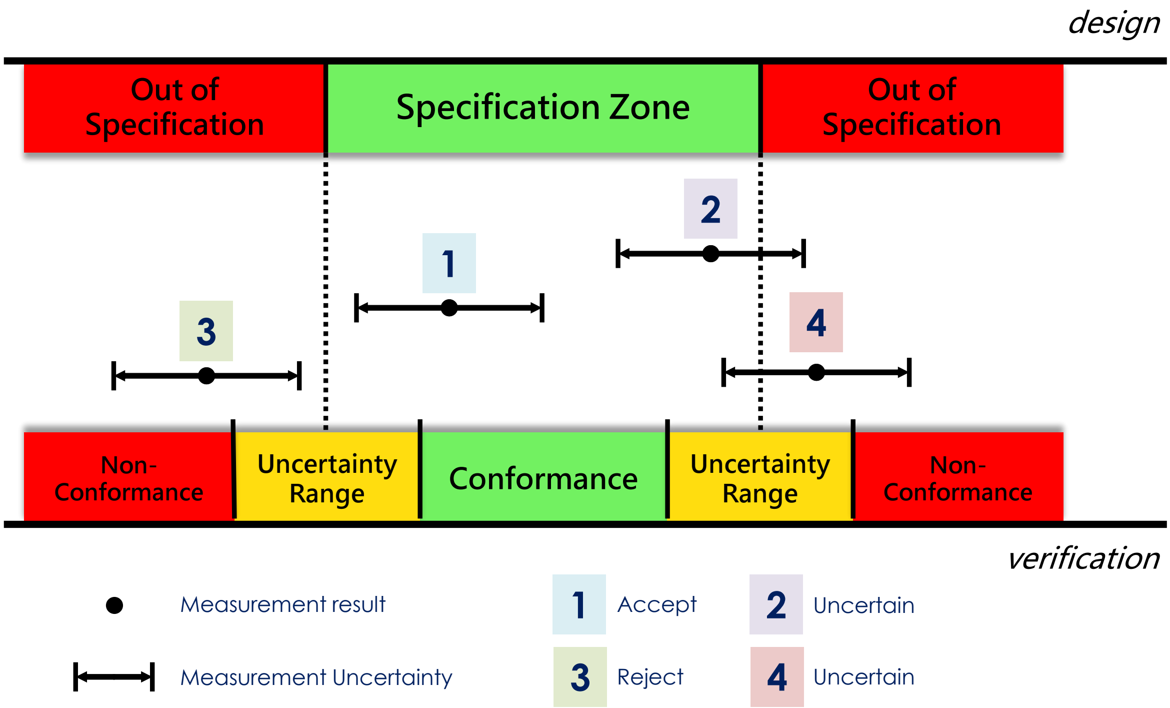


Figure 1-11: Proving (non-)conformance with specification, ISO 14253-1 [17]

Therefore, quantifying OMI measurement uncertainty will be highly relevant to and a key enabler for its full adoption. If uncertainty for any equipment being used to measure aspects of its capability is unknown, users of such systems are susceptible to mis-interpretation of results and therefore are at risk of inducing errors rather than removing them. Since the uncertainty of measurement equipment being used may not be constant, i.e. it is affected by its own variables; the user of such equipment is then relied upon to provide evidence of measurement traceability. Understanding, minimising and eliminating sources of uncertainty is expected to be a key enabler for on-machine measurement.

1.8 Overall aim of research

With the growing interest and importance of bringing measurement into the machine tool, and on reflection of the challenges highlighted, there is a fundamental need for novel solutions to enable this shift in a manufacturing paradigm. To design and implement a system which has high confidence, reliability and that is economically viable is a key enabler for achieving high precision on-machine inspection on industrially based machine tools. Machine tool measurement techniques, industrial standards, laboratory based theory and autonomy are some of the many concepts that have been studied and developed throughout the years. In this thesis, the researcher proposes that a holistic view must be taken and that novelty and new knowledge in the sum of the parts will lead to a more significant and more likely implementation of industrial on-machine inspection as an entire system. This is a broad aim and in Chapter 3 (Research Questions, Methodology and Objective) the more precise research questions are systematically generated as the frame of reference for this work.

From the combination of work carried out in Chapters 1-3 the core research question and hence the objective of this research work is to answer:

“How can traceable on-machine inspection be enabled and sustained in an industrial environment?”

With reference to the ‘industrial environment’, this question aims to capture and appease requirements set by relevant stakeholders, the operation of the manufacturing system, the product, and the machine tool. Additionally, it aims to carry an essence that the most efficient and effective methods for proving and sustaining measurement capability are being used. Furthermore, that the machine is capable to perform and report inspection data and that traceability can be demonstrated as if the machine tool was a co-ordinate measuring machine (CMM). The hypothesis being made is that the necessary technology, knowledge and resource is available to achieve traceable on-machine inspection. This subsequently forms the scope of the research contained within this thesis.

1.9 Scope of research

With the core research question as the backdrop Figure 1-12: ‘EngD on a page’ illustrates the scope of this research exercise.

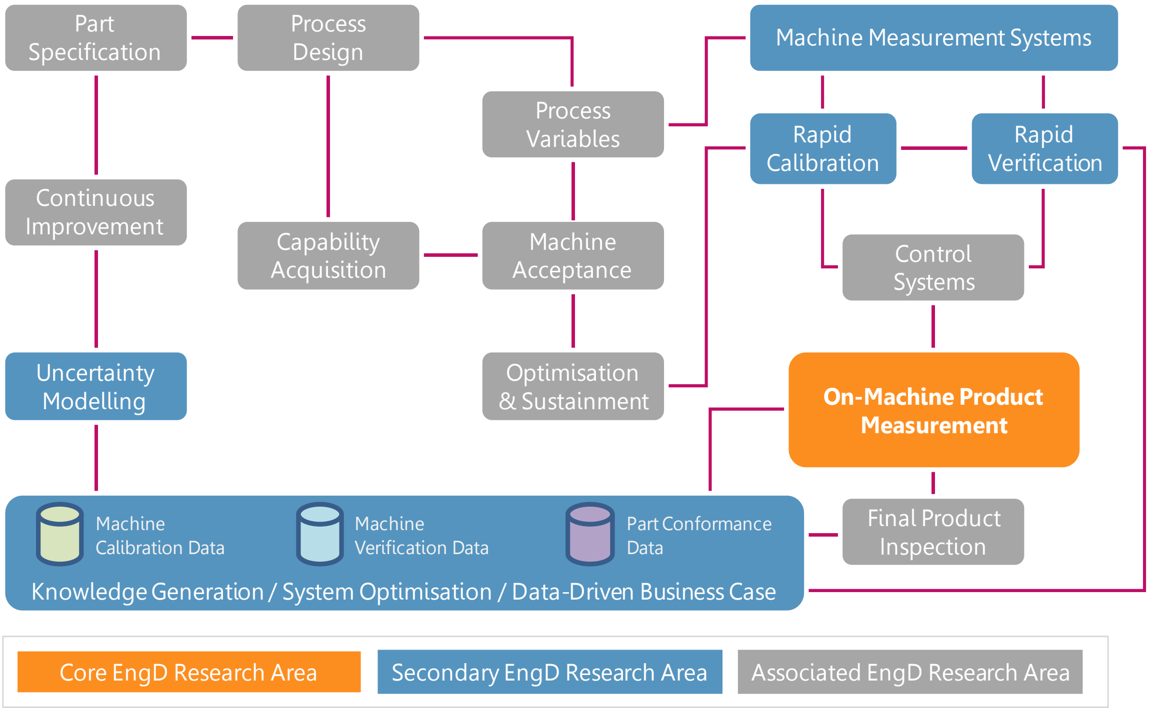


Figure 1-12: ‘EngD on a page’

As indicated by Figure 1-12 a broad number of key research areas must be considered should the researcher wish to answer the core research question in entirety. The research work undertaken herein ultimately aims to generate new knowledge in the area of on-machine product measurement. As shown in Figure 1-12, secondary research areas associated to the core area, will include 1) machine measurement systems 2) rapid machine tool measurement technology 3) machine tool measurement uncertainty and 4) the use of data and evidence to generate knowledge, support the overall system and build and maintain the business case for OMI.

As outlined within this chapter the measurement and compensation of machine tools is well known. There is availability of off-the-shelf probing devices and the principle of using machine tools as measurement devices in a laboratory environment is well known. There is currently off-the-shelf ‘bolt-on’ software and hardware which can be used to enable machine tools as measurement devices. Hence, these are areas that this research work will not directly cover but will utilise.

This thesis develops the utilisation of industrial machine tools as measurement systems, through confirmation of economic case and the development of new methods, technologies, frameworks and systems. The concepts, methods and technologies developed have been experimentally verified in live manufacturing environments and can be incorporated in other high precision machining organisations or applied to similar machine tool equipment, namely high precision multi-axis machine tools.

1.10 Chapter summary and core research question

This chapter has highlighted the industrial opportunity and challenges associated to enabling high precision industrial machining centres as traceable dimensional measurement inspection systems. Multiple messages are presented within this chapter where the most notable facets associated to enabling on-machine tool inspection, are:

1) The challenges facing high-value manufacturing organisations in terms of improving Right-First-Time (RFT) and reducing Cost of Non-Quality (CoNQ)
2) The potential opportunity and challenges associated to machine tools to enable greater up-front product measurement data
3) The challenge of enabling on-machine inspection on a vast array of multi-axis machine tools; due to their variability of size, function and process
4) The unknown metrological capability of industrial CNC machine tools
5) The challenge in understanding, controlling and quantifying the measurement performance of multi-axis machine tool
6) The key requirement of systems connectivity with respect to direct and indirect measurement systems to other enterprise resource systems

An initial question was posed, being *“Why are on-machine probe devices on high precision machine tools not being more frequently utilised for product inspection as well as machine setting?”.* Here it was highlighted that more than often a myriad of challenges and obstacles are expected to be encountered, should industrial machine tool users wish to enable this functionality with their current machine tool asset base. The researcher presumes such challenges often reinforce the opinion of many key stakeholders that the cost, complexity, resource and interruption required to enable such functionality is perhaps not worth the benefit. Furthermore, this chapter introduced a fundamental discussion around this question, which is that if a machine tool is to be utilised for production inspection purposes then it must be treated as a measurement instrument, and therefore must be traceable to international/national standards and hence “in calibration control”. This implies that the machine tool will need to be treated as if it was a coordinate measuring machine (CMM). This is uncovered and expanded on further in Chapters 2 (Literature and State-of-the-art review) and 3 (Research Questions, Methodology and Objective). With this, the core research question for this thesis has been distilled to:

“How can traceable on-machine inspection be enabled and sustained in an industrial environment?”

1.11 Thesis outline

The rest of this thesis is organised as follows:

Chapter 1 (Introduction) – presents the opportunity, industrial context and the overall system associated to enabling machine tools as measurement devices. The overall aim of the thesis is presented, the scope of the study is discussed, and definitions to some concepts used in the thesis are given. As covered.

Chapter 2 (Literature and State-of-the-Art Review) – identifies, presents and critiques the broad academic research associated to utilising machine tools as measurement systems. The same process is also applied to current industrial standards which are of relevance. This chapter also presents a state-of-the-art review of current best practice measurement methods for the rapid measurement, calibration and re-verification of machine tool systems. Finally, the chapter summarises and explores other (publicised) research that is currently being performed globally in order to ensure novelty.

Chapter 3 (Research Questions, Methodology and Objective) – presents the methodology used for defining research strategy, scope, sub-questions and the approach for their investigation.

Chapter 4 (Technical capability of OMP as a foundation of OMI) – presents a real-world case study where machine tools not initially purposed for OMI are augmented with OMP capability. The chapter presents and uncovers key learning points as well as provides evidence for the economic case of OMI.

Chapter 5 (The Machine Tool Metrology Index) – discusses and presents a novel concept of creating ‘Metrology Indices’ for machine tools in order to guarantee that all key performance variables are being measured, re-verified and monitored. The chapter uncovers current industrial and academic best practice. It also tests the concept of ‘Metrology Indices’ in a real-world situation on multiple machine tools.

Chapter 6 (Rapid machine tool calibration to enable industrial OMI) – here an optimal solution for rapid machine tool measurement is generated and tested. In this Chapter a ‘Gold Standard’ approach for the most efficient measurement of multi-axis machine tools is explored and experimented upon in a live industrial environment.

Chapter 7 (An enabling framework for industrial on-machine inspection) – proposes and explores the design and implementation of a robust holistic framework, for which manufacturers can use, in order for them to de-risk and introduce on-machine measurement with their existing machine tool equipment. This framework is then tested and analysed via a real-world implementation.

Chapter 8 (Estimating OMI measurement uncertainty with Uncertainty Estimation Software (UES)) – introduces and explores the use of commercial Uncertainty Estimation Software (UES) re-purposed for use with machine tools and on-machine probing. An approach previously never used in industry. The chapter explores the potential use of UES as a tool for specifying what features and characteristics can and cannot be measured on the machine tool.

Chapter 9 (General conclusions and contributions to knowledge) – concludes the work contained in this thesis by linking findings back to the researcher's original questions. Suggestions for further work are also made.

1.12 List of papers

Authored and co-authored papers connecting to this research are listed below:

Paper I

Willoughby, P, Verma, M, R., Longstaff, Andrew P. and Fletcher, Simon (2010) 'A Holistic Approach to Quantifying and Controlling the Accuracy, Performance and Availability of Machine Tools'. In*: Proceedings of the 36th International MATADOR Conference*. Springer, London, UK, pp. 313-316. **[Published, Co-authored]**

Paper II

Verma, M, (2012) 'The Value Of Industrial Machine Tool Metrology: A Systems Thinking Approach'. **[Unpublished, Author] (Appendix A)**

Paper III

Verma, M. R., Chatzivagiannis, E., Jones, D., & Maropoulos, P. G. (2014) 'Comparison of the Measurement Performance of High Precision Multi-axis Metal Cutting Machine Tools'. In: *Procedia CIRP*, 25, 138-145. **[Published, Author]**

Paper IV

Saunders, P., Verma, M., Orchard, N., Maropoulos, P. (2013) 'The application of uncertainty evaluating software for the utilisation of machine tool systems for final inspection'., *Lamdamap Conference,* March 2013 **[Published, Co-author]**

Paper V

Muelaner, J. E., B. R. Yang, C. Davy, M. R. Verma, and P. G. Maropoulos (2014) ‘Rapid Machine Tool Verification’. *Procedia CIRP,* 25, 431-438. **[Published, Co-author]**

Chapter 2

Literature and state-of-the-art review

Chapter 1 has revealed that the repurposing of machine tools as traceable measurement devices is likely to encounter a broad range of technical and non-technical challenges. This chapter presents existing knowledge and capabilities available to solve and mitigate many of these. Based on the research question and scope, the following areas are covered:

- Machine tool performance contributors
- State-of-the-art machine tool measurement systems
- Machine tool metrology data handling
- Process and Inspection planning
- Machine tools as measurement systems
- Measurement uncertainty evaluation
- Value and impact of metrology

2.1 Machine tool error sources

A machining system consists of four distinct modules: the machine tool, its cutting process, the work piece and fixturing [18]. Each of these modules provides machining capability, however they also provide sources of error. Error refers to the difference between actual and desired relative position and/or orientation [19]. With respect to machine tool error, this is regarded as the disparity between the actual and desired position of the tool tip and the part [14]. There are numerous error sources which must be considered when attempting to optimise the performance of a machine tool [7], [20], [21]. These error sources are often broadly characterised as either being quasi-static

[22]–[24] or dynamic [25]–[27]. An alternate categorisation has also been proposed which divides error sources in to systematic and random [12], [13]. The following sections list and examine common occurring physical error sources associated to machine tool and co-ordinate measuring machines (CMMs) performance.

2.1.1 Geometric errors

The basic accuracy of a machine is determined by its geometry defining components [20]. Errors inherent in the manufacture of machine tools are often termed as straightness, flatness, parallelism, squareness and rotation [14]. Broadly, sources of geometric error are attributed by [20], [29]:

1. Accuracy of components due to manufacture
2. Accuracy of components due to alignment and adjustment
3. Measurement system errors

Typically, these errors are caused by kinematic errors, thermo-mechanical errors, loads and load variations, dynamic forces, motion control systems and software [23]. ISO 230-1:2012 [14] covers definitions and notations of geometric error parameters.

Methods for the measurement of such error sources are covered later in this chapter.

2.1.2 Kinematic errors

Machine tool configurations are classified based on the combination and arrangement of linear and rotary axes [30]–[34]. A “kinematic model” of a machine is defined by *“the model that describes the motion of rigid components within the machine tool structural loop and the joints that link them, without consideration to the forces that generate such motions”* [35]. Kinematic errors are derived from both quasi-static and dynamic motion errors of two or more moving machine tool components [36]. Such errors arise from imperfect geometry and dimensions of machine components as well as their alignment. These errors are more significant where synchronous motion of two or more axes is needed i.e. 5-axis machine tools. Kinematic errors are expected to be very repeatable for high precision machine tools [37]. For a three-linear axis machine tool these error sources are often referred to as the 21 sources of error, illustrated by Figure 2-1.

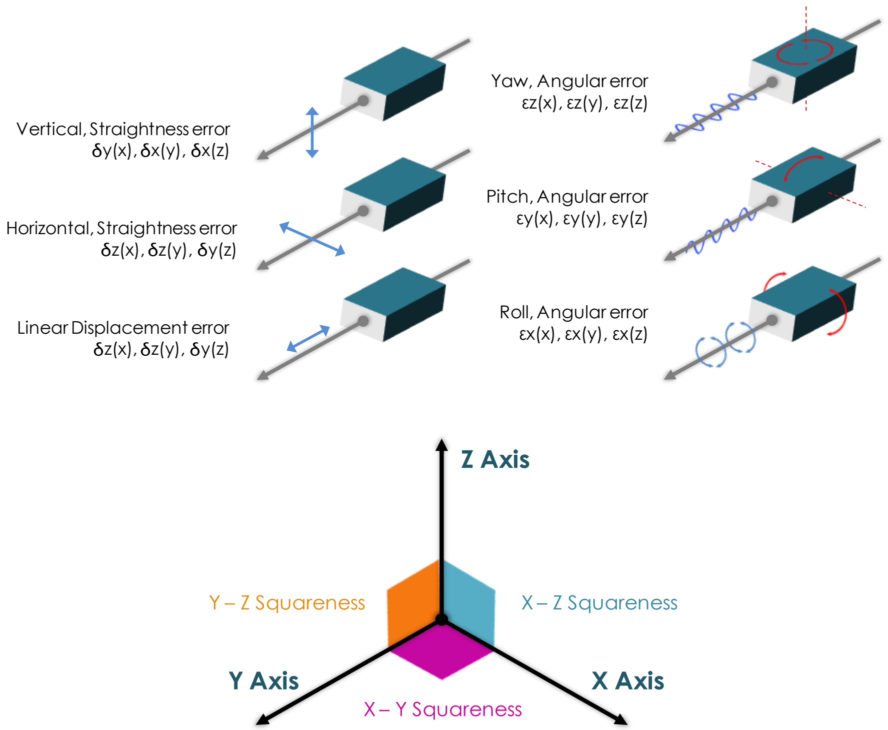


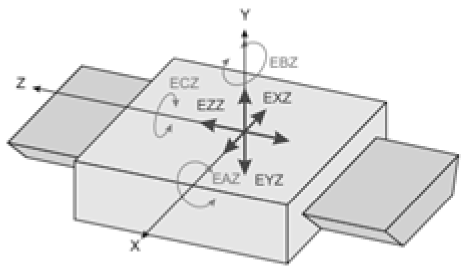
Figure 2-1: The 21 degrees of freedom associated to three linear axes with ISO notation

2.1.3 Linear axis errors

The linear motion of a moving component will always obey rules of ridged body dynamics, in that every unconstrained ridged object will have six-degrees of freedom [38]. Such degrees of freedom involve component trajectory deviations from the nominal path, being:

- One positional deviation, in the direction of motion
- Two linear deviations orthogonal to the direction of motion
- Three angular deviations (ridged body rotations)

Figure 2-2 illustrates such component errors on a linear Z axis according to [14]:



EXZ	Straightness of Z in X (Horizontal Straightness)
EYZ	Straightness of Z in Y (Vertical Straightness)
EZZ	Positioning of Z (only for actuated axes)
EAZ	Tilt motion of Z around X (Pitch)
EBZ	Tilt motion of Z around Y (Yaw)
ECZ	Roll of Z (Roll)

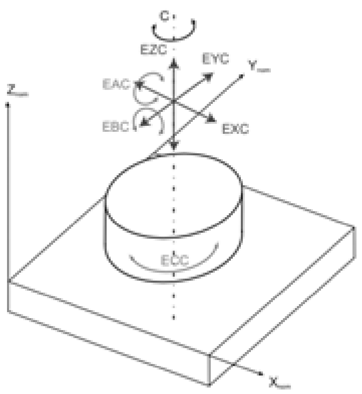
Figure 2-2: Component errors of a linear Z axis (according to [14])

2.1.4 Rotary axis errors

Rotary axes have become more prevalent with machine tools due to their ability to enable free-form surface creation. Error definitions and notations associated to rotary axes (i.e. spindles, rotary tables and rotary axes) are detailed within ISO 230-7 [39]. Rotary axis errors are defined as:

- Radial motion in the X direction
- Radial motion in the Y direction
- Axial motion
- Tilt motion around X axis
- Tilt motion around Y axis
- Angular positioning error

For example the component errors for a rotary ‘C axis’ are illustrated in Figure 2-3, according to [39]:



EXC	Radial motion of C in X direction
EYZ	Radial motion of X in Y direction
EZC	Axial motion of C
EAC	Tilt motion of C around X
EBC	Tilt motion of C around Y
ECC	Angular positioning error of C (actuated axes only)

Figure 2-3: Component errors for a rotary C axis (according to [39])

Measurement and calibration methods for the assessment, calculation, and optimisation of these rotary axis errors are covered in Section 2.4.

2.1.5 Exact constraint design

Designers of machines will routinely use such kinematic principles when designing machines; as an over- or under-constrained machine will not function as desired [20]. For example, components which must remain stable to nanometre precision will not if they are constrained to a structure that deforms by micrometres. The objective exact-constraint design is to achieve some desired freedom of motion, or no motion, through the application of the minimum number of constraints. As a result, an important motivation is to isolate and protect critical metrological components and systems from dynamic affects or manufacturing inaccuracy.

Within academic circles the study and compensation of machine tool kinematic errors has been widely covered for the improvement of machine tool performance [13], [35], [40]–[44].

2.1.6 Thermo-mechanical errors

Machine kinematic errors are compounded by thermal effects, which are considered as the most significant influencing factors affecting machine tool precision [45]. Bryan (1990) has identified six main sources of thermal error [45]:

- Heat generated from the machining process
- Machine energy losses
- Hydraulic oil, coolant and cooling systems
- Local environment
- Thermal memory from previous environment

Mayr *et al.* have completed and presented a state-of-the-art review on research topics associated to the thermal-mechanical influences that affect metal cutting machine tool positional uncertainty [46]. The paper references work relating to the measurement of thermal issues and displacements, computation of thermal errors, reduction of thermal errors and temperature control.

2.1.7 Loading

The non-ridged behaviour of machine tools changes due to internal and external forces [47]. In most cases these forces arise through weight and position of the work piece and moving carriages or via the foundation in which the machine sits [20]. Such loads can have a significant impact on precision. A fundamental challenge confronted by precision machine tool builders is the management of deflection errors associated to static loading, flexibility and structural constraints [20]. Finite element analysis (FEA) is the prevalent tool for the design and modelling of a machine structure [38], [48]–[50].

The measurement devices which can be used to measure such errors will be described in later sections.

2.1.8 Dynamic errors

The accuracy and repeatability performance of a machine tool is affected by the dynamic behaviour of its kinematic chain and or its components [18]. Typical sources of dynamic error come from vibration, acceleration and deceleration of machine axes and thermal gradients [27].

The effects of vibration are often difficult to compensate since vibration amplitude and phase angles are unknown [51]. Methods of prevention rather than correction are usually employed [52].

Motion control errors due to servo drives and controller hardware and software can also significantly impact overall machine tool accuracy. Typically such errors can be identified by running and measuring performance at different feeds and speeds for identical motion paths [53]–[55].

In an attempt to control dynamic errors machine tools are typically run and measured at low feed rates with motion paths optimised to minimise accelerations and decelerations [56]. It is therefore treated as a separate issue to correcting for quasi-static errors.

2.1.9 Motion controller & contouring errors

Motion control errors are often referred to as backlash, servo mismatch and contouring errors [57]. Such errors often arise from interruptions within the CNC system control loop from sources such as the CNC, linear and/or rotary encoders, feed control and interpolation processing ability, friction and backlash [58], [59]. Figure 2-4 illustrates the typical control loop for a machine tool axis.

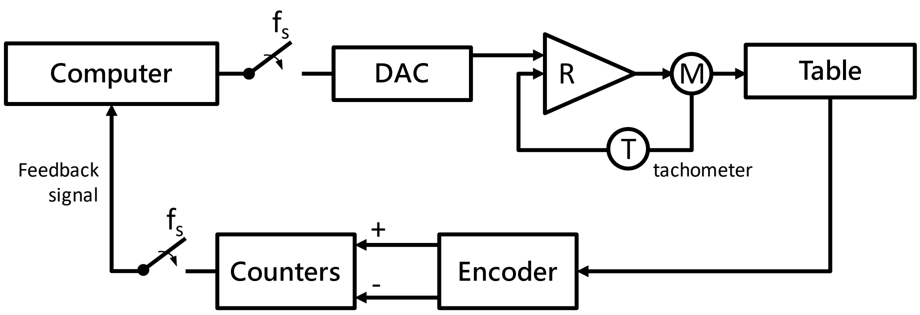


Figure 2-4: Typical control loop of a sampled-data type system [12]

The contouring error can typically be evaluated by recording machine controller inputs and encoder actual values whilst comparing relative position of the tool and workpiece from the two [60]. Poo *et al.* demonstrated that despite the existence of following errors on individual axes of a machine tool, sub-micron contouring could still be achieved through compensation and synchronisation aimed at cancelling effects [61]. Zhu *et al.* have proposed approaches for calculating contouring errors in real time, whilst comparing with previous methods [62].

Measurement methods for detecting and compensating for contouring errors is covered in later parts of this chapter.

2.1.10 Spindle errors

A machine spindle, either work-holding or tool-holding, provides the relative motion between the cutting tool and the workpiece and therefore provides the only interface between them. Key characteristics of a machine tool spindle include power, speed, stiffness, torque, thermal efficiency, bearing life and runout [12]. All such characteristics have a substantial impact on product quality and machine performance. Typically spindle requirements will differ from industry-to-industry as material, production, quality and cost requirements differ i.e. automotive, aerospace, mould & die. Advances in spindle technology allow for higher cutting speeds enabled by bearing technology, cooling and lubrication systems, mechatronics, motor vector control, advanced modelling and in-process control systems [63]–[66].

Spindle errors consist of those listed in Section 2.1.4 in addition to alignment errors, dynamic and vibration errors, thermal behaviour, spindle speed errors, stiffness, taper errors and drawbar tension [12], [51], [67]–[70].

2.2 Machine tool evaluation standards

Machine tool builders and users will often refer to national and international standards for guidance relating to standard verification procedures relating to their machine tools. International and Global standard bodies relating to the verification of machine tools include:

- BS 4656 - Accuracy of machine tools and methods of test (British)
- BS 3800 - Methods for testing the accuracy of machine tools (British)
- VDI / DGQ 3441 - Statistical testing of the operational and positional accuracy of machine tools (German)
- NMTBA / ASME B5.54-92 - Methods for performance evaluation of computer numerically controlled machining centers (United States)

- JIS B 6330-1986 - Test code for performance and accuracy of numerically controlled machine tools (Japanese)
- ISO Standards - International Technical Community 39/SC2 (22 participating countries)

Benefits associated to such documentation includes; the standardisation of machine tool testing nomenclature and procedures, standard procedures relating to existing and new test equipment, test methods for machine tools; dimensional and performance testing of modular units such as ballscrews, spindles and chucks.

2.3 British standards

There are two sets of British standards associated with the installation and verification of machine tools. These standards have now been withdrawn and replaced by international standards under the heading of BS EN ISO 230.

2.3.1 BS 4656

BS 4656 'Accuracy of machine tools and methods of test' consist of a series of 37 standards, all detailing the acceptance criteria for a multitude of specialised metal cutting machine tools [71]. Most standards have now been superseded by an ISO standard or withdrawn.

2.3.2 BS 3800

BS 3800 'Methods of Testing the Accuracy of Machine Tools' are basic standards which clarify definitions used to describe methods of testing, use of instrumentation, application of tolerances and the accuracy of measurement instruments. Again these have been superseded by ISO standards or withdrawn.

2.3.3 BS ISO 230

BS EN ISO 230 series of standards are now the primary test code relating to the testing and acceptance of machine tools. Although written for metal cutting machines many of the methods of test can be applied to other machine tool types. The series of standards are written by an international committee TC/39 consisting of 23 participating countries and are observed by a further 19 countries. These standards are covered in more detail in 2.2.5.

2.4 German standards

The German VDI directive VDI/DGQ 3441 for the Statistical Testing of the Operational and Positional Accuracy of Machine Tools: Basis is often referred to by German machine tool builders when asked to follow a standard machine acceptance procedure.

2.5 US standards

2.5.1 ASME B5.54-2005

The primary machine tool performance acceptance standard is the ASME BS.54-2005 standard, titled 'Methods for Performance Evaluation of Computer Numerically Controlled Machining Centres'. The ASME BS.54-2005 document details the standard process for testing CNC machining centres. In addition to testing procedures the document enables users to compare performance between machine tools though the unification of terminology, machine classifications and management of extrinsic factors i.e. environmental effects. The standard details a series of tests which should be used to for CNC machinery acceptance and the verification of continued capability. Tolerances for acceptance are recommended to be agreed by the supplier and user of the machinery.

2.5.2 NMTBA

The National Machine Tool Builders Association (NMTBA) was founded in 1902 by the Association for Manufacturing Technology (AMT). The documentation provided by the NMTBA with regards to CNC machine acceptance criteria is less detailed than that found within the ASME B5.54-2005 standards.

2.6 Japanese standards

The JIS B 6336 series of standards consists of 11 parts, all written by the Japan Machine Tool Builders Association (JMTBA) and the Japan Standards Association (JSA). These standards all refer to the *Test conditions for machining centres* and predominantly follow the ISO 10791 series of standards (Section 2.2.5). The standards also often reference the JIS B 6191 standards, which detail geometric tests to be carried out on machining centres.

2.7 International standards

The ISO Technical Committee ISO/TC 39 is responsible for creating all standards related to the testing of numerical controlled machine tools. Currently there are 162 ISO/TC 39 standards in circulation which have been created with 22 participating countries [72]. Table 2-1 presents the ensemble of current ISO/TC 39 standards produced and in development.

Table 2-1: Standardization of all machine tools for the working of metal, wood, and plastics, operating by removal of material or by pressure [Source www.iso.org]

SC / WG	Title	Documents
SC 2	Test conditions for metal cutting machine tools	84
SC 4	Woodworking machines	39
SC 6	Noise of machine tools	3
SC 8	Work holding spindles and chucks	11
SC 10	Safety	5
WG 7	Ball screws	41
WG 9	Symbols for indications appearing on machine tools	
WG 12	Environmental evaluation of machine tools	
WG 16	Production equipment for Microsystems	

TC – Technical committee, SC – Subcommittee, WG - Working Group

The ISO TC 39 subcommittee 2 (SC2) “Test conditions for metal cutting machine tools” specify methods for assessing the precision and performance of machine tools via direct and indirect measurements. Subcommittees of ISO TC 39/SC 2 are as indicated by Table 2-2.

Table 2-2: ISO/TC39/SC 2 Test conditions for metal cutting machine tools

SC / WG	Title
ISO/TC 39/SC 2/WG 1	Geometric accuracy
ISO/TC 39/SC 2/WG 3	Test conditions for machining centres
ISO/TC 39/SC 2/WG 4	Test conditions for numerically controlled turning machines and turning centres
ISO/TC 39/SC 2/WG 6	Evaluation of thermal effects
ISO/TC 39/SC 2/WG 7	Reliability, availability and capability
ISO/TC 39/SC 2/WG 8	Assessment of machine tool vibrations

TC – Technical committee, SC – Subcommittee, WG - Working Group

The 84 standard documents written and developed by the ISO/TC 39/ SC 2 subcommittee can be divided into two groups; basic standards and machine specific standards. Basic standards offer fundamental definitions e.g. the definition of squareness, methods of testing and test equipment. Machine specific standards all relate to performance tests, they are sub-divided for: milling, drilling and boring machines and machining centres, turning machines, grinding machines, electro-discharge machines (EDM), broaching machines, hobbing machines and machining heads. Table 2-3 illustrates the grouping and contents for all ISO standards published and in development by ISO/TC39/SC2.

Table 2-3: ISO/TC 39/SC2 Metal Cutting Machine Test Conditions Standards

ISO / TC 39 / SC 2 **Test Conditions for Metal Cutting Machine Tools (84 Documents)**				
BASIC	**MC**	**TC**	**G**	**Other**
Basic Standards *14 Documents*	Milling, boring, drilling machines *33 Documents*	Turning *12 Documents*	Grinding *6 Documents*	Special machines *9 Documents*
230 (1 – 11) 26303	10791 (1-10) 3070 (1-3) 1701 (1-2) 1984 (1-2) 2772 (1-2) 2773 (1-2) 3686 (1-2) 8636 (1-2) 3190 2423	13041 (1-8) 1708 3655 6155 8956	1985 1986 2407 2433 3875 4703	EDM 11090-1/2 14137
				Broaching 6480 6481 6779
				Div. heads 5734
				Hobbing 6545

2.8 ISO TC39 SC2 “Test conditions for metal cutting machine tools” - Gaps

Chairman of the ISO TC 39 committee, Dr. Wolfgang Knapp, comments that the current published standards for the accuracy assessment of machine tools predominantly cover 3-axis machine tools, where the acceptance testing of 5-axis machines is only partially covered [73]. As a result ISO 10791-1:1998 [32], which considers the geometric testing of machining centres is currently under revision to include tests for machining centres with rotary axes. Consequently ISO 10791-6:1998 [74] is being revised to include interpolation checks for machining centres with universal heads, swivelling rotary tables, rotary tables and swivelling spindles (Figure 2-5). Additionally, ISO 10791-7:1998 [75] is being amended to include 5-axis test piece manufacture and validation.

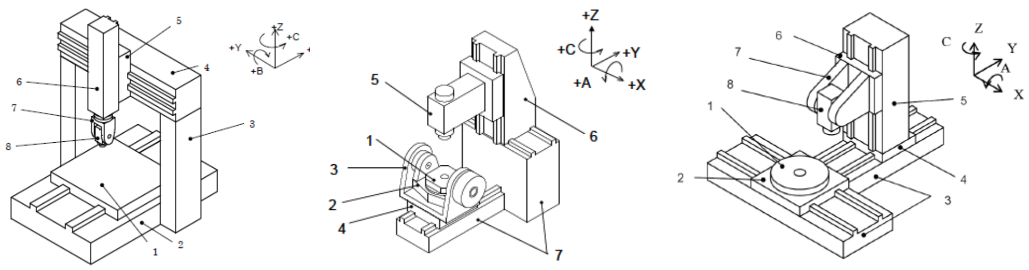


Figure 2-5: ISO 10791-7 considered 5-axis machine tool configurations

2.9 ISO TC39 SC2 “Test conditions for metal cutting machine tools” - Trends

2.9.1 Determination of thermal influences

Highlighted by Knapp, is the importance of measurement of thermal influences due to its impact on 5-axis machine tool performance [73]. Due to research identifying the thermal affects associated to rotary axes [46], [76] the ISO 230-3:2007 [77] is therefore being extended to include the measurement of thermal influences associated to the environment, rotary axes and swivelling axes.

2.9.2 Measuring performance of on-machine probing systems

Due to the growing trend for machine tools to utilise probing systems for the purposes of part location, tool offset calculation and on-machine-inspection the ISO 230-10:2010 standard [78] is being updated to include the validation of probing systems for turning centres, grinding machines and EDM machines. The ISO 230-10:2010 standard is also being updated to include the determination of performance of scanning and non-contact probing systems.

2.9.3 Capability tests for machine tools

The recently published standard ISO 26303:2012, Machine tools – Short-term capability evaluation of machining processes on metal –cutting machine tools, has received criticism from ISO technical committee 69, applications of statistical methods, as it differs from its own capability standards [73]. As a result, the standard is to be amended to clarify the term ‘short-term capability’ and considerations from the TC/69, statistics, working group.

2.9.4 Machine tool environmental issues

Knapp has also highlighted a new draft international standard (DIS) ISO 14955-1, Machine tools – Environmental evaluation of machine tools – Part 1: Design methodology in development [73]. The standard refers to the *“setting up of a process for the integration of environmental aspects into product design and development and evaluation of the integration of design procedures for energy efficiency”*. The objective of the standard is to provide machine tool builders and users knowledge of the energy requirements of their machine tools.

Furthermore, a standard in discussion is ISO 14955-2, Machine tools - Environmental evaluation of machine tools – Part 2: Methods for measuring energy supplied to machine tools and machine tool components. This standard aims to define “system boundaries, modes of operation, shift regimes, measurement procedures and measurement uncertainties, reporting and monitoring of results” [73].

2.10 Test conditions for metal cutting machine tools - future standards

Currently there are no ISO standards that deal with the compensation of multi-axis machine tools [73]. Due to the proliferation of compensation systems being employed by machine tool manufacturers, users are often unclear on their capabilities or differences due to conflicting terminologies and expression usage i.e. the use of the term Volumetric Accuracy. ISO TC 39 is therefore preparing a draft technical report ISO/PDTR 16907.2: 2012-02-21, Numerical compensation of geometric errors of machine tools [79]. The standard aims to maximise upon outputs from SOMMACT [80] and facilitate comparability of machine tool, through the identification of the potential and limits of compensation, based on the ISO 230 series of standards.

“Duty cycles are predictable in a few cases only therefore calculations on reliability and availability are rather vague and often lack reliable data from the application filed” [57]

2.11 ISO 230 series of standards

The set of eleven ISO 230 series of standards provide a general guide for specific measurement methods impartial to machine tool type or configuration [14], [39], [77], [78], [81]–[87]. The ISO 230 series all under the general title of *Test code for machine tools:* consists of:

- Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions
- Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes
- Part 3: Determination of thermal effects
- Part 4: Circular tests for numerically controlled machine tools
- Part 5: Determination of the noise emission
- Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests)
- Part 7: Geometric accuracy of axes of rotation
- Part 8: Vibrations [Technical Report]
- Part 9: Estimation of measurement uncertainty for machine tool tests according to series ISO 230, basic equations [Technical Report]
- Part 10: Determination of the measuring performance of probing systems of numerically controlled machine tools
- Part 11: Measuring instruments and their application to machine tool geometry tests [Technical Report - Pending].

Within the ISO 230 set of standards various methods, equipment, and reporting and calculation requirements are described and stipulated for a selection of measurement processes. The fundamental aim of all such standards is to clarify usage, minimise uncertainty of measurement and guarantee traceability. As a result they are often the most referred to set of standard by equipment manufacturers, users and academics [88], [89].

2.11.1 Limitations

The ISO 230 series of standards can be used to detect some errors in a machine tool but the tests are no way comprehensive. Argued by Perkins *et al.* is that as the ISO 230 (1-10) standards do not refer to OEM operational manuals and documentation and therefore measurement uncertainty can be further introduced rather than removed [88]. This may however be addressed through the release of ISO 230-11 (Pending) [87].

Chapman [90] reports limitations in the results produced by diagonal based measurements. Soons [91] raised additional concerns associated with setup errors. Svoboda [92] describes the results of a set of linear displacement accuracy measurements performed on two vertical CNC machining centres. The scope of this work was to verify or disprove some of the recently claimed limitations of the conventional diagonal measurement method and of the "laser vector" or "sequential diagonal" method.

2.12 CMM acceptance and re-verification standards

Standards commonly used for CMM performance assessment and calibration are namely the ISO 10360 series of standards [93], the ASME B.89 [94] and VDI/VDE [95] standard. All such standards involve the use of traceable artefacts such as step gauges, length bars and gauge blocks. Such artefacts are used to produce both an estimate of the machine performance in terms of a volumetric measuring uncertainty value also known as maximum permissible error (MPE) as well as to perform interim checks.

Irrespective of the artefact used, confidence in results generated is only achieved if a specific set of conditions were met when the evaluation was carried out. These "conditions" refer to certain variables that will have an effect on the measurement result, such as those described in Chapter 1 and Figure 1-9. Fundamentally these standards are used to minimise, estimate and compensate for the effects of systematic and random errors which will impact upon measurement precision [19].

Limitations of these standards, in terms of repurposing them for machine tool applications, is that; there is little or no indication of how and what is applicable; there are a number of estimations and assumptions which cannot be applied to machine tools; the standards do not cover certain machine tool configurations, hybrid or special purpose machine tools; these standards are focused more on "sign-off" and compensation rather than production requirements; there is no guidance on verification for fit-for-purpose on-machine measurements.

2.13 Techniques for machine tool verification

Historically machine tool designers have applied a deterministic approach to machine accuracy and precision with great success [7] [21]. There has always been the view that non-repeatable behaviour in a machine tool or process has root-causes where measurement and metrology can be used to identify and control such causes.

An opposite view, which some may consider defeatist, is to succumb to the belief that non-repeatable and chaotic behaviour is unavoidable [44], [96]. This view leads to the utilisation of statistical methods to describe behaviour of systems [29], [97], [98]. The strength of using mathematical methods which is a reason why they are used frequently to expose error sources within test data. This has led to an emergence of both direct and indirect measurement systems to measure and determine machine tool volumetric accuracy.

Measurement of machine tools is often performed for the following reasons:

- Testing prior to machine purchase
- Factory Acceptance Testing (FAT)
- Site Acceptance Testing (SAT)
- Periodical condition monitoring
- Error detection
- Testing prior to warranty expiration
- Equipment optimisation

In order to perform measurements for any such particular purposes an array measurement devices are available.

2.14 Direct measurement methods

Schwenke *et al.* define “direct” measurement as the analysis of a single error, such as linear positioning error and angular error of an individual axis [23]. Using direct error measurement methods enables single axes to be assessed without the interference of other axes (Figure 2-6). Schwenke *et al.* classify direct error measurement into three sub-groups; material based methods, laser-based methods and gravity based methods. They have comprehensively reviewed current methodologies for the direct measurement of machine tool geometric errors.

Figure 2-6: "Traditional” Direct machine tool error measurement techniques (Source: MTT Ltd.)

Sartori and Zhang [99] described the available equipment and approaches for direct axis calibration. Methods presented are intended to measure single error component of a moving axis at a time. An approach to measure the overall 21 error components of a three-axis machine by measuring the linear displacement errors along 22 lines within the working space was developed. This method was then later improved by Chen *et al.* [100].

A methodology to measure the linear displacement errors and straightness errors simultaneously was presented by Wang [101] and Janeczko *et al.* [102]. This method aimed to reduce the measurement time from what it would typically take from using a laser interferometer to measure one error at a time. This methodology has however been rebuked by Chapman [90] who demonstrated that significant uncertainty exists within the process. This was further proved by Svoboda [92] who showed that the method does not work if large linear displacement errors exist within the machine tool geometry frame.

In-process methods have also been employed by Yuan and Ni, 1998, [103] for direct measurement of machine tool errors. Choi *et al.* [104] employed the use of spindle probes to enhance machine tool accuracy. The method used involved using on-machine measurement devices to predict geometric errors. Jun *et al.* [105] has also developed such a method using non-contact optical methods.

2.14.1 In-direct measurement methods

In-direct methods imply that axis errors are measured via calculation through kinematics analysis or other mathematical relationships between the measured errors and error components [35]. Such methods require significant derivations and mathematical analysis, where uncertainty is often heavily induced within the process, which in-turn affects accuracy. Historically in-direct methods have been used as a quick check of machine tool motion accuracy and are often used for condition monitoring rather than non-diagnostic purposes. Such an example is the use of precision ball-bar systems and or artefacts to estimate geometric errors of machine tools. However, in-direct measurement methods are becoming more fashionable due to their speed of use and the advancement of machine tool electronic compensation systems [35]

Standard artefacts with known dimensions are typically used to obtain geometric error categorisation. Sartori and Zhang [99] have used a 1-D array ball to measure the machine geometric errors whilst Kruth *et al.* [106] proposed a squareness error measurement method by using a single artefact.

In terms of continuous performance improvement Chen and Ling [107] used artefacts to model the positioning and contouring errors whist Balsamo *et al.* [108] employed the use of ball plate based techniques for CMM parametric error determination. Du *et al.* [109] utilised a grid plate to calibrate an optical CMM with a pre-calibrated axis.

Figure 2-7: In-direct machine tool error measurement technologies

A recent paper by Ibaraki and Knapp comprehensively describes current state-of-the-art methods for in-direct kinematic error measurement, analysis and compensation [35]. Equipment under investigation included Ballbar, R-Test, and Laser Tracker measurement equipment (Figure 2-7). The work highlighted numerous deficiencies and limitations of all of the systems investigated, especially with regards to their usefulness in terms of error diagnosis and volumetric compensation. Such deficiencies include; the limitations in measureable dimension i.e. due to only one-dimensional aspects of measurement techniques; the fact that volumetric accuracy can only be calculated through the creation of kinematic models; limitations in measurable positions i.e. depending on method measurements can only be made at pre-calibrated positions, such as with ball-plate artefacts; that measurement uncertainty increases as measurement range increases, such as with laser tracker interferometers; the ability for error separation i.e. when two or more axes are synchronously moved to take a measurement it is difficult to separate errors without the construction of virtual kinematic models; angular error measurement capability i.e. certain technologies such as the Double Ballbar [110] and R-Test [111] measure the position of sphere centres and angular errors can only be estimated through best fitting with kinematic models.

2.15 Rapid machine tool measurement

As discussed machine tool errors can arise from various sources and can be influenced by dynamically changing ambient conditions. To enable the traceability of dimensional measurements from the machine tool one must be able to identify and detect these errors. Once detected errors can be evaluated and corrected or compensated for. However this process demands qualified measurement standards and procedures. A number of machine tool measurement systems have been examined by Knapp *et al.* [23]. Although the work presents and discusses novel measurement methods utilised for multi-axis machine error measurement and compensation; speed of measurement is not discussed in detail; a critical factor for the regular benchmarking, assessment and sustainment of on-machine measurement processes in an industrial setting. The researcher must therefore consider:

- Current best practice methods for machine measurement
- Alternate technology not previously utilised for machine measurement
- Near-future technology designed for multi-axis machine tool measurement.

The measurement techniques typically fall into one of three classes: 1) equipment that determines individual error parameters one at a time; 2) equipment capable of measuring more than one error parameter at a time; and 3) equipment that can only report all errors once a full series of measurements is complete. Current technologies being used for the measurement of multi-axis machine tools on the shop-floor are outlined in the following sections.

2.15.1 Traditional machine measurement systems

Traditional hardware based techniques (for example using straight edges and squares) can only measure one error at a time. Whilst traditional hardware-based techniques may be useful for machine alignment checks they have an advantage that they utilise readily available artefacts.

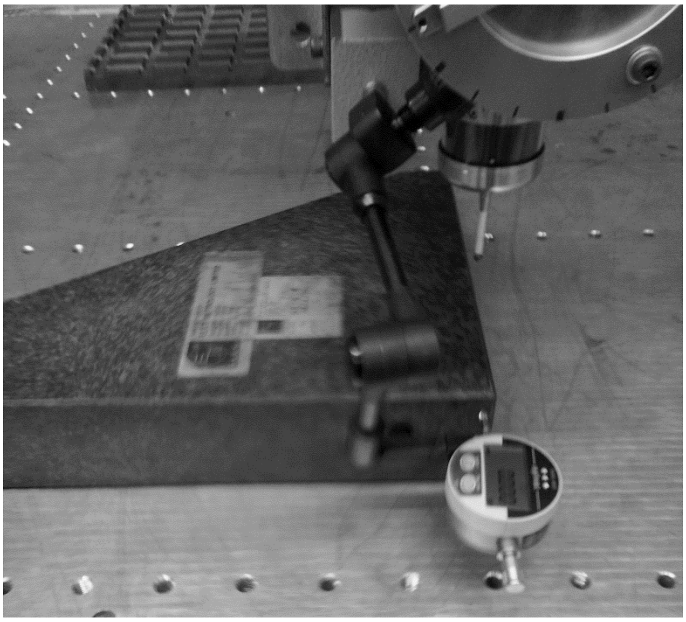


Figure 2-8: ‘Traditional’ machine tool measurement methodology

Traditional methods of machine tool calibration measure each error parameter, one at a time in order to determine the compensation factors necessary for each of the error parameters [14]. This can be a time-consuming process which treats each axis and error independently and therefore requires multiple instruments and setups. Additionally, with each measurement, the machine will stand idle while the data is recorded and processed, often for hours at a time. Depending on the size and the number of axes on the machine, the entire process can take multiple days with temperature fluctuations contributing to uncertainty. A selection of traditional systems and methods are listed below and many of the methods are covered in ISO 230-1. However, ISO 230-1 does state “*When a measurement method not described in this standard can be shown to offer equivalent or better facilities for measuring the* *attributes to be studied, such a method may be used"*. Relevant to this comment is the potential use of on-machine probing devices, in-place of dial test indicator clocks.

2.15.2 Engineer levels

Engineers' levels and machinist workshop levels are often used where high accuracy manual levelling is required. Levels are generally precision ground with flat and 'V' shaped surfaces, and are available in a range of lengths and sensitivities. Levels can be either spirit based or, more common these days, electronic. Electronic levels enable automatic data capture and analysis by computer (Figure 2-9). Electronic levels can act differentially to remove background tilts. Levels cannot though be used to measure the rotation around a vertical axis or the yaw of a horizontal axis. The use of spirit or electronic levels is not considered as a 'rapid' measurement solution.

Figure 2-9: Electronic precision level (Source: www.google.com)

2.15.3 Autocollimators

An autocollimator measures small angles with very high sensitivity. As such, autocollimators have a wide variety of applications including precision alignment, detection of angular movement and angular monitoring over long periods. The autocollimator projects a beam of collimated light, and an external reflector reflects the beam back into the instrument where it is focused onto a photo detector. The device measures the deviation between the projected and reflected beams.

The simplicity of use and repeatability of readings make this popular in the machine tool building industries and calibration environments. It can be used to measure angle, straightness, squareness and parallelism. The high accuracy means it is capable of measurements of indexing heads, and machine tool guide ways.

Autocollimators can be of the visual or photoelectric type. However, more recently increased use is made of automatic position sensing type autocollimators with the added advantage of computerised data collection and analysis [23].

2.15.4 Reference squares

Precision squares can be used to setup or check the perpendicularity between linear axes [112]. They can be used in a reversal mode to separate out errors in the square and those of the machine. They can also be used to assess the perpendicularity of rotary axis centrelines to linear axes [113]. The specification of such artefacts is covered by British Standard BS939 [114].

2.15.5 Reference straightedges

Similar to precision squares, reference straight edges can be used in alignment and setting up ensuring straightness of machine axes. Precision straight edges are generally manufactured from hardened steel or granite that has been ground to produce parallel edges.

Again, use can be made of the reversal technique. Similar to squareness artefacts, straightedges are available in a number of grades and are covered by British Standard BS5204 [115].

2.15.6 Step gauges

Length standards such as step gauges or length bars can be used to check the linear accuracy of machine tools with the use of an ancillary electronic gauge head. Such systems are commonplace with the assessment of CMM equipment [116].

A recently designed machine tool length standards is the IBS MT-check system (Figure 2-10), which comprises a three-axis on-machine probe and calibrated ‘Ball -bar’. The probe comprises three planar elements, which are contacted onto the balls on the artefact. Sensors in the probe head monitor the deflection of the planes thus determining the centre coordinates of the ball.

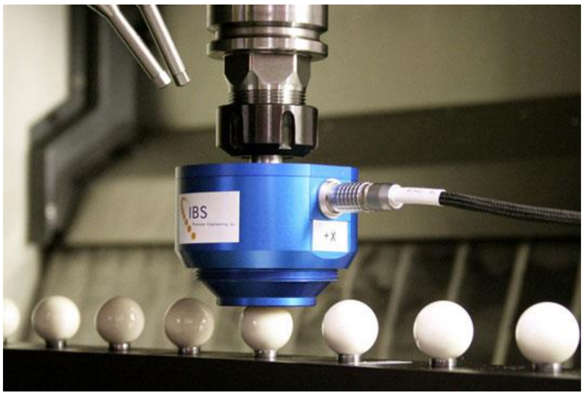


Figure 2-10: IBS Precision MT-Check system (Source: IBS Precision www.ibspe.com)

2.16 Laser interferometer machine measurement techniques

Techniques utilising interferometers are capable of measuring two or more errors in a single axis at the same time. There is a range of different laser interferometer based measurement systems available, which are suitable for machine tool calibration [117]. They generally include additional optics and/or sensor that make them capable of measuring most if not all of the 21 geometric errors. Laser interferometer systems require careful alignment before taking measurements. Additional mounting kits and optical setups tend to be required for the different errors being measured, although some are capable of measuring more than one error at once. These systems are only capable of measuring a single axis at a time.

The main advantages of this class of devices are that they:

- are well understood and accepted in the market place
- available from several competing system suppliers
- can be used for machine setup and diagnostics where it is required to analyse specific error associated with individual axes and
- are relatively cost-effective

The main disadvantages of using such equipment, is that manual alignment and considerable operator skill is required, which therefore makes set-up time inconsistent for different machine tool types and configurations. In addition, all laser based techniques suffer from environmental effects. The main effects are due to bulk refractive index, which affects the accuracy of the distance measurement, and thermal gradients and air turbulence which affect the straightness measurements which rely on the laser beam as a straightness reference.

The following are examples of interferometer base systems on the market:

2.16.1 Automated Precision Inc. (API) XD Laser

The XD Laser is API's latest generation of 5 or 6 degree-of-freedom laser measurement systems [118]. With a single setup per axis it can measure 20 of the 21 error parameters and it has the ability to simultaneously measure linear, angular, straightness, pitch, yaw and roll errors (in the x- and y- axes) for rapid machine tool error assessment. An additional setup and optics are required to measure z-axis roll.

The XD laser system (Figure 2-11) comprises a laser head, a sensor block, a pentaprism and weather station. The laser head is mounted on the bed of the machine and aligned with a machine axis. The sensor block, which contains a retroreflector for the interferometer is mounted on the machine head. The sensor block contains straightness and angle – pitch, yaw and optionally, roll - sensors. The system can therefore measure all six degrees of freedom for a single axis.

Figure 2-11: API XD Laser measurement system (Source: API Inc.)

Once the first axis has been measured, alignment for the subsequent linear axes is easily achieved using a pentaprism, mounted on the machine base. The roll sensor is gravity referenced, so is not capable of measuring vertical axis roll. An additional setup and equipment is required for this measurement.

According to the published specifications the XD6 precision laser measurement system is capable of linear and diagonal measurement with a resolution of 0.02 µm across a range of 0 – 40 m or optionally up to 80 m, and an accuracy of 0.2 ppm. Straightness measurement is measured to an accuracy of ± (0.5 µm + 0.1 µm/m) or

1% of the maximum measured error. Squareness measurement accuracy is ± (1.0 second of arc + 0.2 seconds of arc/measured travel in metres). Angularity measurement resolution is 0.1 second of arc across ±400 seconds of arc. Pitch and yaw accuracy is ± (0.5 seconds of arc + 0.2 seconds of arc /measured travel in metres) or 1% of the maximum measured error [119]. Roll measurement, for the horizontal axis only, has an accuracy of ±0.5 seconds of arc or again 1% of the maximum measured error.

2.16.2 Agilent and Renishaw laser systems

These systems comprise a laser head, fringe counting system and a number of optical configurations that enable various machine tool parameters to be measured (Figure 2-12). These include linear optics, angular optics and straightness and squareness optics. The major manufacturers of this type of equipment are Agilent and Renishaw. The advantage of this type of system is that single error parameters can be quickly measured. The disadvantages are that the alignment of the systems can be time consuming and requires an experienced operator. Measuring a separate parameter may require a change of optics. Both systems are interferometric and have direct traceability to the realisation of the definition of the metre. The XL- 80 measurement system from Renishaw plc. has a specified measurement accuracy, over the full environmental operating conditions, of ± 0.5 ppm, with a linear resolution of 1 nm over its range of 80 m. This system includes the LaserXL software which has modules for linear, angular, rotary axis, flatness, straightness and squareness measurements [120].

Figure 2-12: Renishaw XL-80 laser interferometer system

2.16.3 OPTODYNE (Laser Doppler Displacement Meter)

The Laser Doppler Displacement Meter (LDDM) technology that is the basis of Optodyne's calibration systems, reflects a modulated laser beam off a movable target (Figure 2-13). Similar to radar technology, displacement information is derived by detecting the beam, which the control unit uses to determine position.

A two-axis system, the VS-5020 has a published measurement accuracy of 1 ppm, resolution to 0.001μm, speed up to 5 m/sec, and frequency response from DC to 400kHz [121].

Optodyne promote the stepped diagonal method of calibrating the linear axes as described in ISO 230-6 i.e. to move from one point on the diagonal to another, the machine is moved first in the X-axis, then Y, then Z.

This method has attracted some controversy, with claims and counter claims of its validity. A recent paper by Takeuchi *et al.* [122] summarises some of the alleged issues and proposes a more robust analysis. It is expected that set-up and measurement times will be in the order of hours with respect to this equipment.

Figure 2-13: Optodyne laser doppler measurement system (Source: Optodyne Ltd.)

2.17 Simultaneous error parameter determination measurement methods

In contrast to the methods described above, that measure the geometric error parameters independently using a combination of different sensors, methods and data sets, there are new methods that determine all error parameters simultaneously from a combined data set.

Using these techniques, all error parameters can be determined simultaneously by comparing the measured machine coordinates (scale readings) to reference coordinate measurements, made using some other coordinate measurement system, and mathematically fitting the differences to model equations representing the geometrical errors of the machine.

The advantages of these techniques are:

- setup is relatively quick
- no manual alignment is necessary

With such equipment data fitting process are used to determine all machine error parameters. This optimises data usage and the availability of high levels of data redundancy. This can also lead to the ability to perform uncertainty evaluation and analysis of the quality of the measurement data in real-time.

The main disadvantages of such techniques are:

- All-or-nothing measurement – it is not possible to determine a sub-set of parameters from a sub-set of data, for example for quick diagnosis of errors associated with a single axis during machine commissioning or adjustment
- It is relatively new and not as easily understood by the end user, therefore, not so easily accepted in the market
- It is dependent on laser tracker or LaserTRACER hardware that can be more expensive than traditional systems
- If fixtures or objects are located within the working volume this may hamper the ability to set up and operate equipment effectively

There are currently only two commercial systems that adopt this approach: the Automated Precision Inc. (API) Volumetric Error Compensation (VECTM) system based on their T3 laser tracker and ActiveTarget tracking retro-reflector, and the Etalon LaserTRACER/TRAC-CAL combination [119], [123]. However, more recently laser tracking systems, typically used for large volume measurement, are being investigated as potential lower-cost alternatives [124].

2.17.1 API VEC system

The Automated Precision Inc. Volumetric Error Compensation system was originally developed by P Freeman of the Boeing Company and subsequently developed into a product by API (Figure 2-14). It uses a laser tracker to provide a reference coordinate system. The laser tracker tracks a target fixed to the machine spindle as the machine moves. The target used is a special motorised, tracking retro-reflector (ActiveTarget) that automatically orientates itself such that the retro-reflector is always visible by the laser tracker. This ensures that the tracker never loses track of the reflector.

Figure 2-14: API VEC measurement system (Source: API Inc.)

Setup involves mounting the laser tracker on the machine bed and fixing the ActiveTarget to the spindle. The machine is then moved through a pseudo-random sequence of positions covering the full volume of the machine whilst the laser tracker monitors the reflector position (Figure 2-15).

The system software then calculates the geometric error parameters associated with all axes (linear and rotational) by comparing the commanded coordinates with the reference coordinates measured by the laser tracker.

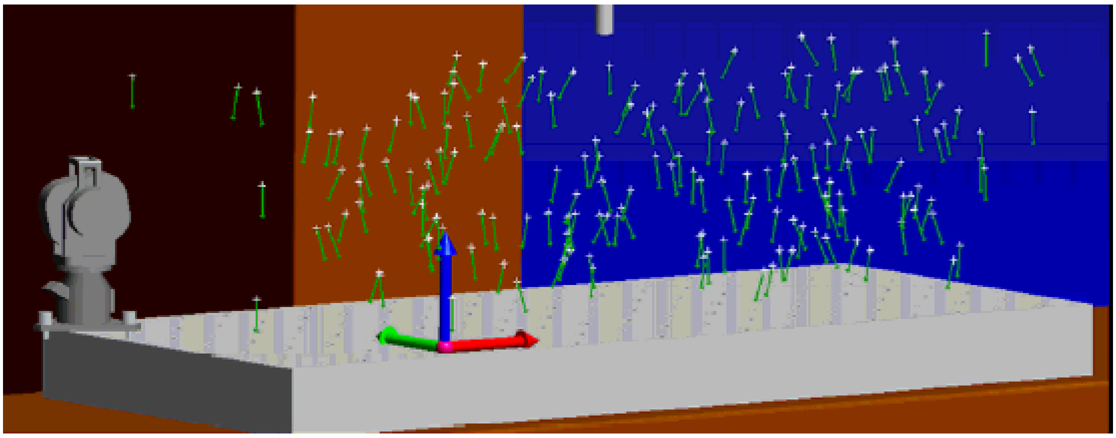


Figure 2-15: Point cloud data as generated by laser tracking system (Source: API Inc.)

Two data sets are required, with different reflector offsets, to enable the system to determine angular errors, i.e. a minimum of two measurement runs is required. There was no published data available on the accuracy of this system at the time of writing this thesis. Additionally at the time of writing there was limited availability and detailed information on this measurement method.

2.17.2 Etalon-AG LaserTRACER and TRAC-CAL software

The Etalon LaserTRACER is a tracking laser interferometer that has been designed to minimise errors in the optical beam path induced by the beam steering mechanism such as misalignment of the rotation axes or laser beam offset with respect to rotation centre [125]. The concept, which was developed independently by the NPL in the UK and PTB in Germany (and patented by NPL UK), relies on a precision reference sphere (Figure 2-16) nominally located at the centre of rotation of a gimbal mechanism that carries the interferometer optics. The interferometer uses the precision sphere as the retro-reflector at one end of the measurement beam path. The interferometer thus measures the radial separation of the reference sphere and the target retro-reflector. This arrangement reduces beam-steering related errors to the level of sphericity of the reference sphere. The Etalon implementation of the concept, known as the LaserTRACER, is based on a PTB design.

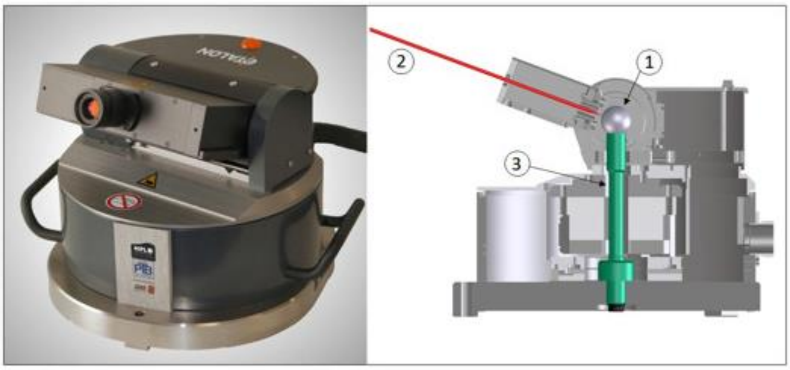


Figure 2-16: Etalon LaserTRACER measurement system (Source: NPL (UK))

Software (TRAC-CAL) adopts the concept of multi-lateration to establish reference coordinates for comparison with the machine under test [123]. In conventional multi-lateration, displacement measurements of a moving target relative to several separate measurement systems are made simultaneously. Provided enough measurement systems (or the same system at multiple locations) are used and enough data points are gathered, it is possible to mathematically establish a “virtual” coordinate frame, determine the location within that coordinate frame of the individual measuring instruments and determine the coordinates of the points that the target was moved to. In other words, the process is entirely self-calibrating. Multi-lateration works by mathematically fitting, in a least-squares sense, the measured displacement data to a mathematical model that describes the setup in terms of the target coordinates, instrument coordinates and measured displacements. The combination of the multi-lateration technique implemented with high-accuracy laser interferometry ensures high accuracy with the added advantage of traceability to the metre. The manufacturers claim a displacement measurement accuracy of 0.2 µm + 0.3 µm/m (k = 2), though, in practice the achievable accuracy may be significantly better. As is the case for all laser-based systems, the achievable accuracy depends on the prevailing environmental conditions.

2.17.3 Etalon-AG LaserTRACER MT

A recent addition (2013) to the Etalon product range is the LaserTRACER MT. This is an interferometric, telescopic ball bar that interfaces to the Etalon software to provide the same machine calibration capability as the LaserTRACER, but at a lower price but with a smaller volume.

Figure 2-17: Etalon LaserTRACER MT (Source: Etalon AG)

Depending on speed of set-up and machine programming both solutions are viable options for rapid machine tool measurement.

2.18 Hole plates and ball plates

2.18.1 Hole plates

A hole plate is a nominally two-dimensional artefact formed by making precision holes in a rigid, stable, plate. The plate is usually made of a low thermal expansion material, such as Zerodur or Invar. The plate is typically several tens of millimetres thick, to ensure sufficient rigidity when supported in various orientations. The holes are typically through holes, arranged on a regular grid. When the machine tool is fitted with a suitable contacting probe, it can be used to measure the grid of holes, whilst the plate is supported in various orientations, *e.g.*, lying in the x-y plane, standing vertically in the x-z plane. The hole positions are either pre-calibrated using a precision CMM, or the hole locations can be inferred by *in situ* measurement using classical error separation techniques (and access to at least one known length). Comparison of the measured hole locations with the error-separated (or pre-calibrated) locations can be used to calculate machine geometry errors. The holes are either measured as cylinders or as a series of bi-directional surfaces (*i.e.,* diametric measurement), depending on the capability of the machine controller.

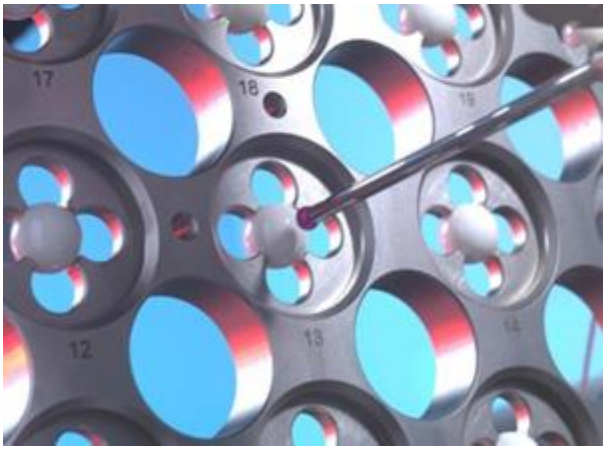


Figure 2-18: Hole plate artefact (Source: NPL (UK))

2.18.2 Ball plates

Ball plates are essentially the same as hole plates, but instead of using holes, the plate is fitted with a regular array of good quality tooling balls. The balls typically sit in quadrahedral holes, designed to allow the balls' centres to lie in the neutral plane of the plate, whilst also allowing access for a contacting probe to touch the ball over a reasonable fraction of the exposed surface. After contacting the ball at several locations, the position of the ball centre may be calculated by data fitting. As with the hole plate, a ball plate may be used as either a pre-calibrated artefact, or calibrated in situ using reversal techniques. Comparison of the measured ball locations with the calibrated (or error-separated) locations can be used to calculate machine geometry errors. A ball plate may be easier to use in 3D as each ball is characterised by one element – the ball centre. With a hole plate, not only is the location of the hole centre of importance, but also any axial misalignment of the hole needs to be taken into account (*i.e.,* manufacturing errors may have caused some holes to be machine at slight angles to one another).

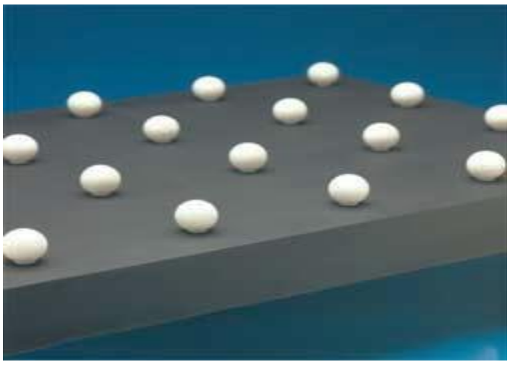


Figure 2-19: Ball plate artefact (Source: Google Inc.)

Both Hole and Ball plate artefacts are potentially usable on the machine tool, but speed of measurement is likely to be low. There is also an additional challenge with loading and unloading such artefacts into the machine tool without damaging them, hence making this a tedious task.

2.19 Laser planes

The L-723 Machine Tool Alignment system from Hamar Laser uses rotating planes of laser light in conjunction with a number of position sensitive detectors and measurement software (Plane 5 software) to measure the geometric errors of machine tools (Figure 2-20).

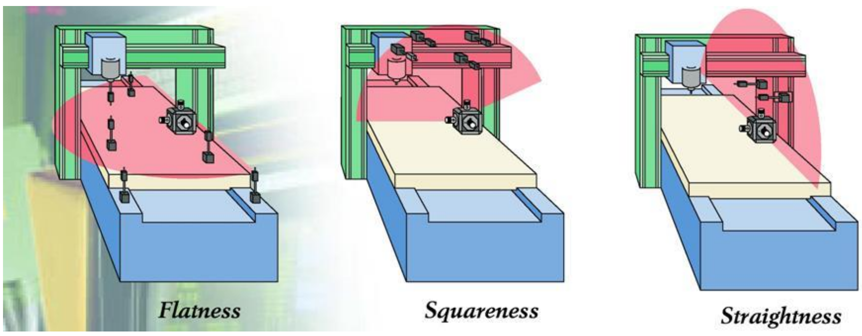


Figure 2-20: Laser plane measurement system (Source: Hamar Laser)

The system appears to be more suited to machine alignment rather than calibration.

2.20 Machine tool performance evaluation / compensation software

Much of the equipment capable of determining the geometric errors sources is also capable of producing a suitable error map. However not all software supports all the machine tool controllers on the market. This is relevant and important in terms of utilising on-machine probing devices, as error compensation files may need ever more regular updating in order to maintain system capability.

Table 2-4 indicates claims of controller support from equipment vendors that have been discussed.

Table 2-4: OEM machine tool metrology software-controller compatibility

Controller/Software	Etalon TRAC-CAL	Agilent 55291A	Renishaw XL	API VEC
Fanuc	X	X	X	X
Heidenhain	X	X	X	-
Mazatrol	-	X	X	-
Siemens	X	X	X	-

Etalon TRAC-CAL software support controllers from Heidenhain, Fanuc, Siemens and others.

With Agilent's 55291A software a compensation table created during machine performance verification, can be downloaded directly to the CNC controller using the 55291A Software. The software directly supports transfers of tables and programs to or from FANUC 0M, 6M, 10M, 11M, 12M, 15M, 16M, 18M, 20M, 21M, and any controllers with compatible compensation table programming codes.

Renishaw software includes (linear) compensation packages to interface with the following controllers:

- Fanuc OM and OT
- Fanuc 10 - 12, 15, 16, 18, 20 & 21
- NUM 750, 760, 1060.
- Mazak M2, M32, M PLUS
- Siemens 810, 810D, 820, 840, 840C, 840D, 850, 880

- Acramatic 2100
- Cincinnati A850, A850SX, A950

At time of writing the researcher could not find any information for API VEC software compatibility other than case studies referring to Fanuc control systems.

2.21 Rotary axis performance evaluation

A standard method for calibrating the geometric accuracy of a rotary axis is described in the ISO 230-7 standard; this suggests the use of a dial gauge to measure both the axial and radial run-out deviation by means of tactile or non-contact sensors. Although this method gives measurements for the five degrees of freedom, it does not allow for measurement of the error of rotation angle as this is measured separately by an interferometer or autocollimator in combination with a polygon (see ISO 230-1 and ISO 230-2).

An indexing table and an interferometer with angular optics is widely used technique for measuring the rotary axis errors. Standard polygons could also be used in conjunction with a calibrated autocollimator to calibrate a rotary axis (Figure 2-21). The disadvantage of this approach is that the number of calibration points is limited to the number of facets on the polygon.

The techniques mentioned above are considered traditional techniques. They require multiple setups and take a significant time to perform. An alternative system comprising precision angle encoders which is gravity referenced using electronic levels, called SwivelCheck, and is available from API. This system, along with associated software allows automated calibration of rotary axes.

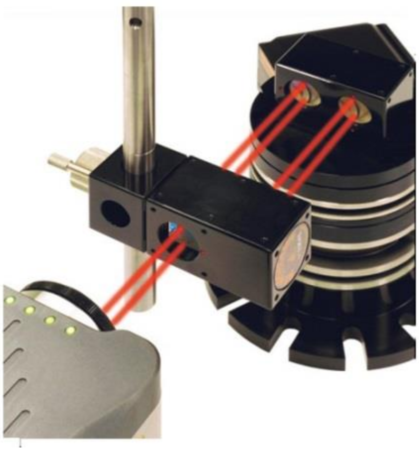


Figure 2-21: Renishaw RX10 rotary indexer system (Source: Renishaw plc.)

Laser tracker based systems such as the API VEC and Etalon TRAC-CAL systems described above can be used to calibrate rotary axes. The Etalon system is currently limited to calibration of a single rotary axis on the part side (rotary table) and two rotary axes on the tool side. This is achieved with additional measurements made after correction of the linear axes. An advantage of this system is that it can measure the alignment of the rotation axis with respect to the linear axes.

2.22 Tool centre point compensation and combined axis tuning

Several other measurement instruments and setups can be used to measure and monitor tool centre point error parameters associated to the combined use of linear and rotary axes:

2.22.1 Double Ballbar (DBB)

Firstly developed by Bryan [126], the double ballbar system is used to inspect and monitor the contouring performance of two linear axes (Figure 2-22). Historically Ballbar measurement devices have been employed to measure geometric errors via circular testing. A magnetic ball bar to collect the positioning errors of two synchronously moving axes; this technique was seen to provide rapid and precise indication of the two or three dimensional performance of a machine tool. Knapp *et al.* further developed such circular tests to evaluate the geometric accuracy of three-axis machines and CMMs [127]. More recently Zargarbashi and Mayer have used a ballbar to assess the trunion axes motion errors on a five axis machine [128]. In terms of a calibration artefact the ballbar can be used to calibrate the circular motion of two contouring axes. However, this has little relevance for touch trigger on-machine probing activities where dynamic effects are minimised through probing strategies. Should scanning probing technology be employed on-machine the measurement and sustainment of machine dynamics becomes more relevant.

Figure 2-22: Renishaw plc. QC20-W Ballbar (Source: Renishaw plc.)

2.22.2 Renishaw AxiSet™

The Renishaw AxiSet™ system (Figure 16) has a similar capability to the IBS system (description to follow) is based on a precision sphere, contact probe such as the Renishaw Rengage™ strain gauge spindle probe and associated software. In operation, the precision datum sphere is mounted on the rotating part to be tested. The coordinates of the centre of the sphere are then measured using the probe fitted to the machine spindle. The axis is then rotated in steps with the ball centre re-measured at each position. The ball centre coordinate data is then analysed to assess the errors of the axis. AxiSet™ can be used to analyse A, B and C axis alignments and offsets as well as pivot length. More recently this approach has been improved, in terms of measurement speed, through use of on-machine scanning probes [120].

2.22.3 IBS R-Test

IBS Precision Engineering has developed a measurement system for rotary axes based on the probe head shown in Figure 2-23. This cluster probe measures the position of the centre point of a precision sphere, which is mounted on the rotating part of the machine. During the test, the measuring head, or MT-Check probe, is fixed to the spindle or non-rotating part of the machine. The probe contains three planar elements that are brought into contact with the sphere. Three accurate measuring systems within the probe monitor the displacements of three corresponding contacting elements during this motion. In this way, the centre point coordinates of the ball are determined with sub-micrometre accuracy in x-, y- and z-directions. The test can be performed to determine axis deviations during movement of the rotary table or the trunion table only, or during the simultaneous movement of both.

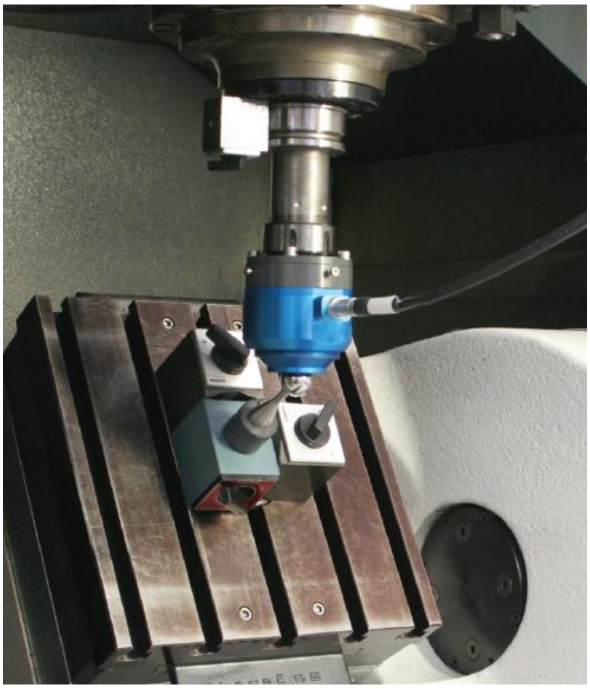


Figure 2-23: IBS R-test measurement system (Source: IBS Precision)

2.22.4 Heidenhain systems

Heidenhain measuring systems KGM 181, KGM 182 and VM 182 are non-contact measurement systems, which are designed to be used to directly measure the dynamic and static components of error of a machine tool (Figure 2-24). As opposed to measuring the machined piece to identify any dynamic motion effects on the system these sensors can be used to measure them directly from the machine. The advantage of this direct inspection method over inspecting only the results of the machining lies in its separation of technological influences from machine influences, and in its capability of distinguishing individual factors of influence. Dynamic measurements at high speeds are capable of providing information on contouring behaviour allowing conclusions to be made about both the condition of the machine tool and the control loop parameter settings, CNC control, drives and position feedback systems etc. Static measurements – such as the measurement of position deviations in the linear axes using a comparator system - permit conclusions about the geometric accuracy of the machine. The manufacturers publish an “Accuracy grade” of ± 2 μm for the KGM 181 and 182, while the VM 182 has an accuracy grade of ±1 μm longitudinally and 1.5 μm in the transverse direction. The researcher could not find any practical example of the use of this equipment throughout the Rolls-Royce manufacturing supply chain. It is anticipated that the measurement time for such technology would be considerable.

Figure 2-24: Heidenhain grid plate measurement system (Source: Heidenhain GmbH)

2.22.5 Machining spindle performance measurement

Another aspect of machine tool errors, which can contribute up to 30% of the overall error is spindle-associated errors [129]. Characterisation of spindle errors is covered by ISO 230-7 [39]. A standardized framework for considering the many facets of spindle behaviour is also available in the ASME B89.3.4 Axis of Rotation standard [130].

An ideal spindle allows motion in a single degree of freedom: pure rotation. Any movement in the other five degrees of freedom is therefore either spindle error (motion due to the spindle's design and manufacture) or due to external influences, for example: thermal changes, applied forces, vibration, out of round bearing components, misaligned bearing seats, wear, improper preload inadequate stiffness or even resonant machine frequencies.

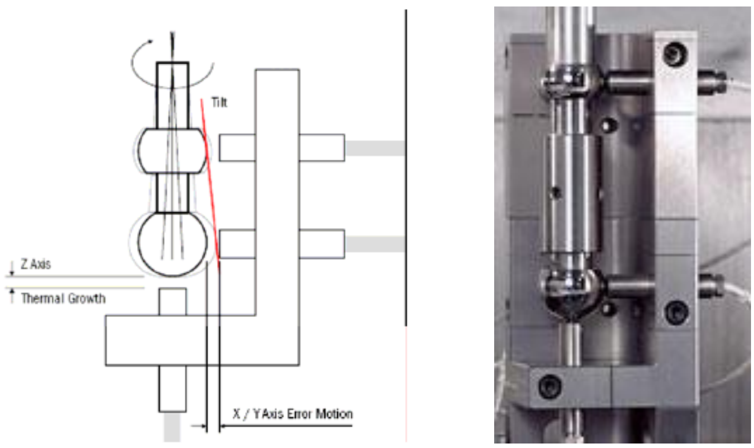


Figure 2-25: IBS Precision spindle error analyser (Source: Lion Precision)

Lion Precision/IBS produces a spindle error analyser (Figure 2-25), which measures the motions of a machine tool spindle at operating speeds. This system works by using a non-contacting capacitance probes mounted together to measure the dynamic displacement of precision ball targets mounted in the spindle's tool holder, or equivalent. This system allows measurement in five axes by mounting a probe from the bottom to measure the movement in the z-axis. A pair of probes, at right angles, measures the x-axis and y-axis; and a second pair is used to provide the data for tilt measurements. Software collects readings from the probes while the spindle is turning, analyses the results, and reports them on screen with polar and linear plots and discreet measurement values. Measurements are made in accordance with ISO 230-3 and ISO 230-7.

This system is compliant with:

- ANSI/ASME Standard B5.54-2005, Methods for Performance Evaluation of CNC Machining Centers
- ANSI/ASME B5.57-1998 Methods for Performance Evaluation of CNC Turning Centers
- ANSI/ASME B89.3.4-2010, Axes of Rotation, Methods for Specifying and Testing
- ISO230-3, Test Code for Machine Tools Part 3, Determination of Thermal Effects
- ISO230-7, Test Code for Machine Tools Part 7, Geometric Accuracy of Axes of Rotation

Spindle thermal performance is less relevant for the application of on-machine probing devices on the machine tool as the spindle is unlikely to be used. It is however important to benchmark the spindle performance at either manufacture or installation phase, and subsequently monitor performance and alignment over time.

2.23 Continuous 'self-monitoring' systems

During the course of this research work Etalon AG has launched an 'Absolute Multiline Technology' [131]. This technology employs a number of fibre optic laser sensors able to continuously monitor dimensional change in machines structure, thus allowing for self-monitoring.

In this method, a standard linear interferometer can be directed along several independent lines through the working volume of the machine. The machine is then driven to several points along the laser beam and the interferometer reading and machine scale readings logged. The resulting data is then processed to determine the machine geometry errors. This technique has been demonstrated in a CMM. It is not known whether it is extendible to multi-axis machine tools.

Key advantages of this solution are that machine capability measurement time is now redundant, it is self-calibrating and that the solution claims to be robust enough for any industrial application. In terms of relevance to on-machine measurement application this in-effect can defeat the argument of 'independence' in that the on-machine measurement system can be independent of machine tool control systems. It is claimed that this technology solution has been validated by the NPL where a measurement uncertainty of only 0.5 µm per meter of length up to 20m has been demonstrated. The researcher has not yet found a single real-world application of this technology, presumably due to its recent launch (2014). Therefore, it is expected that this technology is still far away from being used by many machine tool users.

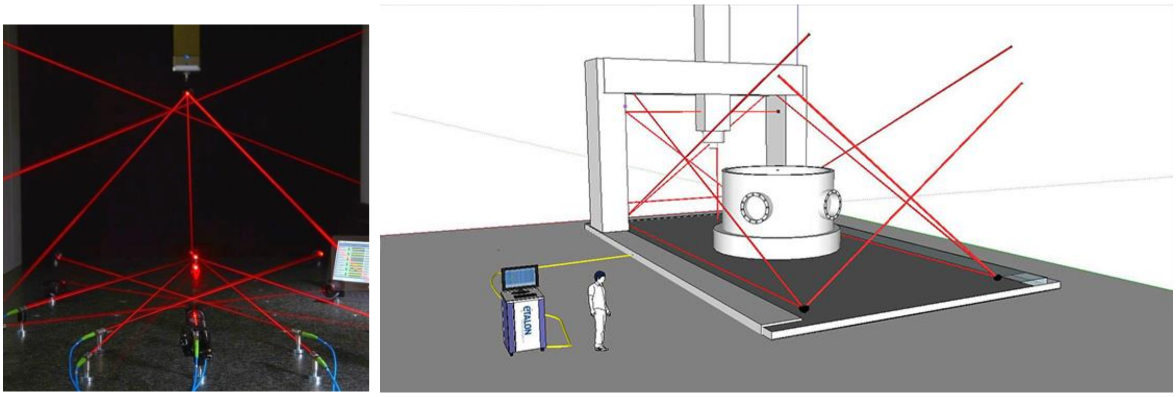


Figure 2-26: Geometric monitoring of machine tools using ETALON AG multiline technology

2.23.1 Applications of Laser Ball Bars

A number of researchers have demonstrated laser ball bar based approaches to multi axis machine tool calibrations. For example, Fan *et al.* have demonstrated a 3D laser ball bar (3D-LBB) that uses a combination of laser interferometer and two angle encoders for application in machine tool and robot calibration [132]. Srinivasa *et al.* have used a laser ball bar to measure thermally induced drift in a spindle on a two axis CNC turning centre [133]. They were able to measure the spatial coordinates of the spindle centre and the direction cosines with the same instrument.

Pahk *et al.* have patented a method of assessing three-dimensional volumetric errors in multi-axis machine tools using a ball bar [134]. The patent suggests that the method can determine position, straightness, angular (not roll) and squareness errors associated with linear axes as well as backlash and servo gain mismatch. At time of writing these methods have not yet been commercialised and therefore no off-the-shelf solutions exist.

2.24 Alternative methods

As discussed earlier, other methods have been suggested, including a plurality of gyroscopes and accelerometers to detect relative movement of machine parts in inertial space, a technique that has the potential of achieving rapid machine calibration [135]. An advantage of this method is that is relies solely on robust, self-contained sensors, so it could be envisaged that such a system could be deployed permanently on a machine tool thus obviating the need for manual setup prior to use. Again as no commercialised solutions exist this is not considered as a rapid machine tool measurement solution.

2.25 Machine error compensation

Historically machine tool error correction has been typically performed by direct mechanical, electrical or electronic interventions [4], [5]. However, full error compensation techniques are increasingly being utilised [136]. Such techniques have transcended from CMMs where such error correction is common-place [137]–[139]. Since ever higher accuracy demands are being imposed on machine tools as well as the intention to decrease the cost of their manufacture, error compensation strategies are becoming more widely employed. Due to the semi-closed loop control nature machine tools i.e. indirect position feedback; compensation systems are essential to counter effects of geometric inaccuracy, mechanical wear and thermal effects. As a result machine tools will be equipped with systems for pitch error and backlash error compensation [140]. However, these systems are inadequate for modern multi-axis machine tools as they are typically designed to counteract effects of ball screw and static wear. As the effects of these error sources are becoming less relevant, due to improvements in machine design, focus has turned to more continuous forms of error compensation [23], [141].

The fundamental principle behind machine tool error compensation techniques aims to control the tool end position along all axes trajectories via continuously adjusting by compensation values in machine control systems [142]. The most common forms of compensation are via encoder feedback signal interception and origin shift methods [103].

Real-time error compensation can be also achieved through the utilisation of external computer systems [103][143]. Such systems can collect in-cycle measurement data and inserts/removes the equivalent number of pulses of the quadrature signals [144]. The machine tools' servo system can therefore adjust the positions of the moving slides in real-time. The advantage of this technique is that it requires no extra controller software and therefore be used irrespective of machine type or make. However, specially developed electronic devices are needed to insert such signals into the servo loops. These insertions can be difficult to achieve and require extreme caution in such a way that they do not interfere with the feedback signals of a machine.

The origin-shift method involves adjustment of reference origins of the machine tool control system through an I/O interface, which add to the command signals for the servo loop automatically [145].

2.25.1 State-of-the-art error compensation methods

Satori and Zhang [99] define three modes of numerical compensation: Continuous compensation in the path generation of the CNC controller i.e. real-time transformation; End-point compensation i.e. geometric errors still appear in the tool path; Final result compensation for co-ordinate measuring machines i.e. results of measurement are corrected by known deviations.

Work by Longstaff *et al.* [146] has shown that volumetric compensation for machine tools can reduce geometric errors up to 97% and thermal errors up to 75% on 3-axis and 5-axis machine tools. However Schwenke *et al.* [23] highlighted that even if the rotational errors of a 5-axis machine can be compensated, due to the distance in pivot length significant movement in the linear axes is often required, which potentially generates additional errors. Also highlighted was the dependency on CNC controller processing ability to transform interpolated trajectory points to a kinematic model and subsequently adjust compensation parameters in a space of milliseconds. Alternatively, soft real-time methods can be used where pre-processing of the tool path is performed.

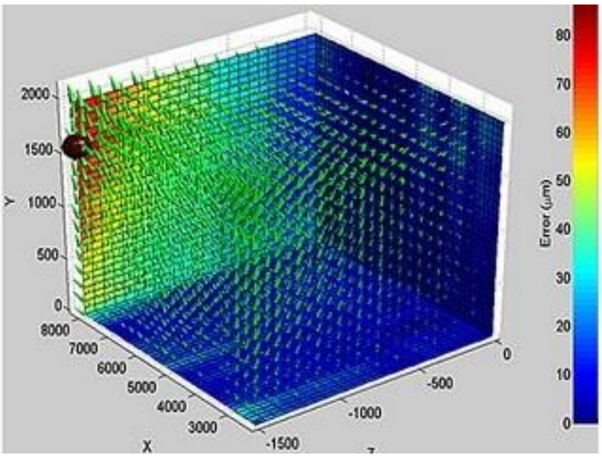


Figure 2-27: University of Huddersfield Volumetric Compensation System [147]

More recently Zhu *et al.* [62] have proposed the use of a ballbar system to measure and compensate for six geometric error components associate to 5-axis machining utilising standalone software. In a further piece of work Zhu *et al.* [148] proposed a method able to distinguish between random and repeatable errors, reducing contouring errors to one-third of their original.

Shen *et al.* [47] highlighted that significant product quality improvement could be attained without significantly increasing complexity and hardware cost. The paper proposed an on-line asynchronous compensation method for position dependant and position-independent geometric errors and an offset compensation methodology to mitigate for thermal deformations. This methodology was tested on a dual-spindle grinding machine.

Ramesh *et al.* [149] have presented a state-of-the-art review of thermal error compensation methods. The work dissects thermal error-compensation methods into three stages; modelling, measurement and compensation as per [150]. Measurement methods include the use of multiple temperature sensors, laser interferometer, ballbar equipment, and precision artefacts.

More recently laser tracker technology combined with multi-lateration techniques has been applied as a holistic technique for measuring, calculating and verifying machine tool volumetric accuracy [35], [123], [152–158]. However there is still industrial resistance to these techniques; due to the challenges involved in programming point clouds via NC code, the required amount of downtime for measurement and the availability of the generated compensation tables to be used on legacy machine tool equipment [154].

Alternative approaches without the need of mathematical models have been developed [149], [159–161]. Such methods are based on statistical calculations based on embedded environmental and metrological sensors.

2.26 Computer-Aided-Inspection-Planning (CAIP)

Since the 1980's Computer-Aided-Inspection Planning (CAIP) has been used by manufacturing firms to optimise shop-floor product inspection [162–164]. Today inspection process planning is more integral to manufacturing flow and quality than ever; due to low volume, high variety, and high precision complex products. Due to such manufacturing challenges manufacturers rely on in-process inspection methods to maintain and control quality rather than rely on end of line accept and reject, shown in Figure 2-28. Critical requirements for such inspections are speed, quality, and robust integration with the product lifecycle. In a bid to improve such requirements manufacturers are ever looking for greater automation in the form of technology and process planning [164–167]. Cost and production time are often the main key performance variables when scheduling inspection activities, where optimum sequencing leads to the closure of quality assurance loops which ensures product conformance to design throughout the manufacturing lifecycle.

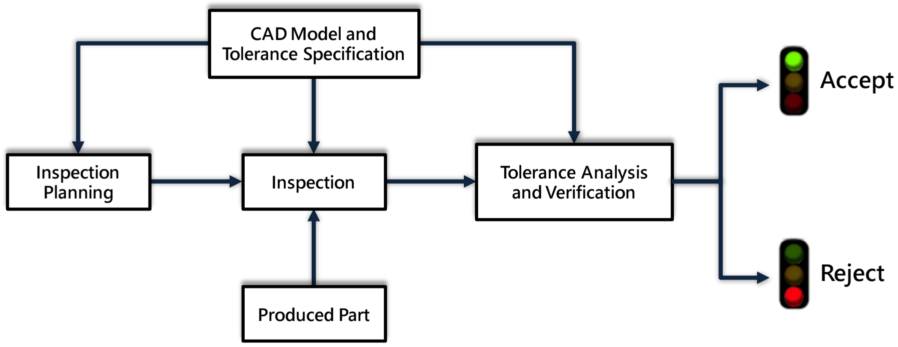


Figure 2-28: Inspection planning verification procedure adapted from [168]

Zhao *et al.* have recently published a survey paper covering state-of-the-art CAIP research topics [169]. The work covers CAIP systems for coordinate measuring machines (CMMs) and on-machine inspection (OMI), shown in Figure 2-29. Zhoa covers tolerance based CAIP systems, geometry based CAIP systems, feature inspection section and sequencing, probing path planning and STEP and STEP-NC integration.

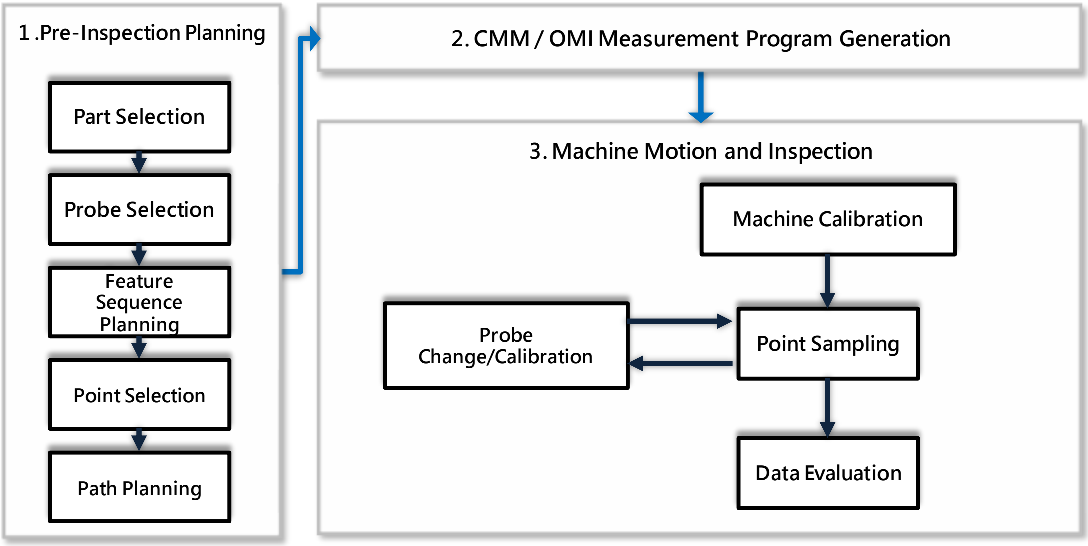


Figure 2-29: CAIP Procedure adapted from [170]

Highlighted by Zhao was that CAIP systems for OMI/OMM are based on prior research on CMMs and some issues are still unaddressed, being: (1) measurement process planning is carried out in isolation from machining process planning; (2) OMI solutions often focus upon one-off solutions rather than integrated solutions, a problem that exists around metrological systems; (3) The level of feedback from OMI solutions is currently very low due to the limitations of G/M code and STEP methods are not yet universal.

2.26.1 On-machine Process Inspection Planning

Cho *et al.* presented schematic diagrams for global and local planning strategies for on-machine-measurement (OMM) [172-173]. Based on existing CAD-CAM-CAI systems the two-stage process presented; (1) optimum sequences for the generation of a 'global' inspection plan covering feature identification, grouping and sequencing; and (2) a local inspection strategy for the decomposition of features, determination of probing points and probe-workpiece collision checking. Figure 2-30 illustrates this difference between an OMI/OMM inspection process planning structure to that of a CMM.

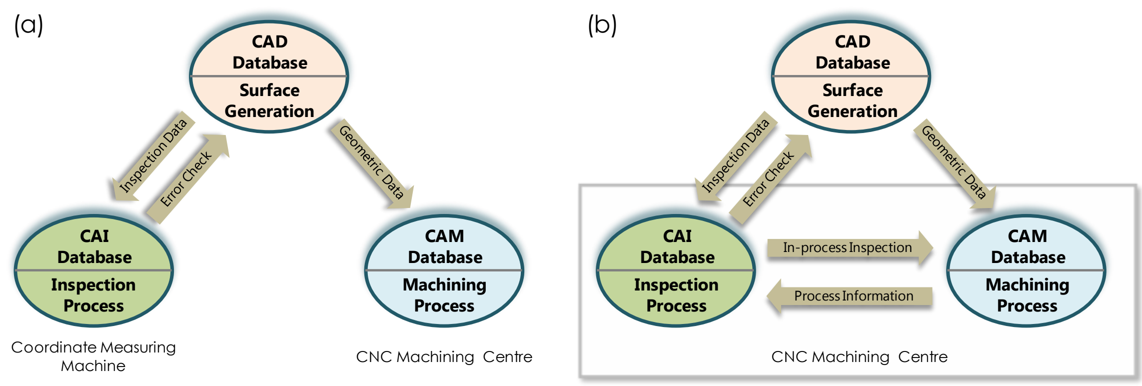


Figure 2-30: Inspection processes using (a) CMM and (b) OMM adapted from[171]

Newman *et al.* highlighted and demonstrated the need of STEP-NC capability profiles for machine tools which can be used to verify and optimise machine tool process plans off-line [173].

2.26.2 Calibration sequencing

Parkinson *et al.* developed Hierarchical Task Network (HTN) and Planning Domain Definition Language (PDDL) models for the automated planning of the machine tool calibration process i.e. in terms of optimum testing routine and equipment selection. Criticism is that calibration is used in the sense of measure only not adjust, the process of calibration strongly depends on customer requirements i.e. do they want to stop process and intervene when problem is detected or complete a full audit first. Models do not consider extrinsic factors i.e. fixturing required to be removed or removal of machine guarding. There is an assumption that the Double Ballbar [110] is ideal for squareness measurement. Uncertainty of measurement is not considered as key requirement. The method requires academic experts to create a 'metrology index'. How this 'metrology index' is created is undefined.

2.27 Machine tools as measurement systems

Length measurement on a workpiece involves comparing the distance to two points on the workpiece surface to a length standard [174]. Therefore, in order to make length measurements, for the purpose of size, distance, perpendicularity, runout, and roughness definition, it is necessary to probe the desired point(s) using a sensing element. Other than this no other literature or research could be found with regards to enabling machine tools as measurement systems.

2.27.1 Probing systems

There are numerous and different probing systems available for CMMs. Typically such probing systems are classified as contact probing systems and non-contact probing systems, such systems have been reviewed by Weckenmann *et al.* [175]. Contact probing systems are often referred to as tactile and non-contact methods optical probing systems. Contact probing systems are considered more accurate and reliable than optical systems despite them having to make mechanical contact with the workpiece potentially introducing deflection errors [175]. Examples of such probing systems can be seen in Figure 2-31.

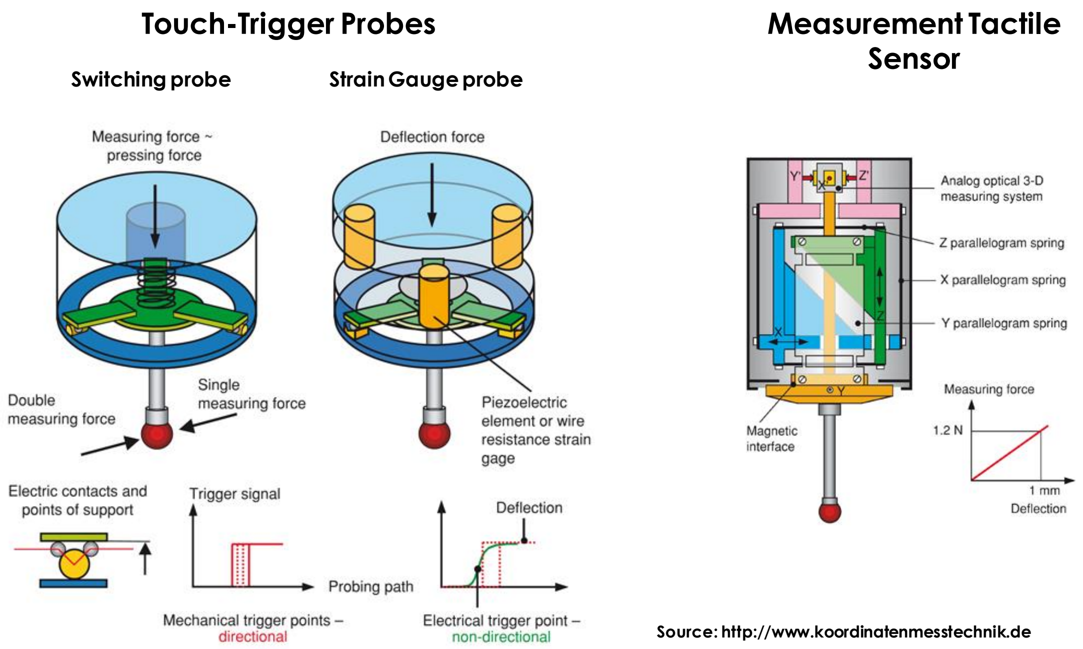


Figure 2-31: Tactile probing systems

The most common probing system for CMMs and machine tools is the touch-trigger probe. Through gauging the diameter of the probing tip, the position relative to the contact surface can be determined. The most common touch trigger probes will make use of an electrical switch or strain gauge. Other probing systems, referred to as *tactile* probes, will detect deflection of the probe tip as well as deflection of the stylus, consequently compensation for the deflection and enhancing precision. Scanning probes are also often utilised due to their speed of measurement and data capture volumes, however these systems are susceptible to stick-slip and reversal affects and generally regarded as less accurate.

Non-contact probing systems, such as vision systems are sometime utilised on CMMs for purposes of defect detection and measurement of free-form surfaces. The advantage of such systems is that these can measure multiple-thousand points per second which enables to digitise surfaces with high precision. The accuracy of CMM and machine tool vision systems is not yet competitive with contact probing systems [176].

The recently released standard ISO 230-10:2011 [78] has been published to provide testing procedures for the evaluation of measuring performance of contacting probing systems. The standard aims to provide guidance for the correct use of probing systems on machine tools, in order to minimise extrinsic effects and minimise measurement uncertainty associated to test set up, implementation and data reporting. This standard is currently in revision to include scanning and non-contact technologies [73]. This standard focuses specifically on the qualification of the probing system on the machine tool rather than its use in the overall process of on machine measurement.

2.27.2 In-situ/on-machine inspection

With the advancement of machine tool, measurement and compensation technologies manufacturers strive to improve their manufacturing processes through increased on-machine feature/product inspection. Clear benefits associated to this paradigm change is a reduction in reliance on CMM inspection systems, resulting in lower process queuing and higher CMM availability, plus reduced part set-up times. In-situ measurement also referred to as process-intermittent measurement or on-machine measurement is a measurement performed on a workpiece, which is held on a machine tool and the machining process being stopped before starting the measurement [177]. Benefits of on-machine inspection are summarised as per Table 2-5.

Table 2-5: Benefits associated to on-machine inspection [12], [169], [172]

Benefit	Through
Cost and Time Saving	• Decreasing lead-time required for gages and fixtures • Minimising need for design fabrication, maintenance of hard gages, fixtures & equipment • Reducing inspection queue time and inspection time • Reducing part set-ups • Reducing CMM part queuing • Eliminating rework of nonconforming product
Reactive Inspection to Pro-active Control	• Integrating quality control into product realisation process, • Characterized and qualified processes to increase product reliability • Focusing resources on prevention of defects instead of detection in the end (a post-mortem process) • Utilising real-time process knowledge and control and part acceptance/disposition • Enhancing small lot acceptance capability
Elimination of non-value adding activities	• Lot inspection • Sampling plans • Receiving inspection • Design, fabrication and maintenance of hard gages • Reworking of nonconforming parts
Agile Machining	• Quick responses to product design changes • Rapid integration of new and existing technologies such as probing strategy, error compensation, data analysis software • Fixture design technology can be integrated into the OMI system • Machine health monitoring

Davis *et al.* have proposed a Direct Machining and Control (DMAC) system to conduct on-machine inspection of parts post machining [178]. In the study the machine tool was controlled by CMM PC-DMIS measurement software and a DMAC controller. Yongjin Kwon *et al.* investigated the closed-loop measurement errors on a CNC machine tool using a spindle probe [179]. The study involved the machining and measurement with varying material and cutting settings. Results were compared with a CMM which showed wide variation with regards to the machining and on-machine measurement of soft-hard components. A draft International Standard ISO 14649-16.3 is being written to provide a data model for on-machine inspection, which can be integrated in to a CNC machining process [180]. Tan *et al.* studied capability gaps with regards to STEP-NC controller software [181].

Although there is a wide body of research associated to the framework surrounding the use of machine tools as measurement there is much less on the actual utilisation of these assets as measurement devices. The researcher therefore could not find any material in this area.

2.28 OMI measurement uncertainty

It is obligatory that a quantitative indication of the quality of a measurement result be given so that its reliability can be assessed. The word “uncertainty” refers to doubt, in that “uncertainty of measurement” means doubt about the validity of the result of a measurement. Without such measurement results cannot be compared, either amongst themselves or against reference values provided by a specification or standard [182]. The VIM [19] describes measurement uncertainty as a “non-negative parameter characterising the dispersion of the quantity values being attributed to a measurand, based on the information used” (Figure 2-32).

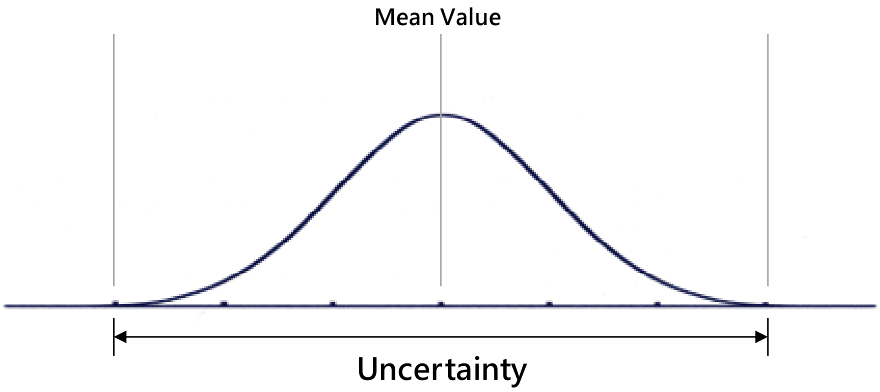


Figure 2-32: Measurement uncertainty

In ISO-GUM [182] (paragraph 0.1) it is stated that:

“When reporting the result of a measurement of a physical quantity, it is obligatory that some quantitative indication of the quality of the result be given so that those who use it can assess its reliability. Without such an indication, measurement results cannot be compared, either among themselves or with reference values given in a specification or standard. It is therefore necessary that there be a readily implemented, easily understood, and generally accepted procedure for characterizing the quality of a result of a measurement, that is, for evaluating and expressing its uncertainty”

2.29 Estimating OMI measurement uncertainty

Typically Type A and B evaluation studies are performed to define the uncertainty of a measurement system [182].

In most cases, a measurand *Y* is not measured directly, but is determined from *N* other input quantities $X_1, X_2 ...... X_N$ by a functional relationship *f* [182]:

$$Y = f\,(X_1, X_2, \ldots\ldots, X_N) \tag{1}$$

To estimate the measurand Y, denoted by *y*, input estimates x_i for input quantities X_i are used, giving:

$$y = f\,(x_1, x_2, \ldots\ldots, x_N) \tag{2}$$

The combined standard uncertainty $u_c(y)$ is the estimated standard deviation associated to *y* as given by (2). The standard deviations are derived from the estimated standard deviations associated with the input x_i, termed as standard uncertainties, denoted by $u(x_i)$:

$$u_c^2(y) = \sum_{i=1}^{N}\sum_{j=1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i\,, x_j) \tag{3}$$

Utilising the GUM method [182] Equation (3) is approximated using a first-order Taylor series approximation deriving (4), termed the ‘rule of propagation of uncertainty’(also referred to the general law of error propagation) [174]:

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}u(x_i\,, x_j) \tag{4}$$

The partial derivatives in (4) are termed sensitivity coefficients. When all input quantities are independent Eq. (4) is simplified to:

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) \tag{5}$$

In order to calculate the standard uncertainty from Eq. (5) the standard uncertainties of all input estimates x_i must be known. The ISO-GUM therefore specifies two forms of standard uncertainty evaluation, termed Type A and Type B:

- Type A: evaluated from a series of repeated observations (i.e. statistical method)
- Type B: evaluated from available knowledge (i.e. deterministic method)

Although these are both valid approaches, the challenge for manufacturing measurement is that it is difficult and expensive to perform such studies on live manufacturing equipment, where even then the results may not be truly representative due to the variable nature of the manufacturing environment. In the case of utilising machine tools as measurement systems this challenge becomes more complex and subsequently more time consuming; due to part and process specific uncertainty contributors needing to be examined.

2.30 Expanded uncertainty

Typically, an expanded uncertainty is used when one wishes to define an *interval* that covers a proportion of a distribution of values which can be attributed to the measurand. The expanded uncertainty is defined as the standard uncertainty multiplied by a coverage factor *k*, giving Eq. (6):

$$U = k \cdot u_c(y) \tag{6}$$

Therefore, the result of a measurement is expressed as Y = y ± U. If the probability distribution of y is approximately normal and there is a sufficiently large number of degrees of freedom, k = 2 corresponds to an interval with level of confidence, *p*, of 95% and k = 3 corresponds to an interval with level of confidence of 99.7%.

Once again results obtained in a laboratory environment may not match those to a live manufacturing environment, resulting in the requirement to use a large coverage factor. This may therefore reduce the value of performing the measurement process altogether as this may exceed product tolerance requirements.

2.31 Machine tool error budgeting

The pre-eminent stage of machine tool design is the error budget calculation, a challenging task which requires heavy scrutinisation by precision engineers and designers [183]. A design methodology utilised to predict the uncertainty of a kinematic system is a vital tool for focusing engineering resource and effort for machine tool construction [45].

During the construction of an error budget key precision uncertainty contributors are described qualitatively and quantitatively in order to predict a total error value for the proposed machine tool. The main uncertainty contributors with regards to machine tools are [20]:

1) Uncertainty due to work piece i.e. size, location, alignment

2) Uncertainty due to machine tool position
3) Uncertainty due to trajectory errors
4) Uncertainty due to tool deflection
5) Uncertainty due to the tool-holder
6) Uncertainty due to thermal changes
7) Uncertainty due to wear

The key contributors towards these sources of error are subsequently broken down and design iterations are made on an exponential number of components and system configurations. The final design solution is decided on a customer driven resource vs. cost basis. Principally the manner and success in which a machine tool budget is constructed and implemented wholly depends on the philosophy, views, experience and skill of the machine tool manufacturer [184]. When repurposing the machine as a measurement device these uncertainty contributors alter in relevance, become more critical and are added to. Therefore an approach to enabling OMI could be the full prevention and preservation of a machine tool's error parameters; which can be done through measurement of the machine as if it were a CMM.

2.32 CMM uncertainty evaluation

In order to evaluate the measurement uncertainty of CMM measurements, many uncertainty contributors need to be understood and quantified. There are several approaches to classify all uncertainty contributors, these are described in the ISO 15530-1 standard [185]. With the numerate opportunities for measurement uncertainty contribution and their strong interaction, there is an emerging body of research associated to task-specific uncertainty estimation techniques [167]. Table 2-6 indicates typical methods used for CMM uncertainty evaluation.

Table 2-6: Uncertainty estimation techniques and their applicability to on-machine tool inspection (OMI)

Sensitivity Analysis	Methods that use 'error budgeting' approaches, where each uncertainty source is listed and quantified. This approach is described in the ISO Guide to Uncertainty in Measurement (GUM) [182]. This approach is viable for machine tool applications. However, there is little evidence that this method has ever been applied in this way.
Expert Judgement	A popular method in industry. Measurement uncertainties are calculated or estimated based on expert knowledge and experience. As experience is limited with regards to using machines as measurement systems, it is unlikely this is a viable option for OMI.
Computer Simulation	Methods where virtual models are created of the CMM in question. These models are then used for simulation via a parametric approach or a simulation by constraints approach [54], [186]. This approach is a viable one for use with OMI.
Measurement History	A method where historical data is used to place an upper bound on measurement uncertainty. This fails to detect measurement bias. It is unlikely that this method can be used of OMI due to immaturity and subsequently lack of available data.

Standard methods for CMM uncertainty evaluation are:

2.32.1 Method of substitution (ISO 15530-3)

The ISO/TS 15530-3 standard aims to provide an experimental technique for simplifying the measurement uncertainty evaluation of CMM equipment [187]. The standard follows a method of substitution approach whereby a workpiece or standard artefact is measured multiple times under various conditions. This enables one to determine the repeatability and reproducibility of the equipment in question.

Repeatability is determined under constant measurement conditions, reproducibility is determined under changing conditions [19]. Guidance from the standard is to use a calibrated artefact with similar dimensions, features and characteristics to the test object i.e. the product in question. This measurement method takes into account both an upper and lower limit of measurement uncertainty and therefore accounts for any systematic errors in the measurement system. This is considered as a reliable method for determining measurement uncertainty, however it is a time consuming and expensive one.

2.32.2 Use of computer simulation (ISO 15530-4)

The ISO/TS 15530-4 standard presents a technique for calculating task-specific measurement uncertainties using a simulation approach [188]. These simulations make use of Monte Carlo methods where in effect one is running CMM programmes multiple times on a 'Virtual CMM'. Software that is used to perform measurement uncertainty simulations by this method is commonly referred to as uncertainty evaluation software (UES). As this is a non-experimental approach, it is much faster and cheaper. However, the difficulty with this approach is correctly incorporating all input variables and quantities, where in many cases this poses a significant challenge and requires considerable experience and expertise.

Driven by industry there is much interest in these digital techniques for the evaluation of uncertainties associated to CMM measurement [167][16]. However, despite much potential, research in the area and the availability of commercial software it is still not being fully adopted by industry. This area of research has been covered in much detail via another concurrent EngD carried out on the topic of '*The study of the relationship between design and measurement technology*' by Saunders [*Unpublished at time of writing*], as well as a preluding EngD research exercise on the topic of '*An investigation into CMM task specific measurement uncertainty and automated conformance assessment of aerofoil leading edge profiles*' by Lobato [167].

Known commercial or available methods for CMM uncertainty estimation are: Virtual CMM (VCMM), developed by PTB, Germany [189]; Offline Virtual Coordinate Measurement Machine (OVCMM), developed by Carl Zeiss [190]; and PUNDIT CMM developed by Metrosage LLC [191]. In terms of utilising commercial UES tools for machine tool inspection activities, at time of writing, there has been no direct research in this area.

2.33 Use of digital tools to enable OMI

Most high precision manufacturers today have a heavy reliance on integrated software systems to define, simulate, engineer, source, manufacture, and assemble high quality products [192], [193], [194]. As a result, computer-aided manufacturing (CAM), computer-aided engineering (CAE), product data management (PDM) have become central to competent PLM systems [195]. Figure 2-33 indicates the functionality in which these software solutions offer.

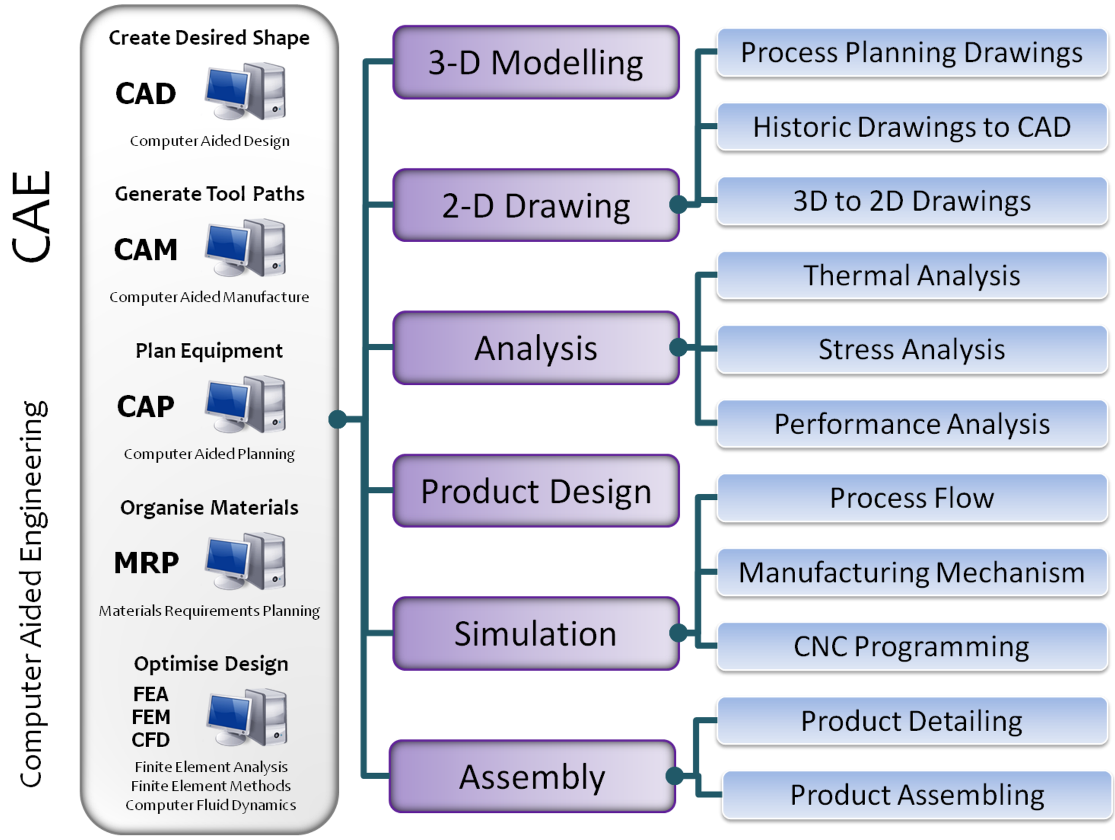


Figure 2-33: Typical manufacturing software system architecture

Figure 2-33 shows that the manufacturing process involves multiple objects, including operational processes, resourcing of equipment and tooling, organisation, and identification of material status from a raw material to final product. When manufacturing organisations need to quickly adapt or develop new products, processes, or factories the efficient use of these digital models is paramount. In order to achieve maximum efficiency these digital models need to mirror the real environment as closely as possible in terms of equipment, layout, capability, and condition. Therefore, there is a reliance on the speed, quality, integrity, traceability, and relevance of data being used to construct them. Such tools will either be relied upon or require adjustment to accommodate a change of paradigm. The challenge for

OMI will be to seamlessly integrate with current CAx systems which perhaps will not have been designed for such amalgamation. This is not a key research area in terms of scope of this thesis.

2.34 Current research activities

This section contains a summary of selected relevant research activities in academia and national measurement institutes. There are many relevant patent applications covering machine tool measurement, however patent applications with no associated commercial products or documented on-going R&D are considered beyond the time-horizon of this research work. However, for completeness, on-going research programmes being pursued in parallel to this work are presented.

2.34.1 National Institute of Standards and Technology (NIST), USA

As part of the National Institute of Science and Technology (NIST) there is a machine tool metrology group. This group specialises in measurement, modelling, simulation and control of motion with regards to multi-axis machines. There are several programs of research some of which are of relevance to this research.

Work is currently underway in metrology and standards for coordinated 5-axis motion – *"this project will develop mathematical models; measurement methods and tools to characterize the performance of complex precisely coordinated 5-axis motion that enables the production of complex shapes. The new measurement methods, test patterns, and analysis tools will be used to verify the model predictions. These methods will lean to new standards for testing complex 4- and 5- axis machines used in the production of high-value complex products."* - NIST website [164].

Major accomplishments from this project are quoted as:

- Developed a method to determine the orientation of a non-orthogonal axis of rotation of a rotary table in the machine coordinate system, providing a means to compensate for inaccuracies in the orientation and thus greatly improving the performance of 5-axis machine tools.
- In collaboration with an international working group, designed and machined a test artefact for testing 5-axis machine tools. The form measurements of the test artefact were compared to kinematic test results obtained by the telescoping ballbar to validate the method of using test artefacts to quickly evaluate 5-axis machine performance.

- Completed experiments that compared multiple test methods, patterns, and data analyses considered for the new draft standard (ISO/CD 10791-6) for assessing the contouring performance of coordinated 5-axis motion to ensure the uniformity and consistency in the test results. The results of the study were presented to the ISO committee to modify the draft standard.
- Developed kinematic and control system models of the NIST 5-axis machine tool to predict its contouring performance. Such models will be used to interpret measurement data and for diagnostics.
- Developed solid models of the 5-axis machine structure, measuring equipment, and the fixtures to virtually assemble the measurement setup to reduce time for designing and carrying out tests for various machine structures.'

Work within this group is also going ahead researching the performance metrics for manufacturing equipment used as measuring tools.

"This project will develop the performance standards and standardized performance metrics for on-machine measurements and their associated uncertainty budgets that are critical to achieve accurate, in-situ part inspection as well as cost-effective product and process certification. These standards are necessary to drive product and process innovations of sensors for manufacturing, manufacturing control systems, product fabrication systems, and metrology tools for manufacturing."

The researcher has not yet seen any outcomes from this work other than this release.

2.34.2 European Association of National Metrology Institutes (EURAMET)

There are two current projects relevant to this research:

1) Freedom of movement (IND58) - Measurements for positioning in six degrees of freedom

As quoted by the EURAMET website [196]:

"This project will develop measurement instruments to support traceable six degrees of freedom (6DoF) measurement. 6DoF refers to the ability of an object to move freely in three-dimensional space.

The project will use interferometry techniques to establish a direct link to the definition of the metre. Traceable measurements of position, angle and straightness will be made accurate to the nanometre. Novel hardware and improved sensor systems will improve *nano-positioning. This will benefit industry through more efficient production processes, reducing the number of defective parts and this will lead to savings in raw materials and time."*

This project is currently in progress (Due to complete 2015) therefore there are no outcomes as yet. Expected outcomes anticipated to be:

- Development of optimised 6DoF measurement instruments
- A 6DoF compact measurement instrument with a single plane mirror interface and air refractive index tracking possibilities will be developed
- Different methods for the measurement of straightness and orthogonally will be implemented and compared
- A test bed will be constructed and used for characterisation of stages, this will enable traceable characterisation of stages used for nano-precision machines
- Use of laser tracers which uses balls as angle insensitive reflectors

2) Measurements during production (IND62) - Verifying in-process machine tool measurements

As quoted by the EURAMET website [174]:

"Existing machine tool calibration techniques are not able to characterise and mitigate against the in-process effects. A lack of suitable procedures to assess the uncertainty of dimensional measurements on machine tools also makes it impossible to rely on in-process measurement results, leading to long production downtimes and high manufacturing costs. Laser-based techniques offer an alternative solution but they do not currently account for all the possible measurement errors.

This project will develop a portable test chamber that can simulate environmental in-process conditions and verify the measurement performance of machine tools in situ. The resulting traceable in-process dimensional measurements will offer better product quality control, lower manufacturing costs, higher productivity and faster assessment of product quality."

This work is directly relevant to this research exercise and therefore is continuously monitored during this study (Completion date is 2015). At time of writing the following achievements have been publicised:

- A summary of existing artefacts available on the market as well as other artefacts developed by industry and academic laboratories relating to in-process metrology
- A 1st draft of a specification detailing technical requirements and geometrical attributes for a mobile simulation chamber
- The formation of a stakeholder committee
- The creation of a website www.ptb.de/emrp/tim.html

2.35 Value and impact of metrology

The economic impact of metrology within manufacturing can be difficult to quantify due to its complex interactions with the manufacturing system. Some work has been done previously to evaluate the benefits of implementing metrology systems within manufacturing cells [10][197-198]. However, these models often purely look at the operating inputs such as design, manufacturing, and inspection costs and relate them to manufacturing outputs such as rework, lost production and final product quality costs. Although economic cases are difficult to form it is widely accepted that reliable and capable metrology plays a key role in achieving consistent manufacturing excellence [10]. Manufacturing metrology is the core requirement for process control and quality management and therefore of vital importance for profitable manufacture of high quality products.

Often literature is, as expected, favourable towards the use of industrial metrology where benefits are well defined and communicated, where the 'non-benefits' are often unspoken of [198-199]. An interesting paradox highlighted by Kunzman [197] is that although metrology is widely accepted as important it is not necessarily perceived as value adding. This is made on the argument that metrology does not in-fact generate new knowledge due to its focus on the application of measurement rather than its utilisation. Kunzman therefore introduced the term 'Productive Metrology' to enforce this argument and describes mechanisms in which such pro-active metrology can generate business benefit via intervention (Figure 2-34).

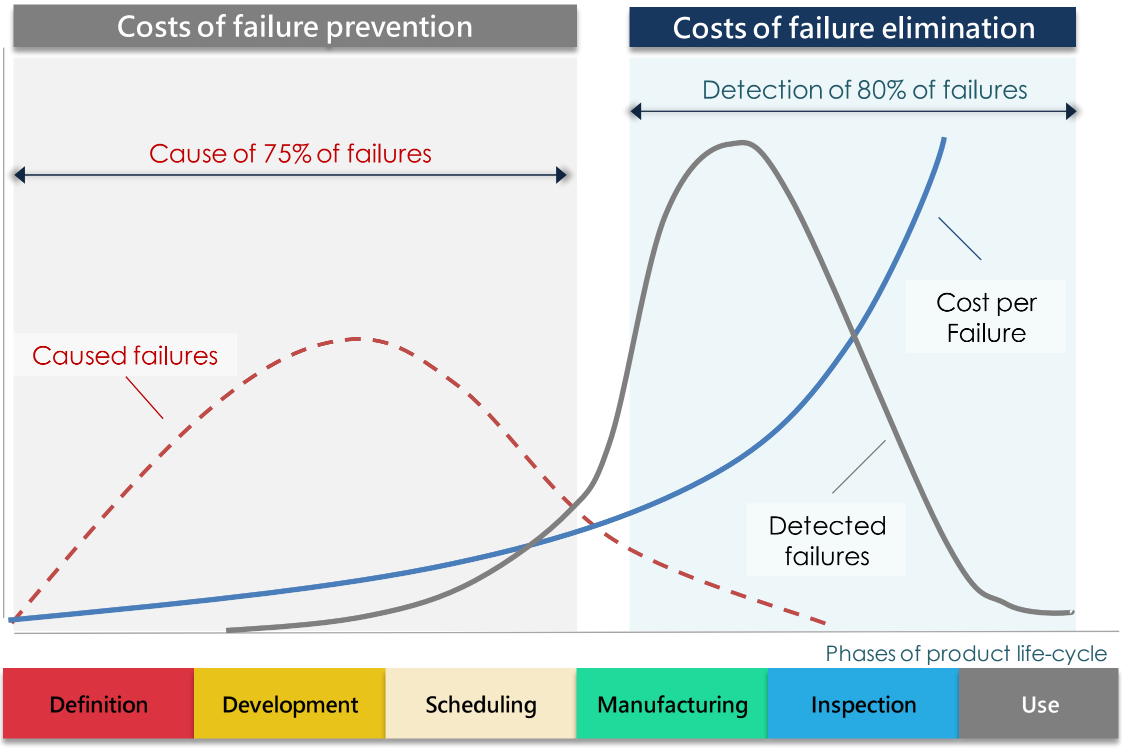


Figure 2-34: Origin, elimination and cost of faults [197]

Modern manufacturers typically concentrate the majority if not-all their metrology budgets on final product inspection activities as a means of preventing in-service product failure and incurring costly penalties [10]. This manufacturing model emphasises the importance of defect detection over prevention i.e. customer protection rather than customer cost-reduction. A reason for this behaviour may be attributed by a difficulty to quantify benefits of metrology within and prior to the manufacturing process [3]. As a result, it is often up to decisions by managers to make choices with limited information, where high ratios of fixed costs to marginal costs and externalities exist.

It is believed by applying productive metrology more holistically and better integrating management and engineering systems this paradigm can be changed; in order to add greater value through; more efficient control of processes i.e. manufacturing processes; and testing of conformance to specification.

2.36 Enabling on-machine inspection in an industrial environment

This literature and state-of-the-art review has surveyed and examined academic, industrial and commercial activity relevant to the research question and scope. The majority of the research and technology presented here can be incorporated to enable on-machine inspection in an industrial environment; however, this is not being achieved. According to the researcher, important reasons for this are as follows:

1) *Key machine tool measurement parameters are not defined for every machine type*: Knowledge is plentiful in terms of machine tool error types and sources. Standards and equipment are available for measuring the majority of these. However due to the vast array of different machine types and configurations, pin-pointing specific measurements that must be carried for a specific machine is not a straightforward task. Where machine tool users may be able to turn to the original equipment manufacturers for this guidance, it is likely that either they will not know themselves, as they have not purposed their equipment for on-machine inspection, or that they will provide a biased viewpoint. There is therefore a need for a novel approach for generating machine and application specific error lists. These lists can then be referred to by machine users for purposes of machine acceptance, calibration, re-verification and ultimately OMI sustainment.

2) *Machines cannot be measured fast enough*: There is a requirement that if OMI is to be achieved, the machine itself needs to be measured on a continuous basis. It has been shown that there is an array of technology available for measuring key machine tool errors. However, counter to claims made by technology providers, current machine tool measurement equipment is still perceived to be too slow and intrusive for industrial use. As machine downtime is a key operational metric, dramatically minimising measurement time for purposes of audit, calibration and re-verification is a vital enabler. Much of the equipment presented in this chapter has never been independently appraised for measurement time and purpose. Thus, optimum solutions, which consider the integration of equipment types for rapid measurement of multi-axis machines has never before been identified and tested. This presents an opportunity for significant improvement.

3) *Standards do not provide engineering guidance for OMI conversion*: Machine tool standards provide excellent guidance on how to assess the performance of machines. There is a recently published ISO 230-10 standard purposed for on-machine probing devices [86]. This standard, although valuable, does not go far enough in terms of how to enable and qualify a machine tool for OMI. Therefore, there is a need for an engineering standard, guidance or framework to fill this gap. If a tested gated process could be provided to machine tool users, the decision of moving to OMI could be based more on quantitative data and mutual agreement.

4) *There is no clear and proven method for OMI uncertainty evaluation*: Task-specific uncertainty evaluation is a current on-going challenge for shop-floor CMM systems. There are numerous ways one can estimate measurement uncertainty for both CMM and OMI systems. However, the majority of these will be unfeasible for production machine tools. Where simulation techniques are becoming more popular for CMM applications, there is potential for this approach to be applied to the machine tool. Until now, this has never been attempted or achieved.

5) *There is little evidence of economic case*: A major blocker for enabling converting existing machinery to perform OMI activities is a proven business case. Where often the benefits of OMI are prophesised by academics and technology vendors, there is little factual evidence that this is a worthwhile exercise. Without such, industrial machine tool users are left to debate the value of measurement and why the machine tool, a clear value adding asset, should not be sacrificed for OMI.

2.37 Chapter summary

This chapter has highlighted that the measurement of machine tools for their optimisation and sustainment has been investigated for a significant period of time and in much depth. It has also uncovered a vast array of measurement systems available on the market to complete this task. Additionally, it has been highlighted that the usage of machine tools as measurement systems is not a new concept. Here new and available standards and research material in this area have been explored. As the researcher could not find a significant amount of material on the topic of enabling and controlling on-machine inspection (OMI), therefore the researcher turned to the topic of co-ordinate measurement machine (CMM) inspection, which has direct parallels. Here the researcher explored how measurement uncertainty was currently being managed for these ‘similar’ equipment types.

The review has shown an abundance of machine tool measurement research, international standards and new technology associated to the measurement of machine tools. However, there is less maturity and experience in the way of utilising machine tools as shop floor measurement systems. Especially in terms of establishing traceability of dimensional measurements on machine tools under ‘real-world’ conditions and the haste in which measurements need to be performed.

From this literature and state-of-the-art review, the researcher therefore concluded, that:

- International standards are limited in terms of providing direction of how to fully qualify and implement OMI onto a machine tool
- There is little instruction on how to set the capability foundation for on-machine measurement
- Much of the literature surrounding the measurement of key machine tool errors does not critically appraise the time it takes to perform measurement process; a critical metric for machine users
- The implementation of on-machine inspection onto industrial machines, often designed for this intervention, has not been looked at from a 'systems perspective'
- A clear and viable method for estimating machine- and task-specific on-machine inspection measurement uncertainty is not available and therefore unproven
- Despite many references purporting the benefits of up-front on-machine inspection many have not questioned or demonstrated the true economic case

The researcher hypothesises that much of the technology, knowledge and experience associated to enabling machine tools as measurement system exists, however these have not been brought together holistically in a systematic way in an industrial context. By employing 'systems thinking' methods and techniques the researcher purports that such gaps can be closed whereby new knowledge and novelty can be generated. This can be achieved by utilising an appropriate framework, generating relevant sub-questions and scoping work accordingly. This will therefore be the focus of the next chapter.

Chapter 3

Research questions, methodology & objectives

Chapters 1 and 2 have explored the industrial and academic need and context associated to the core research question. These chapters have uncovered key gaps and the fundamental need for a systematic and holistic approach if industrial scale on-machine measurement is to be made possible. This chapter presents the overall strategy, structure and methodology of this research work. With this research sub-questions are identified, purposed to generate new knowledge and solutions. The method for exploring each of these research questions is presented. Subsequently discussion around validity and reliability is made. The chapter concludes with a summary of the forthcoming chapters which confirm linkage of objectives to deliverables.

3.1 Research strategy

The 'Achievement Advance!' model created by Isaksen *et al.* is used to create and define the research strategy [200]. With this approach various research tools and techniques are considered for exploration, understanding, scoping and engaging the problem space described in chapters 1 and 2. The 'Achievement Advanced' framework describes four key activities associated to the execution of this research: Navigate, Explore, Engage, and Develop, as shown in Figure 3-1. The purpose of these elements can be summarised as:

- Navigate – Linking the following three phases with questions of scope, need and level
- Explore – Understanding the system and encouraging a focus of the research exercise
- Develop – Understanding complexity and developing a research methodology
- Engage – Focusing on a strategy of engaging the problem space and implementing change

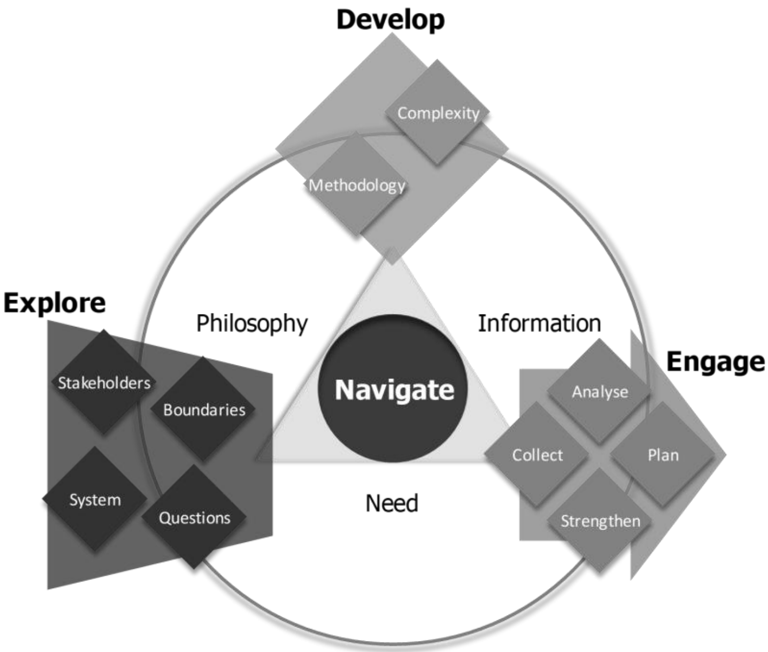


Figure 3-1: Achievement Advanced Model 2010© (University of Bristol - Systems Centre) [200][201]

This research strategy bases itself on gauging the relationship between research and theory whilst considering ontological and epistemological issues which may be present in the research arena [202].

3.1.1 Research strategy philosophy

A common situation for many organisations is that where research goals are set exact requirements are often unspecified and/or unknown. This can lead to not only under-performance of a new/optimised system but emergent factors may be missed which could lead to undesirable outcomes [203]–[208]. Therefore, in addition to technical questions, questions must also be asked to also understand the ontology of the current environment and the epistemology of the situation i.e. there must be a social reason why this research is important or who, what, where and how will this research be applied in an industrial environment. For example, accepting that there will be a requirement for a human operator and maintainer of any new technology; in that with any new technology there will be a lack expertise or information needed to integrate human capability with the capability of new hardware or software.

This research undertaken in this thesis is designed to have both an academic and industrial impact. This will be achieved through the utilisation of academic theory to inform business practice, whilst creating new theory based on its practical application (Figure 3-2).

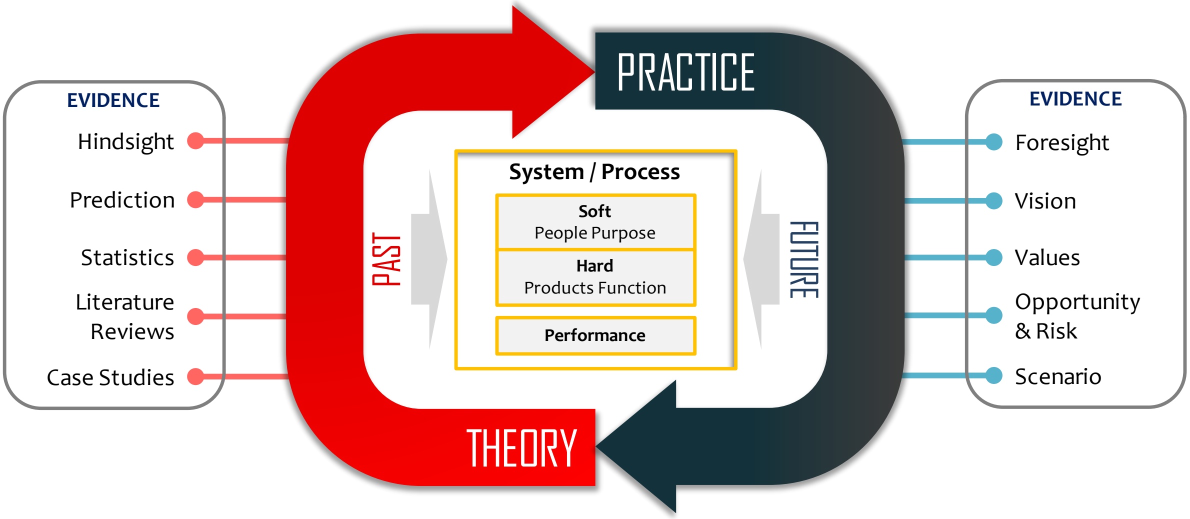


Figure 3-2: Twin focused approach to Systems integration (University of Bristol - Systems Centre)

Illustrated by Figure 3-2, is a need for a dual approach to enable successful systems intervention. In this model ambition of new best-practice is combined with past experience in order to enable robust system intervention. This is the philosophy that this research work will apply.

3.1.2 Explore and Develop

With regards to the Achievement Advanced framework (Figure 3-1) the researcher has already 'Navigated' the underlying concepts as well as the philosophical and theoretical principles upon which this research is based (Chapter 1) and explored and understood the context in which the research is being performed and the research requirements and aims (Chapter 2). This chapter therefore aims to:

1. Consider all stakeholders needs in order to understand the overall system viewpoint and scope of research (Explore)

2. Consider and select between appropriate questions and methodology choices whilst considering external validity (Develop)

3.2 Research exploration

Within manufacturing organisations, the impact of measurement intervention can be observed throughout the organisational hierarchy, where depending on viewpoint perceptions of value can vary dramatically. Additionally, stakeholders external to the host company (Rolls-Royce plc.) must be considered in order to maintain the researchers' independence of the research and for reasons of generating academic validity.

3.2.1 Stakeholder engagement

Stakeholders associated to this research were identified via organisational charts, community of practice events as well as through word of mouth and direct referrals.

With all stakeholders identified they are grouped into one of four categories, being; 1) is the user involved with or 2) affected by changes in manufacturing capability and/or is the user 3) interested in or 4) influenced by changes in manufacturing capability (Figure 3-3). Due to the sensitive nature of the information details of location, facility and user names cannot be disclosed.

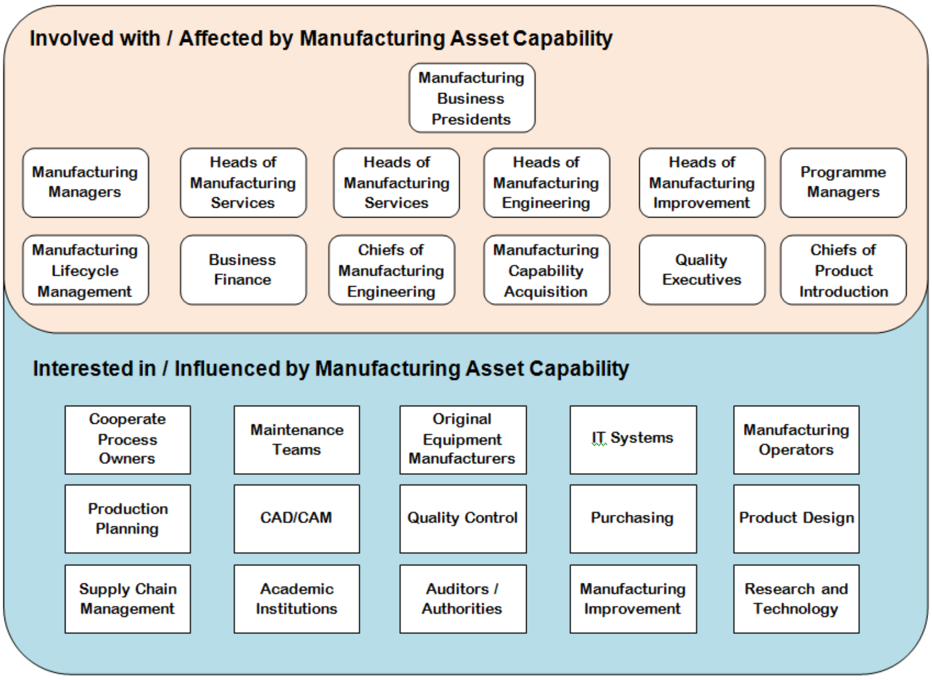


Figure 3-3: EngD research stakeholders

Most, if not all, stakeholders indicated within Figure 3-3 have been involved in this research; via conferences, group meetings, and semi-formal interviews. Over 40 people were engaged in total. One such example of this stakeholder engagement involved performing facilitated focus group exercises followed by semi-structured interviews with stakeholders from multiple business functions. Both sets of data were used to understand the opportunities and problems encountered by manufacturing engineers when choosing to implement machine tool metrology systems into their production process. A significant outcome of such stakeholder engagement has been the creation of a shared 'manufacturing vision' associated to this research topic.

3.2.2 Stakeholders' manufacturing vision

Based on questions emerging from the various stakeholders (Figure 3-3), a rich picture has been developed to identify, communicate the problem space and future vision associated to this research work (Figure 3-4 and Appendix F), this systems diagram also represents stakeholder interactions.

It is not anticipated that Figure 3-4 is a true representation of the current manufacturing process. This rich picture has been primarily developed with communication and understanding of stakeholders' thoughts and needs associated to the repurposing of machine tools as product measurement systems.

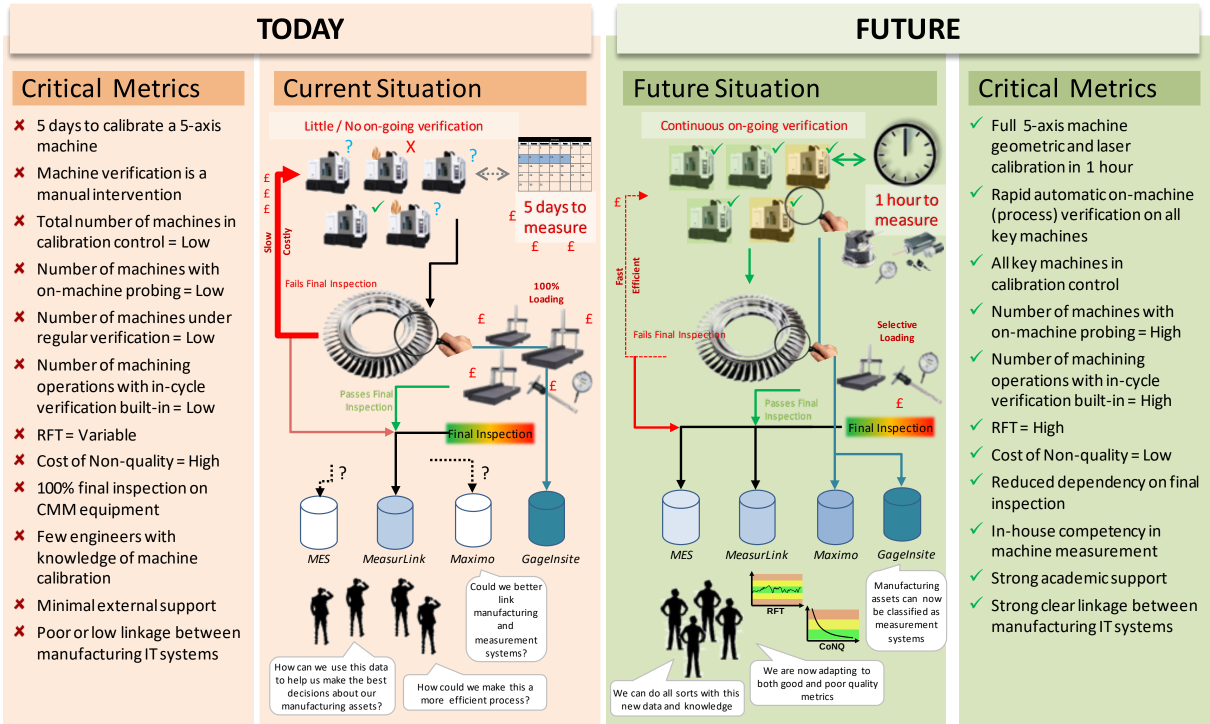


Figure 3-4: Researchers interpretation of the industrial context and future vision (Appendix F)

Multiple messages are presented within Figure 3-4, where the most notable facets associated to this research are:

1) The importance and impact of product right-first-time, quality and throughput for high precision manufacturing organisations.

2) The unknown capability of industrial CNC machine tools due to long and non-existent calibration and re-verification routines

3) The potential utilisation of machine tools to enable greater up-front product inspection data, enabled by rapid machine tool measurement

4) The need for strong connectivity between direct and indirect measurement systems to other enterprise resource systems; such as Manufacturing Execution Systems (MES) [209]; Statistical process control systems (i.e. MeasurLink [210]); asset maintenance systems (i.e. Maximo [211]); and gauge control systems (i.e. GageInsite [212]).

5) The challenge of enabling machine tools as measurement systems to enable selective loading of final inspection equipment

Key industrial metrics required to enable on-machine inspection were highlighted as:

1) The requirement of a rapid calibration solution. Which in effect could calibrate a multi-axis machine in less than 1 hour

2) The requirement for an on-going machine tool verification system to be installed on each machine

3) A system for maintaining and tracking calibration status of machines, and hence bringing them in control

4) Ensuring that all machine tools are enabled with on-machine probing devices

5) Choosing machines that already have a high production right-first-time rate

6) Choosing machines that should on-machine inspection should fail, impact to business is low

7) A requirement for capable and skilled asset operators and maintainers

8) Having strong linkage to academic theory and support to manage technological complexity, uncertainty and risk

9) Ensuring strong clear data-links between database systems

Thus, with reference to these messages presented by key industrial stakeholders, as indicated in Figure 3-4, and gaps highlighted in Chapter 2, there is much consistency between academic and industrial needs. This is in terms of gaps and need for innovation.

3.3 Scope of the thesis

As indicated in previous chapters, and by Figure 3-4, the potential research area surrounding the core question is very broad. The core question being:

"How can traceable on-machine inspection be enabled and sustained in an industrial environment?"

This potentially covers areas of manufacturing engineering, metrology, machine tool capability/metrology, capability acquisition, business process improvement, business management, systems engineering amongst other socio-technical topics such as complex systems and cybernetics. As introduced in Chapter 1, an 'EngD on-a-page' diagram has been created in order to scope the research included within this thesis (Figure 1-12).

As indicated by Figure 1-12, the research is primarily focused upon on-machine product measurement. Figure 1-12 has been colour coded to identify core, secondary and associated research areas. Therefore, areas to be explored and developed by this research are to include: new measurement systems used to calibrate and verify machine tools; the creation of systems and processes to enable on-machine inspection; the modelling of machine tool systems to understand their measurement uncertainty; and the generation of new knowledge associated to the industrial case for on-machine inspection.

3.4 Core research questions

In reference to the industrial and academic stakeholder vision encompassing the research (Figure 3-4); the core research question; and the scope defined as per Figure 1-12; the researcher will therefore consider the following research questions in this research:

- Q1. Should more product inspection be brought onto the machine tool?
- Q2. What are the errors within a machine tool system that should be measured and how can they be identified?
- Q3. How can a multi-axis machine tool be measured and re-verified with least disruption?
- Q4. Is there a consistent strategy for enabling machine tools as measurement systems in an industrial environment?
- Q5. Can a machine tool system be modelled in order to estimate its measurement uncertainty?

Based on the ‘Literature and state-of-the-art’ review (Chapter 2) and thorough stakeholder engagement presented here, the researcher proposes that these are valid and entirely relevant questions which have not previously been investigated. This therefore provides a clear opportunity of new knowledge and technology generation.

3.5 Research methodology

Six prominent research designs are often utilised within technical research: experimental; longitudinal; cross-sectional; case study, ethnography and modelling [202]. There is much discussion about the nature and relevance of each such approach

[213]. Experimental design a positivist approach is explored by [214–216]. Longitudinal research, often but not always, a positivistic methodology is covered by [215], [217]. Cross-sectional research designs, again mainly positivist, are often used to investigate numerate actors and or nodes i.e. large numbers of people or organizations [214]. Case study research is associated with the study of phenomena. It is a form of exploratory research, which is classified under the umbrella of a phenomenological methodology [214], [218]. Modelling, sometimes considered as comparative design, is useful in uncovering findings between multiple cases, it is a relatively cost-efficient method of research [202], [217]. Action research (AR) originally coined by Lewin (1946), follows a cycle of planning, observation and reflection [217], [219]. It is highlighted that with AR collaboration between researcher and researched as important when developing shared understandings [219].

As this research is classified as 'Engineering doctoral' research it is anticipated that, as per intended, the researcher will not just champion observation, but will also champion intervention [220]. Ethnographic research, a phenomenological approach, translates from Greek with "Ethnos" meaning foreigner and "graphos" meaning writing, thus "Ethnography" means writing about foreigners [214]. Ethnographic research is useful for observing change within organisations, looking for inferences taken from observation in the development of new theories. As the researcher is facilitating the research within a host organisation (Rolls-Royce plc.) it can be argued there are ethnographic aspects to the research.

Therefore as described, this exercise considers both a positivistic and a phenomenological research approach with regards to answering the fundamental research questions.

3.5.1 Multi-methodology approach

This methodology choice is also influenced by these philosophical perspectives and the perceived complexity of the question at hand versus the time and resources available (Figure 3-5).

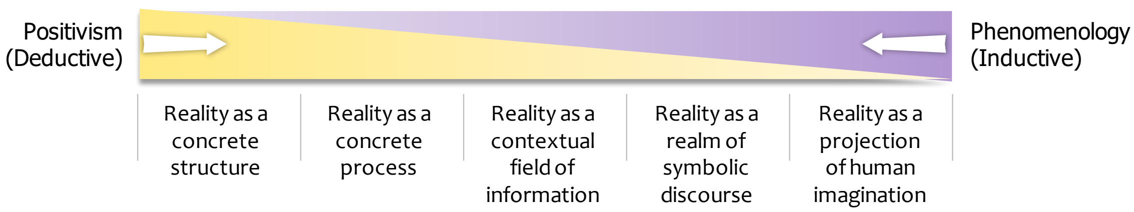


Figure 3-5: Positivism vs. Phenomenology [214]

A multi-methodological approach is relevant to this research as opposing, and often unrealised, philosophical standpoints are observable within the problem space i.e. metrology literature typically focuses on the science of measurement as opposed to the philosophy behind it, machine tool design literature discusses the views behind robust design where often non-scientific philosophical knowledge is presented.

For example, Figure 3-6 indicates the design considerations in which a machine tool builder will consider when designing and producing a machine tool. In some cases, the inputs are considered as 'black boxes' where experience is used to judge the overall systemic impact of the input variable. However, the true output of such a machine tool is potentially unknowable due to the metrological disparity of what is desired, what is measured, and what the 'true' value is.

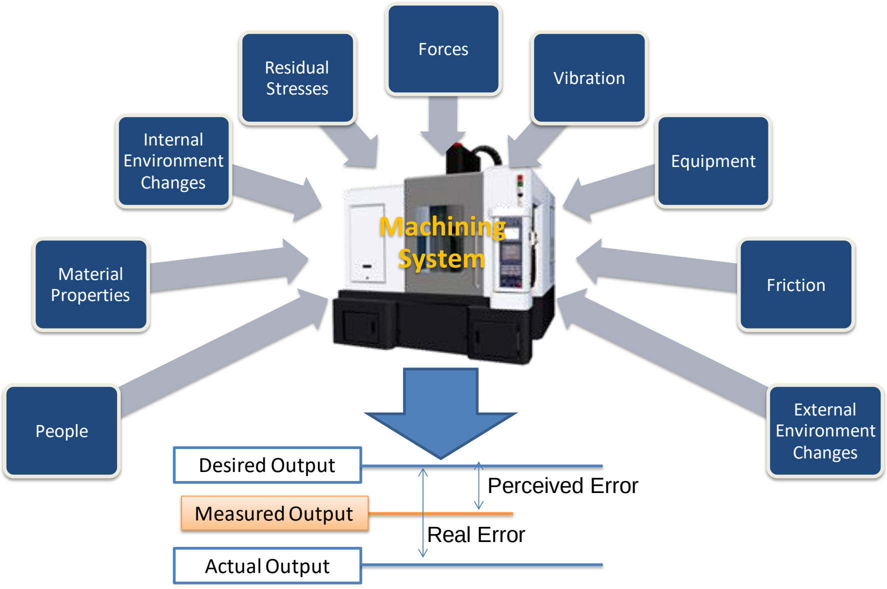


Figure 3-6: Machine tool input- output uncertainty

3.5.2 The 'Onion Model'

With reference to the research methods discussed earlier in this chapter, the 'onion model' (Figure 3-7) by Saunders *et al.* [213] is used to select the appropriate research approach to best explore research sub-questions identified in 3.4

This model enables the researcher to explore options available in terms research paradigms choice, approaches, strategies, time horizons, and data collection/analysis methods.

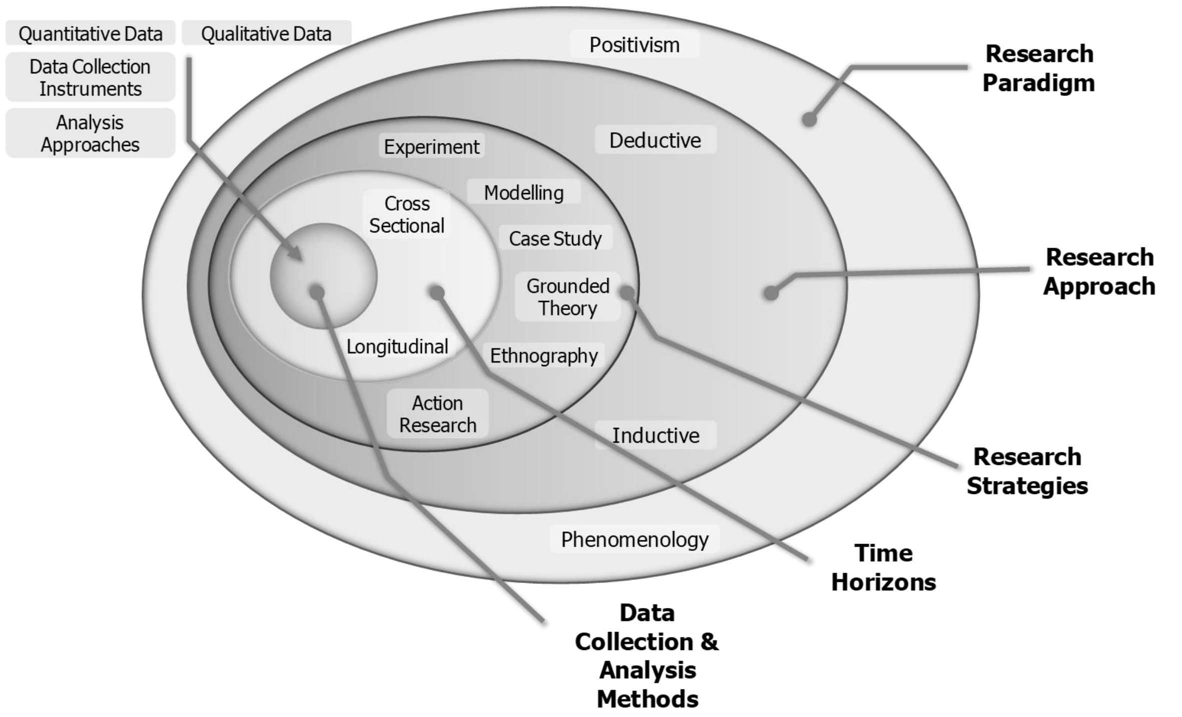


Figure 3-7: The Research Onion (Saunders *et al.*)

The onion model has therefore been applied to derive the following research approach for this EngD study.

Table 3-1: The 'Onion' model applied to EngD research questions

Research Question / Method	Positivistic		Phenomenological	Experiment	Survey	Case Study	Ethnographic	Action Research	Cross Sectional	Longitudinal
Q1	✓		✓	✓	✓	✓	✓	✓	✓	✓
Q2	✓				✓	✓		✓	✓	✓
Q3	✓			✓	✓	✓		✓	✓	✓
Q4			✓		✓			✓	✓	
Q5	✓			✓	✓	✓		✓	✓	

In line with the objective to pursue a multi-methodological approach this research study will not be entirely positivistic nor does it utilise a single research method throughout. With the aim of bringing measurement onto the machine tool, all listed research approaches will be employed to fully explore and strive towards this. Indicated by Table 3-1 is that an action research approach is applicable in all areas due to the nature of EngD research; being to solve an immediate problem via the generation of new knowledge which provides both academic and industrial value. Also notable from Table 3-1 is that a cross-sectional time horizon is applicable in all areas as the researcher aims to explore the use of machine tools as measurement devices; rather than comparing and analysing the results of such an intervention within a number of different situations.

With this research strategy in place, Table 3-2 presents the overall content of this study.

Table 3-2(*a*): An overview of studies contained

Research Question	Study	Contribution	Research Method	Resources Utilised	Data Collection Method
Q1: Should more product inspection be brought onto the machine tool?	Paper II Chapter 2 Chapter 4	Generate new evidence and knowledge in terms of the challenge and value of introducing on-machine measurement systems into a cell of industrially located machine tools	Experiment, Survey, Case Study, Action Research, Ethnographic Study	Rolls-Royce Production Facility	Literature review, Interview, Documentation, Quantitative Methods
Q2: What are the errors within a machine tool system that should be measured and how can they be identified?	Paper I Chapter 2 Chapter 5	Identification of the methods available to generate performance indices. Propose and test the concept of a 'Machine tool metrology index' for machine error parameterisation	Survey, Case Study, Action Research	Rolls-Royce Multiple Sites, University of Bath – Laboratory for Integrated Metrology (LIMA) University of Huddersfield – Centre for Precision Technologies (CPT), Advanced Manufacturing Research Centre (AMRC) - Sheffield	Literature review, Interview, Questionnaire Documentation

Table 3-2(*b*): An overview of studies contained (*cont.*)

Research Question	Study	Contribution	Research Method	Resources Utilised	Data Collection Method
Q4: Is there a consistent strategy for enabling machine tools as measurement systems in an industrial environment?	Paper III Chapter 1 Chapter 2 Chapter 4 Chapter 7	New knowledge generation resulting in the creation of a novel on-machine inspection implementation framework. This framework is subsequently tested in a live manufacturing environment.	Experiment, Survey, Case Study, Action Research,	Rolls-Royce Multiple Sites, Advanced Manufacturing Research Centre (AMRC) - Sheffield	Literature review, Interview, Documentation, Quantitative Methods
Q5: Can a machine tool system be modelled in order to estimate its measurement uncertainty?	Paper V Paper IV Chapter 8	New knowledge generation based from real-world assessment and testing of commercial software for the purpose of on-machine inspection uncertainty evaluation	Experiment, Survey, Case Study, Action Research,	University of Bath – Laboratory for Integrated Metrology (LIMA) Rolls-Royce Production Facility	Literature review, Interview, Documentation, Quantitative Methods

3.5.3 Research validity & reliability

The validity and reliability of this research is important due to the level of action research being carried out. The researcher aims to enable both internal and external validity i.e. provide direct solutions that can benefit the host organisation whilst also able to generalise upon findings to benefit similar companies with the same existing needs and challenges. With this, the questions as identified in Table 3-2 are therefore chosen and worded to imply an objectivist ontologist viewpoint.

Voss *et al.*, stated that a way to ensure validity is by using multiple sources of evidence [221]; this approach is employed in this study, as indicated by the usage of several data collection techniques (Table 3-2). Additionally, in all studies the researcher has also taken into consideration a “chain of evidence” approach. Here it is possible for an external observation to trace the evidentiary process backwards via referencing, data or investigation.

All studies contained within this thesis are designed to ensure external validity is maintained. As such the results and conclusions will be valid in similar settings outside the study objects [222]. This study focuses on a concept which is based on a theoretical framework and opportunity, therefore this has driven the need for generalising results and conclusions.

To ensure research reliability i.e. the extent to which a study's operation can be repeated with the same results, the researcher has utilised the host companies' internal standards and guidelines associated to minimising errors and bias. Much of the research contained has action case study elements to it. This is to enable research findings and new knowledge to be immediately disseminated and utilised by the host company (Rolls-Royce plc.) at its various manufacturing facilities. As a result, all work contained will have been peer reviewed either via experienced technical managers, academics, or via group stakeholder acceptance. This is in line company internal processes and requirements [223]. In combination with this approach the research contained has been regularly peer-reviewed via publication, annual conference presentations, poster sessions and academic and industrial supervision.

3.6 Chapter summary

This chapter has presented the research strategy, questions and design used for this investigation. This purpose of this is to offer the reader transparency and logical structure regarding the research contained within this thesis. The research area and its connections have been described, as well as the approaches used in this research.

The 'Achievement Advanced Model' developed by the University of Bristol - Systems Centre has been used to systematically generate and map the design of this research. The 'Achievement Advanced Model' methodology consists of tools and methods that guide the researcher in how to conduct research associated to the core research question (i.e. Navigate, Explore, Engage, and Develop). This methodology choice is made as this research can be classified as 'manufacturing engineering'. As such, a multidisciplinary approach to research and intervention is required. Using such an approach the researcher can draw on other sciences and domains, such as machine tool capability, measurement technology, metrology, process planning, simulation, management science and systems thinking.

Within this chapter the scope of the research is described as an 'EngD-on-a-page', where the practical approach is subsequently described. As the research is based around an industrial challenge i.e. enabling industrial machine tools as measurement systems, this indicates that there may not only be one working solution but many. As a result, a multi-methodological research design is employed where the research questions proposed follow an objectivist ontological standpoint i.e. an objective reality exists and can be increasingly known through the accumulation of more complete information.

Findings from the literature and state-of-the-art review (Chapter 2) consisting of knowledge from the academic community (i.e. papers, books, journals) are considered with industrial knowledge (i.e. technology, commercial solutions, standards, industrial partners). Additionally, key stakeholders within the host company have been engaged, resulting in a shared manufacturing vision (Appendix F). This work has been performed to define research sub-questions. Subsequently, 'The Onion Model' has been applied to these research sub-questions to define research methodology choice. This has resulted in a research design which predominately consists of case study, action research, and experimental work. The researcher believes this approach provides the optimum in terms of generating new academic and industrial contribution with an appropriate level of external validity.

Chapter 4

Technical capability of OMP as a foundation for OMI

4.1 Introduction

Chapters 1 and 2 have presented and discussed the theoretical technical and economic case for on-machine measurement. From this, the researcher has found that despite the prevalence of technology, processes and theory, real-world cases of utilising on-machine probing systems for on-machine inspection are fragmented and often not documented. This chapter therefore aims to explore elements of the first of the research questions being "*Should more product inspection be brought onto the machine tool?*". This question has also been explored from a soft-systems perspective via an un-published study (Appendix A). In this chapter the researcher presents a study in which on-machine probing has been applied to existing machine tools at a live production site at Rolls-Royce plc. This study is structured and implemented via a Define, Measure, Analyse, Improve and Control (DMAIC) methodology [224]. Using such a methodology has ensured a complete and holistic approach as well as maintained compatibility with the host companies' guidelines and procedures for process intervention. From this, it is illustrated that introducing on-machine inspection can have a profound impact on product quality and operational performance.

4.2 Background

This study has been conducted at a key Rolls-Royce aero-engine manufacturing site, purposed for the creation of critical aero-engine combustion chamber components, such as those used in Trent 700 engines. The product under investigation is processed from a forged high-performance alloy, via operations such as machining, grinding, plating, electro-discharge machine and laser drilling amongst others. Critical metal removal operations are completed via high precision multi-axis metal cutting machine tools.

This case study focuses upon the turning operation of inner and outer combustion casing wall features on a 3-axis horizontal turning machine tool from a forged billet. The product undergoes a number of subsequent operations following this manufacturing process, therefore it is foundational. Simplistically the turning of the wall is completed in three distinct phases. Initially, the outer wall is rough machined using a turning tool. With this surface now considered the datum, the inner wall is then rough machined. Finally, via operator intervention and quality checking the machine completes a finishing turning operation on the outer wall. The total operation time is not disclosed for commercial reasons. Figure 4-1, an example of a machine tool used to manufacture such components.

Figure 4-1: Typical machine tool for combustion casing turning

4.3 Customer need

The core strategic objective of this chosen supply chain unit is to improve product right-first-time and reduce overall cost. This case study therefore focuses on two areas: 1) achieving a robust process and a 2) efficient process. This in turn will look to satisfy two customers:

1) The External Customer - to provide them with a component to the required specification and when they require it. Therefore, emphasis in terms of the project will be on achieving a robust process. This will enable the manufacture of a components to the required specification as well as in a predictable timeframe.

2) The Internal Customer - to provide the business with an efficient process, as well as being robust. Therefore, this will require focus on improving the overall cost rate. This will allow the business to be competitive as well as profitable.

4.4 Case study methodology

As this study involves improving a business process, a Define, Measure, Analyse, Improve and Control (DMAIC) approach was utilised [224-226]. The methodology choice was largely influenced by current organisational practice. The DMAIC approach, a Six Sigma tool, consists of a Design, Measure, Analyse, Improve and Control phase [227-229]. In this case study this approach was used to identify improvement opportunities, suspected to be measurement related, and act upon them.

4.5 Manufacturing process opportunity

Figure 4-2 presents the current work content breakdown for the manufacturing cell under investigation; this is based on real manufacturing data. It is believed that process variation is also caused at the stages highlighted and not associated to machining. It is hypothesised that if the processes in question could be better stabilised and standardised the amount of variation could be reduced; subsequently improving right-first-time (X). It can also be seen that the majority of these activities, are ‘non-value’ adding. Therefore, by reducing the time spent on these stages, the process can become more efficient and therefore improve component cost (Y).

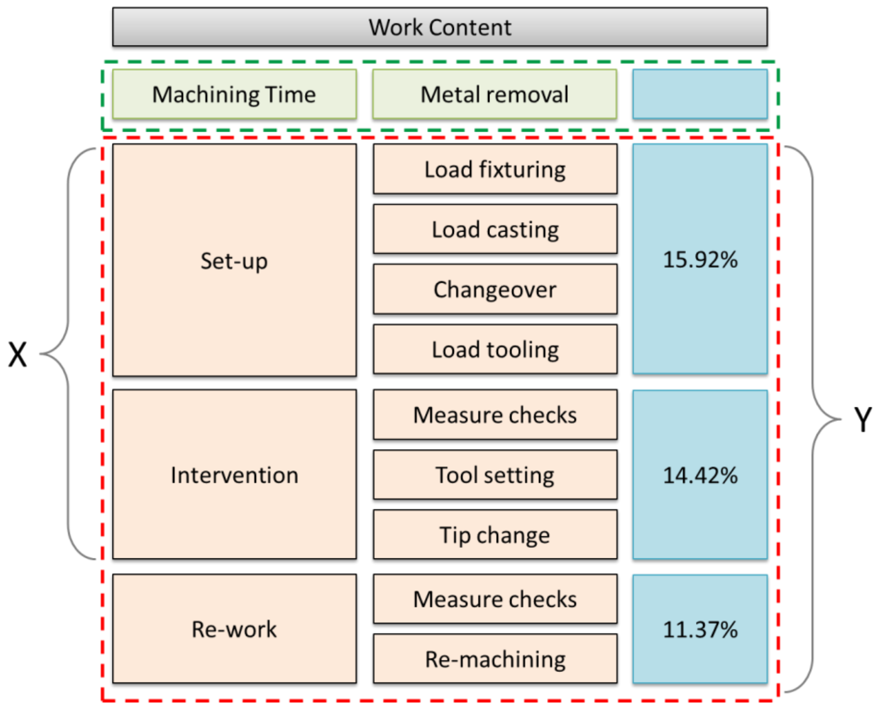


Figure 4-2: Work content breakdown for combustor turning

Table 4-1 presents the number of non-conforming features per part generated by the manufacturing process. Product names are disguised for confidentiality reasons.

Table 4-1: Product RFT before intervention

Parts through turning machines (Year 1)					
Part No.	Conforming	Non-conforming	Total	Part RFT	Average Non-conforming features per part
Product A	31	23	54	57.41%	1.59
Product B	21	35	56	37.50%	1.82
Product C	17	19	36	47.22%	1.27
Product D	6	27	33	18.18%	2.15

As indicated by Table 4-1, some products average two features per component as non-conforming 80% of the time. A total of 587 features per part are being inspected. The significance of this non-conformance is that, every time, the part has to be assessed by manufacturing engineering and then either re-scheduled for rework or scrapped; depending on which feature is non-conforming. As a result, the lead-time for producing combustor walls is not predictable and therefore ultimately impacts upon the customer.

4.6 Technical justification for on-machine measurement

Figure 4-3 displays the form of a typical combustor wall. Figure 4-3 also indicates where the in-process ‘measure-checks’ are carried out on the wall; indicated by a vertical arrow. These ‘measure checks’ are performed by the machine operator using a micrometer gauge. This process is necessary as the product is machined from casting where there is no datum and dimensional variability occurs.

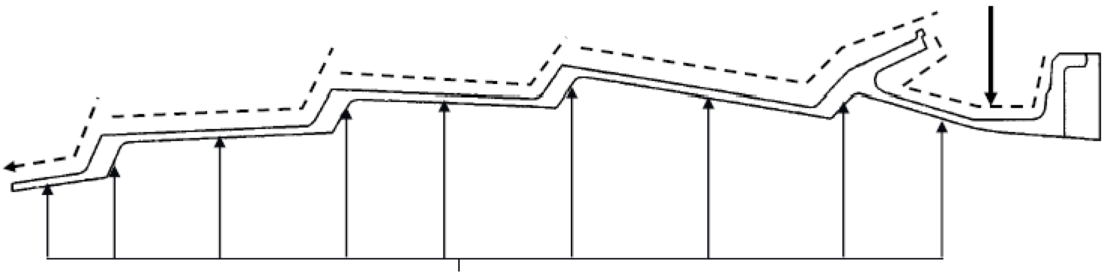


Figure 4-3: Profile of typical combustor wall

The pareto chart (Figure 4-4) presents the total non-conformance by type of feature for all wall types for the 1st quarter 2013. It was soon discovered that the commonly occurring ‘Height’ issues were due to parts not being de-burred properly. The solution was to put in de-burr ops as part of the CNC program. The next two highest non-conforming items, diameter and thickness issues, were discovered to be directly influenced by the manual in-process checks.

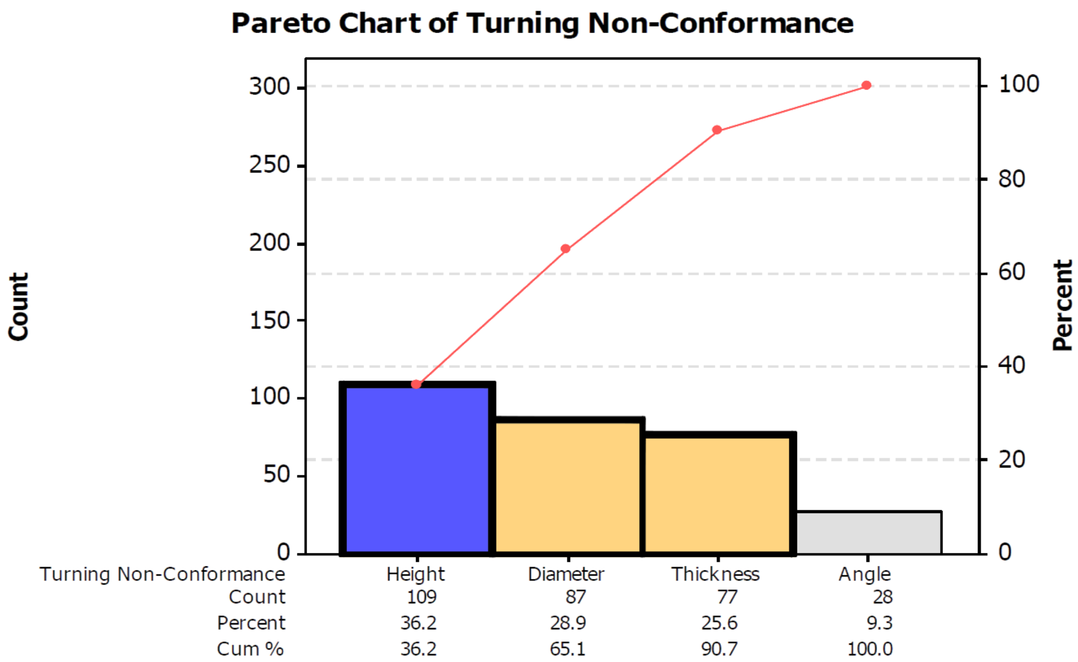


Figure 4-4: Pareto non-conformance for combustor wall turning

Plotting data derived by current CMM inspection equipment, Figure 4-5 and Figure 4-6 present individual-moving range (I-MR) control charts for a finished diameter and wall thickness respectively [230]. This method of presenting data is used as production volume is low and products have a long cycle time during machining.

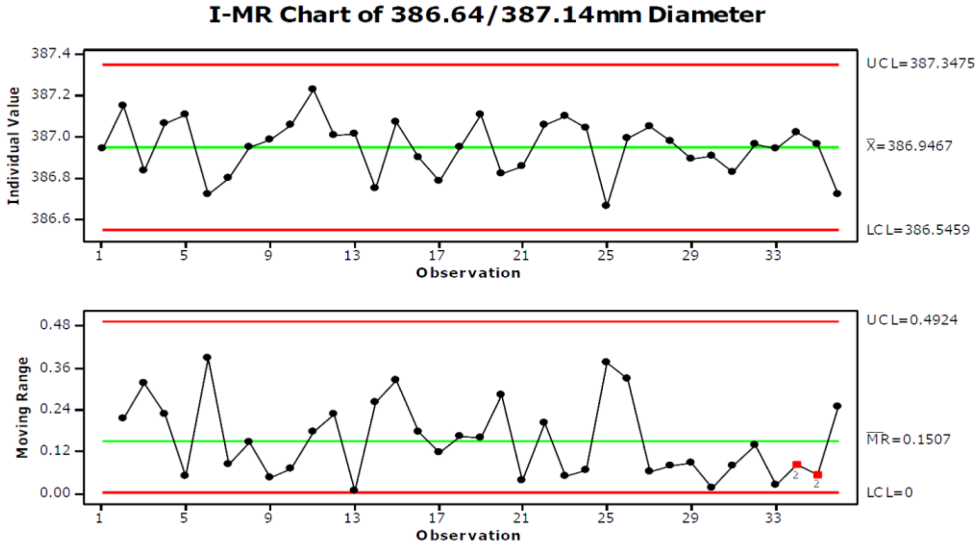


Figure 4-5: I-MR chart for combustor wall diameters

Figure 4-5 indicates that diameter measurements are varying randomly around the centreline but are within upper and lower control limits (UCL, LCL). The data does not show a trend, therefore indicting that this process is at a steady state.

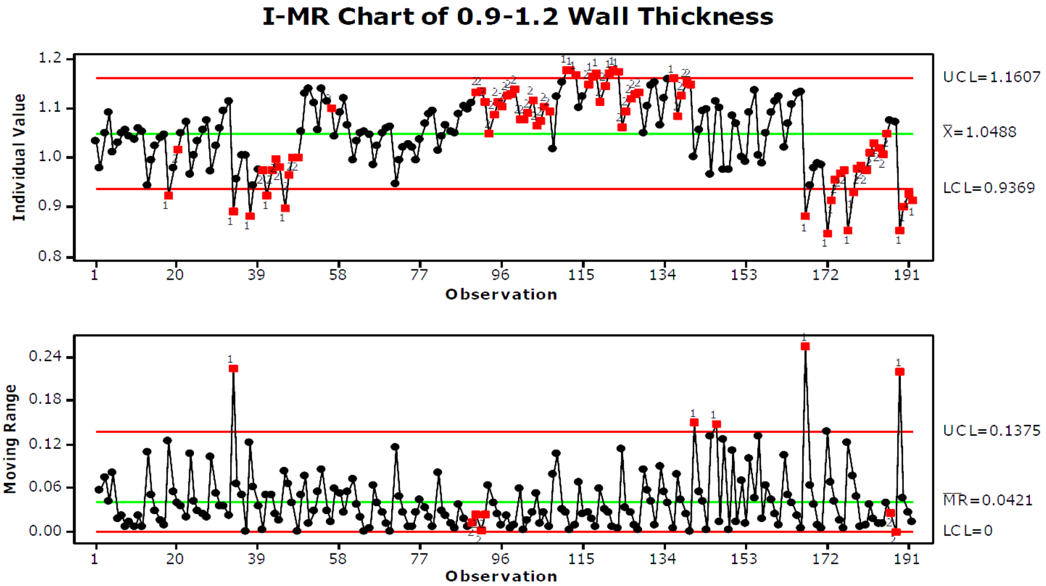


Figure 4-6: I-MR chart for combustor wall thicknesses

Figure 4-6 indicates that combustor wall thickness is not centred and often exceeds specification limit tolerances. This appears to be happening at random intervals, as no trends are being observed before non-conformance. Where trends are appearing after non-conformance this is due to manufacturing interventions.

To eliminate the CMM measurement device itself as a potential source of variation, a study, required for measurement process acceptance, was performed. This generated evidence that the measurement process was capable for the relevant measurement tasks. With this knowledge the researcher can conclude that this is the baseline capability of the machining process.

As all product measurements are not completed by CMM inspection, a subsequent study investigating other measurement devices associated to combustion wall machining was completed. The Pareto chart in Figure 4-7 presents results from this investigation. Here it can be seen that the largest variation comes from the micrometer gauge, followed by the ultrasonic gauge, clocking and tip changing activities. It was also discovered that the out of roundness on the CMM was due to the product being un-restrained during the measurement process. This was corrected.

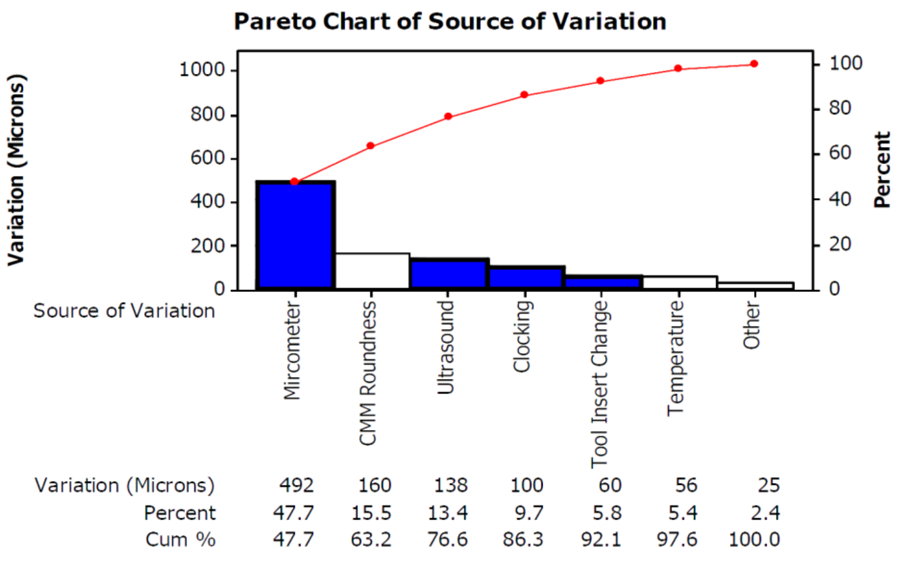


Figure 4-7: Pareto variation analysis for gauging used for creating/validating combustor thicknesses and diameters

4.6.1 Gauge Repeatability & Reproducibility (GR&R) studies

Gauge R&R studies were carried out on the micrometer and ultrasonic gauging that were being used by operators [224]. This study demonstrated that the micrometer exhibited up to 70%-gauge error versus tolerance (Figure 4-8) and the ultrasonic gauge represented 10% (Figure 4-9). The micrometer GR&R study also indicated a reproducibility error of 21%. This was due to the application of the micrometer; as it is used whist the part was still in the machine. Additionally, as combustion casings are fairly large in diameter, it proves difficult to sustain a repeatable reading between the operators. The micrometer was thus proved to be incapable, although the ultrasonic gauge was acceptable for this application.

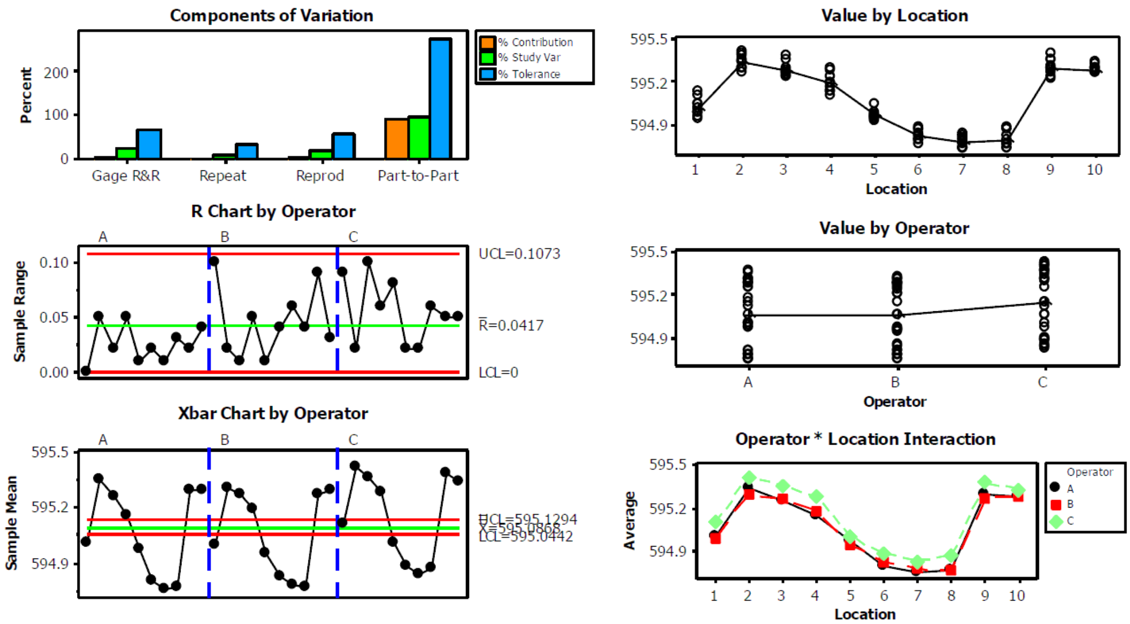


Figure 4-8: Gauge R&R (ANOVA) for micrometer used for diameter measurement

Figure 4-8 presents a 'Measurement Systems Analysis' plot for the micrometer gauge, this was generated by Minitab software [231], [232]. In this study, "part-to-part" variation indicates different locations across one component. Results indicate there is significant variation and that operators had trouble measuring this, as indicated by the wide range of results produced at each location.

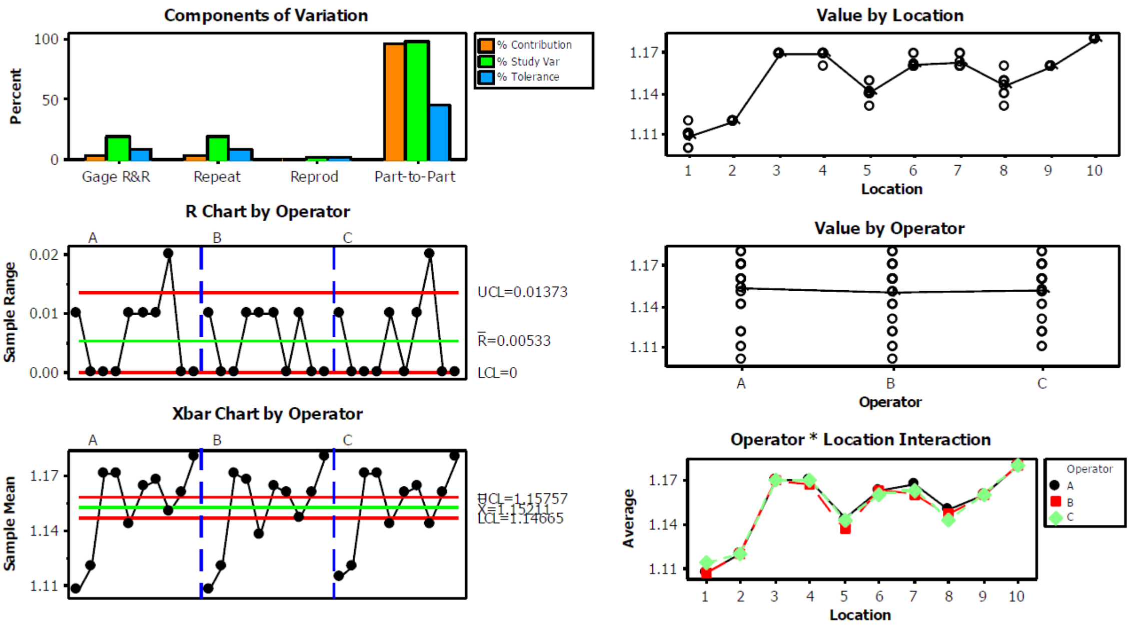


Figure 4-9: Gauge R&R (ANOVA) for ultrasonic gauge used for diameter measurement

Figure 4-9 presents a ‘Measurement Systems Analysis’ plot for the ultrasonic gauge, again this was generated by Minitab. This study indicated better gauge repeatability and reproducibility, where total variation is well within tolerance bands.

4.6.2 Machine tool condition measurement

Calibrated Renishaw XL-80 and QC-20W Ballbar machine tool measurement systems were used to audit and re-calibrate machines where required [120]. Tooling is set using Renishaw Automatic Tool Setting Unit (ATSU), that again has proven capability in machining applications [233].

Figure 4-10 maps out the operational definition for the machine tool condition measurement checks. The condition measurement is broken down into two key areas: Ballbar and Laser measurement. Here the Ballbar is used to regularly assess the squareness of machine axes, as well as their backlash and their synchronisation. Laser measurements are taken to assess the linear accuracy and repeatability of each axis.

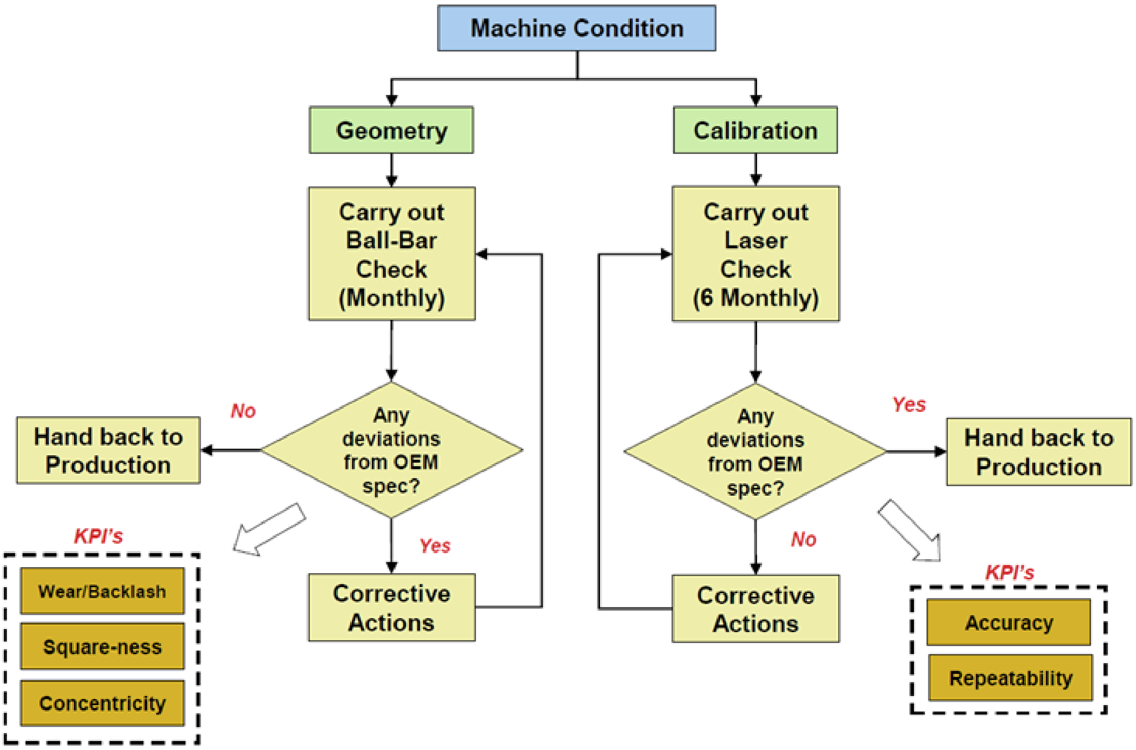


Figure 4-10: Machine tool condition measurement process

4.7 Technical justification for on-machine probing

Based on the data and findings presented so far the researcher deems that this is an ideal test base and opportunity to implement in-process measurement capability into a machining platform. With this intervention, focus will be made to eliminate or reduce the non-value-added tasks i.e. looking at removing manual gauging, rework time and improving the overall measure-cut process.

4.7.1 Manual in-process measurements

Figure 4-11 maps, via process flow chart, the current in-process product measurements that are undertaken. It is split into two strands; Profile 1 & 2 measurements; the profile numbers represent which side of the wall is being machined and therefore dictates what checks are required. Key measurements or performance indicators (KPIs) for these areas are also highlighted.

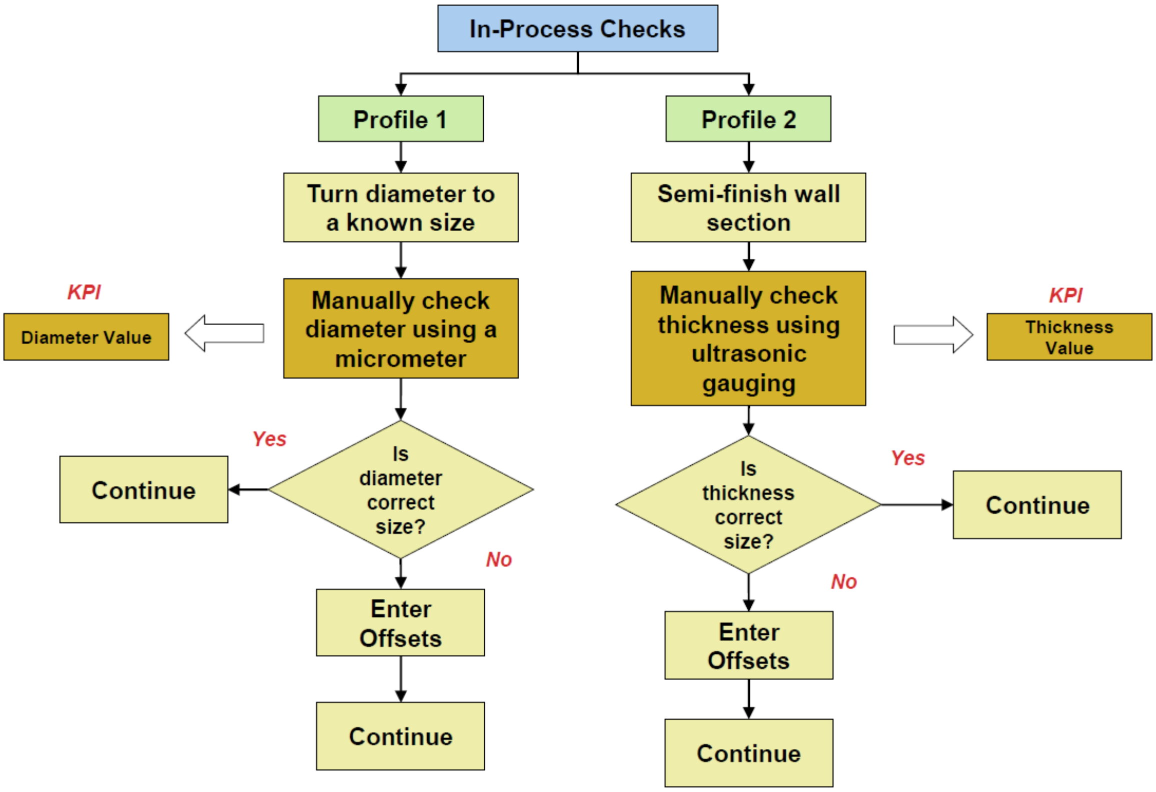


Figure 4-11: In-process measurement - process flow

4.7.2 Product set-up

Figure 4-12 presents a flow diagram for fixture and workpiece set-up on the machine tool. The key measurements being taken are the concentricity and flatness of the fixture and part to relative to each other. This measurement also considers part and fixture alignment to machine linear axes and work holding spindle centreline.

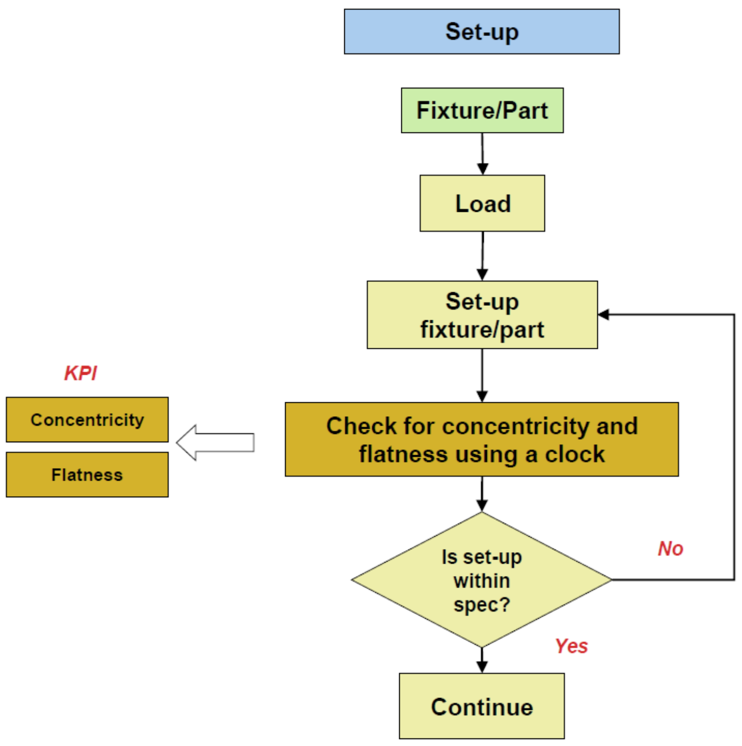


Figure 4-12: Workpiece set-up and measurement – process flow

4.7.3 Tooling set-up

Figure 4-13 presents the process steps for setting up machine tool offsets. Key operations involve the setting of tool tip length and subsequent assessment for tip changeover. Both operations utilise on-machine probing via a Renishaw ATSU system.

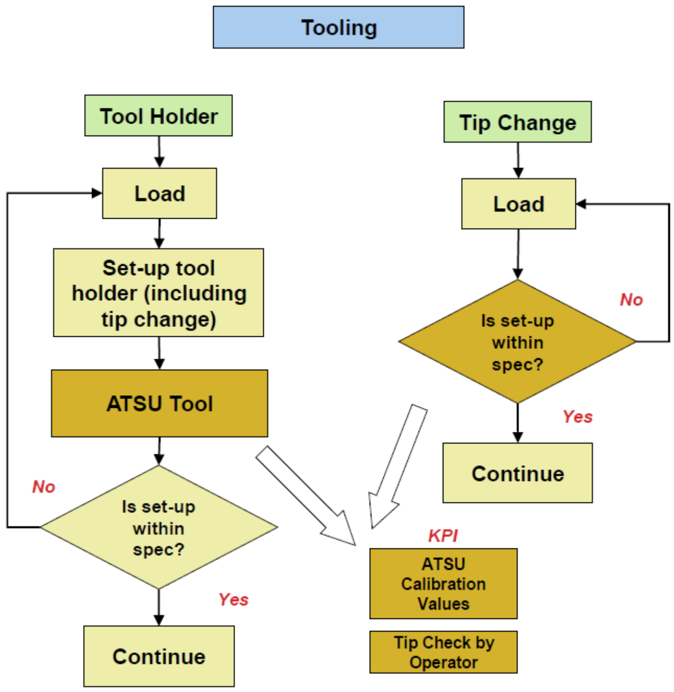


Figure 4-13: Tool set-up and condition measurement – process flow

4.7.4 Final inspection post machining

A Mitutoyo CMM checks 587 features and has an operation time of 135 minutes. Reducing or eliminating this inspection load will inevitably lead to increased product throughput and subsequently reduce cost per product.

4.7.5 Summary

Based on this evidence it is anticipated that the introduction of on-machine probing will significantly improve the manufacturing process; via improving product cost and throughput as well as quality. This will be as a result of improving product and fixture set-up times, machine datuming, machine condition monitoring, adaptive machining and eventually reducing final inspection burden.

The researcher therefore moves forward in benchmarking machine performance, without on-machine probing, and subsequently implementing an on-machine measurement solution.

4.8 Baseline machine performance (without on-machine probing)

Figure 4-14 and Figure 4-15 present CMM generated capability 'Six-pack' plots for typical wall thicknesses (for two different product variants) as produced by the turning process [232].

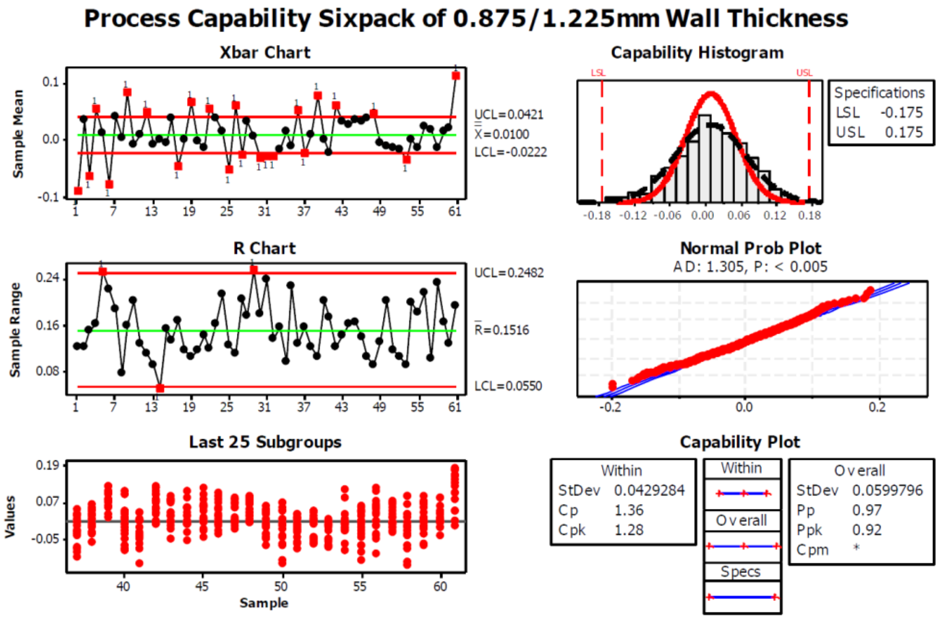


Figure 4-14: Process capability plots for combustor wall thickness - Product A

Figure 4-16 shows that wall thickness results follow a normal distribution, are well centred and show good short-term and long-term capability. However, the process often falls outside of upper and lower control limits. This indicates that the machining of wall thickness is good but can be improved.

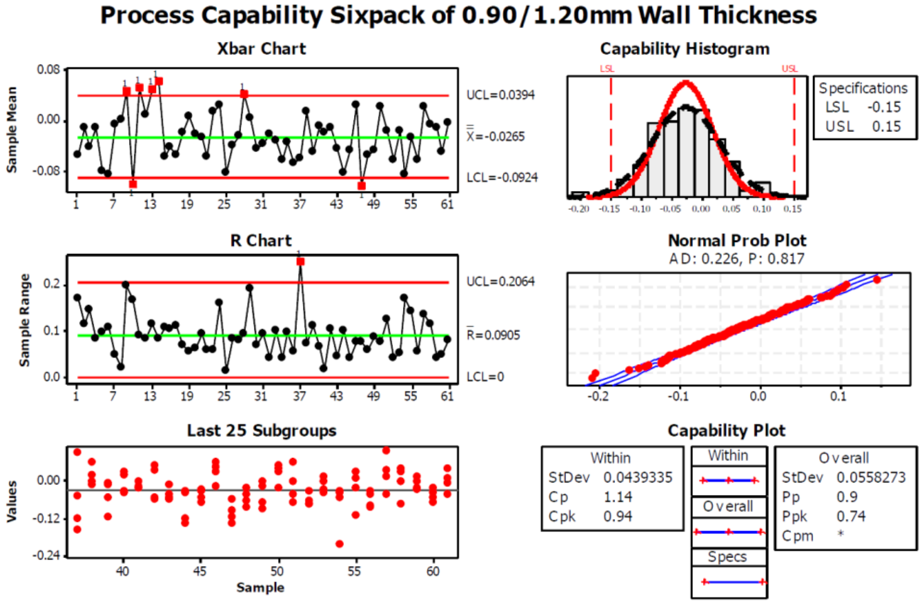


Figure 4-15: Process capability plots for combustor wall thickness - Product B

Figure 4-15 similarly shows good thickness capability for Product B, however in this case the process is less centred and there are several values which are out of tolerance. As the CMM inspection process involves taking several points around a section on a wall, in some cases a single reading will indicate that the product is out of tolerance. Hence, this often results in a product concession whereby, depending on size and location of the outlier, the product can proceed to the next manufacturing operation but at a reduced value.

Figure 4-16 and Figure 4-17 present capability plots for diameter dimensions for the same combustor walls.

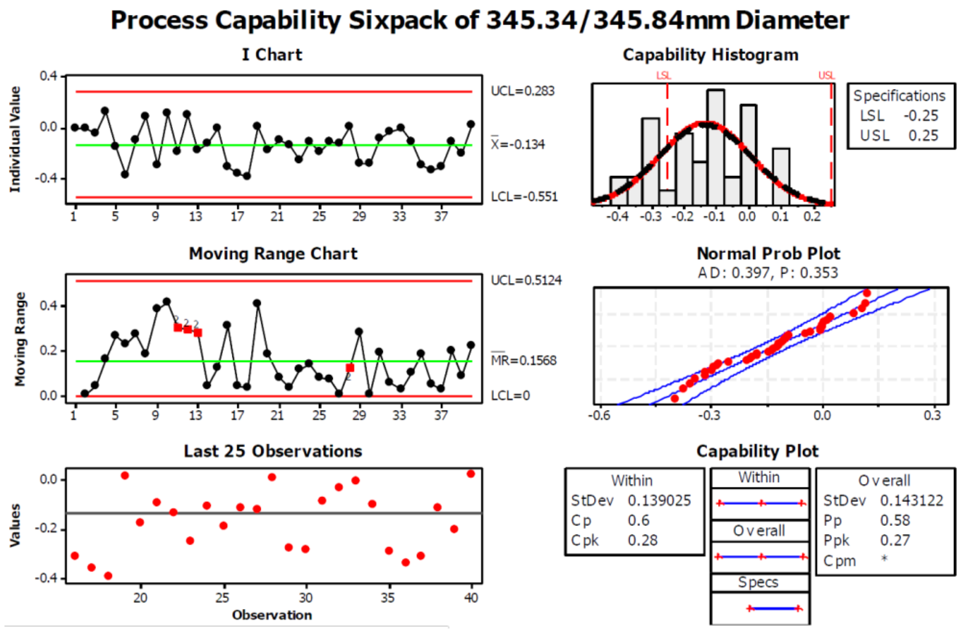


Figure 4-16: Process capability plots for combustor wall diameter - Product A

Figure 4-16 presents capability metrics for Product A diameter characteristics. As indicated by the ‘Capability Histogram’ and ‘Capability Plot’ the process is not centred and poor short-term and long-term capability values are calculated. On observation of the last 25 values taken there appears to be significant random variation in the manufacturing process.

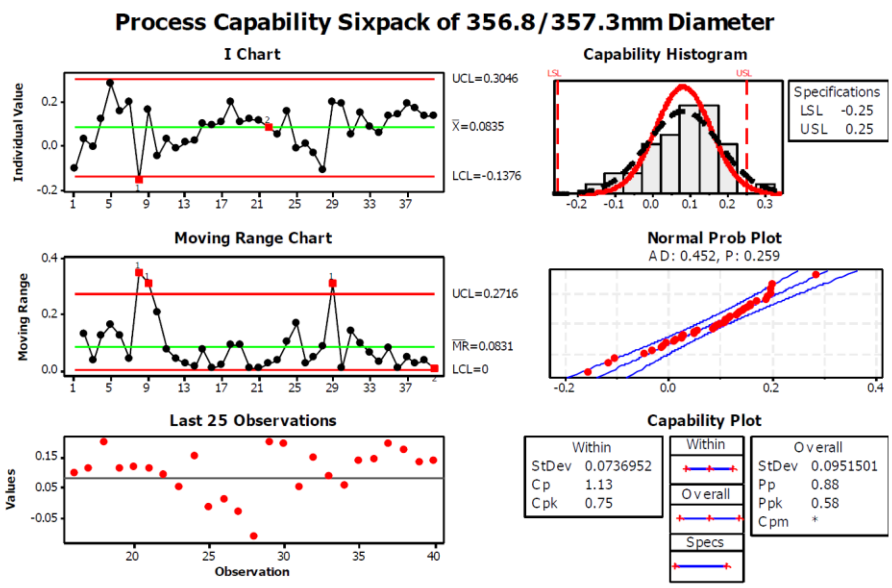


Figure 4-17: Process capability plots for combustor wall diameter Product B

Figure 4-17 presents process capability plots for Product B wall diameters. Here again the process is normal but not centred and, in this case, short-term capability is acceptable, but long-term and overall capability is poor.

Due to the nature of the manufacturing process, product diameters are calculated using wall thickness values. Therefore, inconsistencies in thickness values read across to the diameter results. As regular machine tool maintenance and calibration is being carried out, the machine condition is not considered as the primary source of this manufacturing variation. Therefore, the focus of this research work is to gain an understanding into the impact of on-machine diameter and thickness measurement.

4.9 Turning of combustor walls (manual intervention method)

Figure 4-18 shows a breakdown of the process for the machining of a typical combustor wall through the turning process. Where necessary a level of detail is added to highlight areas where manual intervention is required; through the use of in-process manual gauging and potential rework. It is proposed that these are the areas that are potentially causing the variation in the final product.

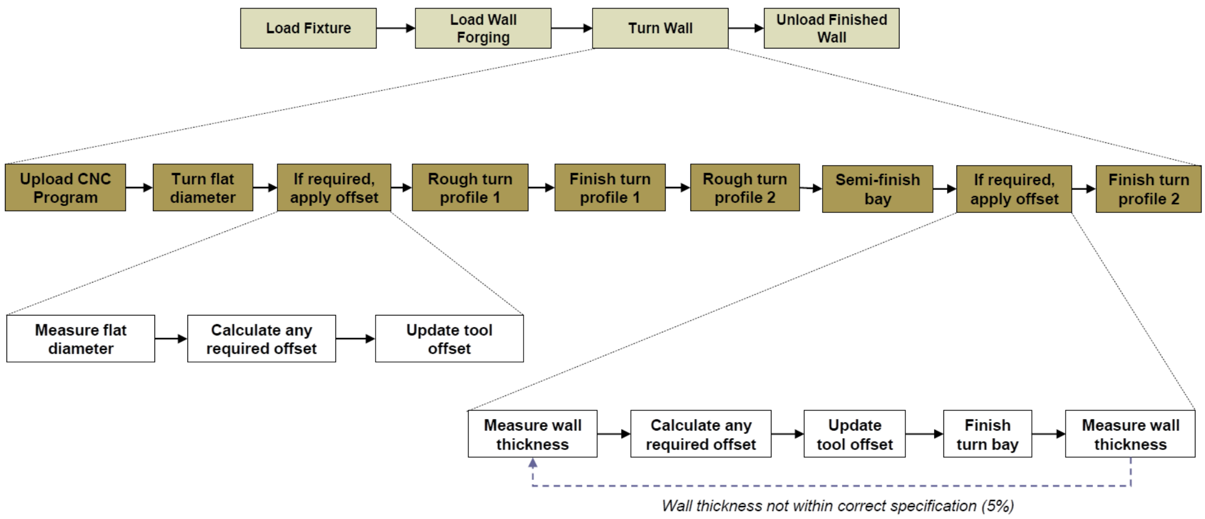


Figure 4-18: Process flow for measure-cut process for combustor wall machining

Figure 4-18 details the first measure cut process when turning a combustor wall. Firstly a flat diameter is turned in a defined place on the wall. It is then measured to a known size and any deviations from that size then make up the offset required.

The size of the diameter is defined in the CNC program. Once it is turned, the diameter is measured using a manual micrometer when turning an outside diameter and a manual stick micrometer when turning an inside diameter. The operator then calculates the required offset to complete the profile of the combustor wall and manually enters it via the CNC Human-Machine Interface (HMI). Difficultly arises as diameter is only measured and offset the machine in the X-axis; however, angled profiles require an offset in Z also (Figure 4-19).

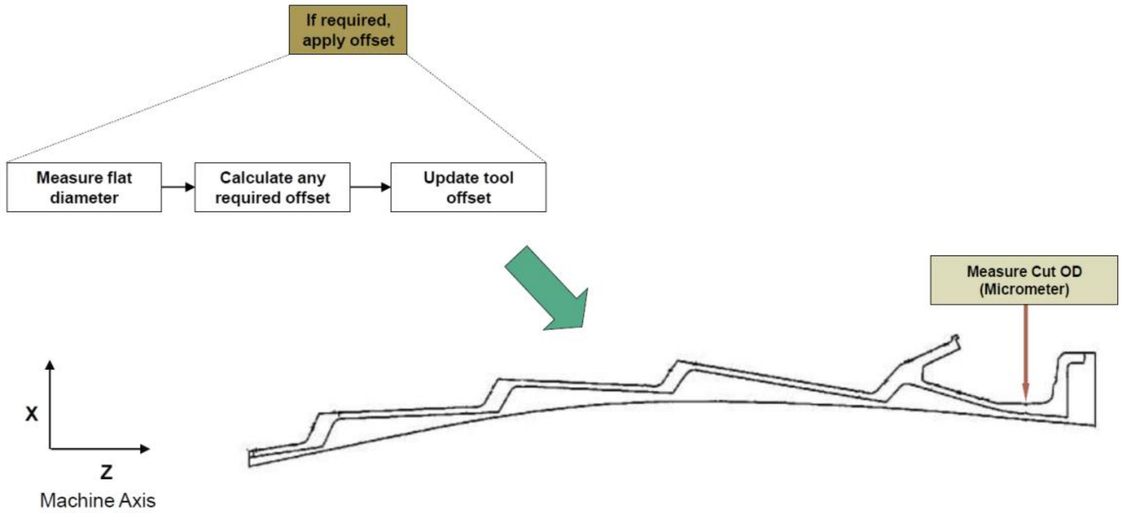


Figure 4-19: Measure-cut process issue

4.10 Failure modes in manual method

The next step was to carry out a cause and effect analysis for the current turning method. This was done over two facilitated workshop sessions involving machinery operators, inspectors and manufacturing engineers. Through these sessions all the potential factors that could introduce variation into the process were identified. Following this a process of identifying significant inputs was completed by grouping non-conforming features by category (i.e. thickness, diameters, length etc.). Here the process knowledge of the operators and inspectors was called upon.

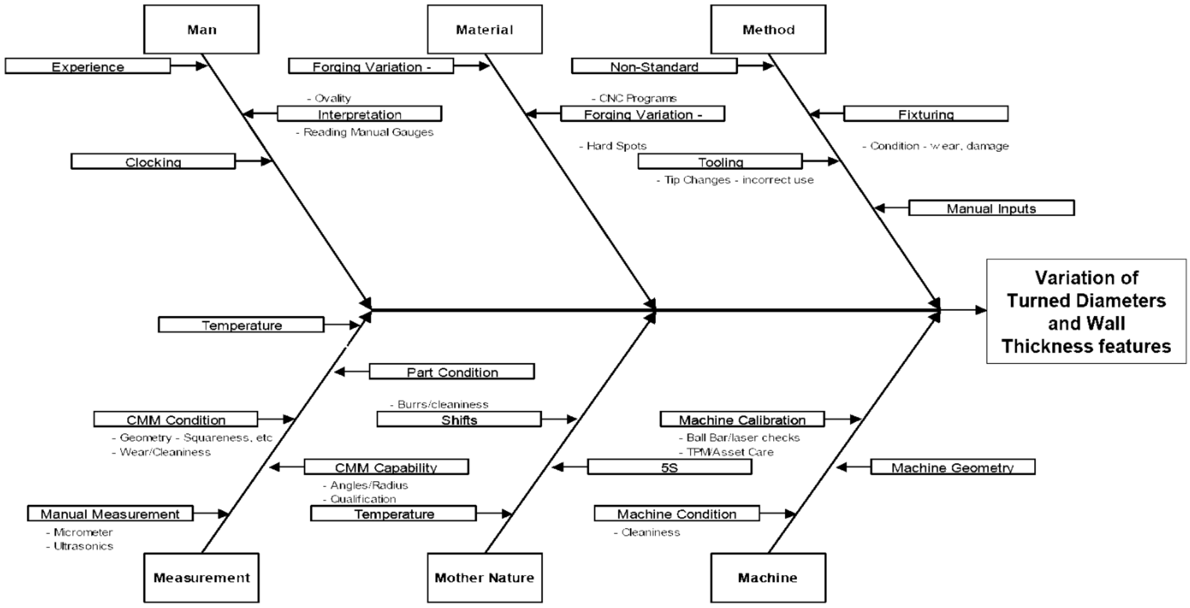


Figure 4-20: Ishikawa diagram illustrating common failure modes

The cause & effect diagram generated via the workshop sessions (Figure 4-20) identified the significant sources of variation with regards to the defined turning method. Subsequently a Process, Failure Mode Effects Analysis (PFMEA) was generated over four further workshop sessions. The PFMEA highlighted that the manual in-process measurement tasks using manual gauging are the most likely and most frequent sources of failure and had the highest impact on the turning process (Figure 4-21).

5	Carry out in-process checks with manual gauging	Incorrect Reading	Dimensional non-conformance	6	Reproducibility of using gauges	5	No control	7	210
				6	Gauge out of calibration	2	Calibration Control	1	12
				6	Mis-reading of gauge	5	Skilled training	3	90
			Scrap Part	7	Reproducibility of using gauges	5	No control	7	245
				7	Gauge out of calibration	2	Calibration Control	1	14
				7	Mis-reading of gauge	5	Skilled training	3	105

Figure 4-21: Snapshot of Process Failure Mode Effects Analysis for turning process

The researcher therefore chose to focus the rest of the study on the in-process manual gauging process and its substitution to on-machine probing methods.

4.11 Stakeholder engagement

In order to gain acceptance from the organisation that on-machine probing was a viable solution for eliminating manual measurement issues a stakeholder workshop event was held. During this workshop results from capability studies were presented as well as the run chart presented in Figure 4-22.

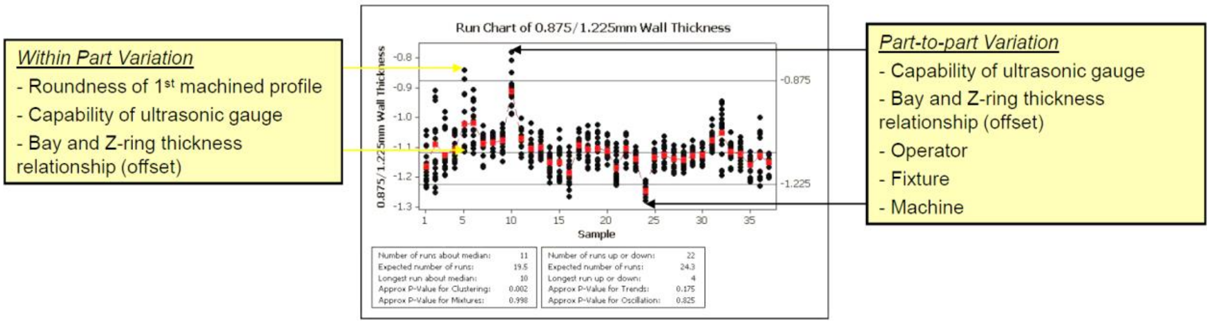


Figure 4-22: Process run chart for typical combustor bay thicknesses

Figure 4-22 plots the data of a typical wall thickness feature of a single product over time. It shows that variation can in some cases be as high as 90% of the tolerance, and the part-to-part variation can be significantly greater than the complete tolerance.

As a result of the analysis presented a stakeholder brainstorming session was held in order to establish the causes for the variation being observed. The two main factors identified were once again the capability of the manual gauging and the relationship of the bay and the Z-ring wall thickness when establishing any machine offset. These verified statements made in the PFMEA.

Issues such as changing over fixtures, swapping products between machines and different shifts also accounted for the other potential factors that would contribute to the variation seen. Therefore, these are the factors that directly affect the identified key process variables (KPVs) in the measure stage of diameter/thickness check (capability of ultrasonic gauging & Bay and Z-ring thickness relationship), concentricity & flatness (machine).

4.12 Removal of manual in-process measurements

In-process manual measurements have been demonstrated to have a direct impact on the outcome of the finished wall diameters. This is indicated by the gauge R&R studies and run charts as presented earlier in this Chapter. From this, the amount of the process variation attributed by the manual measurement system can be determined.

From the Gauge R&R carried out for the measurement system, the variance was calculated as 0.00317 (σ^2). For a typical wall diameter, the variance of the process was calculated as 0.0122. Therefore, the percentage of variance attributable to the gauging is (0.00317/0.0122) = 26%.

4.13 Bay and Z-ring relationship

The machining approach to a combustor wall consists of turning a bay and Z-ring together as one defined shape. Therefore when trying to define either the bay or the Z-ring, it directly effects the other. This is explained in Figure 4-23.

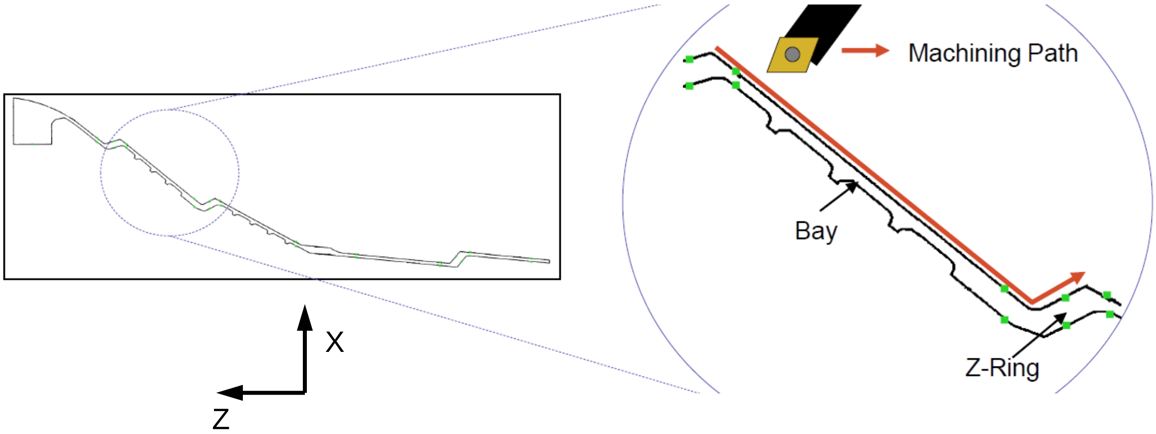


Figure 4-23: Bay and Z-ring relationship

As indicated by Figure 4-23 when measuring the component in-process with the ultra-sonic gauge, only the perpendicular to the component surface is measured. If a manual offset is inputted into the machine numerical controller to create the finish-cut offset the measurement result must be translated into X and Z machine axes movements. However, as indicated by Figure 4-24 if an offset is only made in one place, this results in a shortfall in the nominal size of the final component.

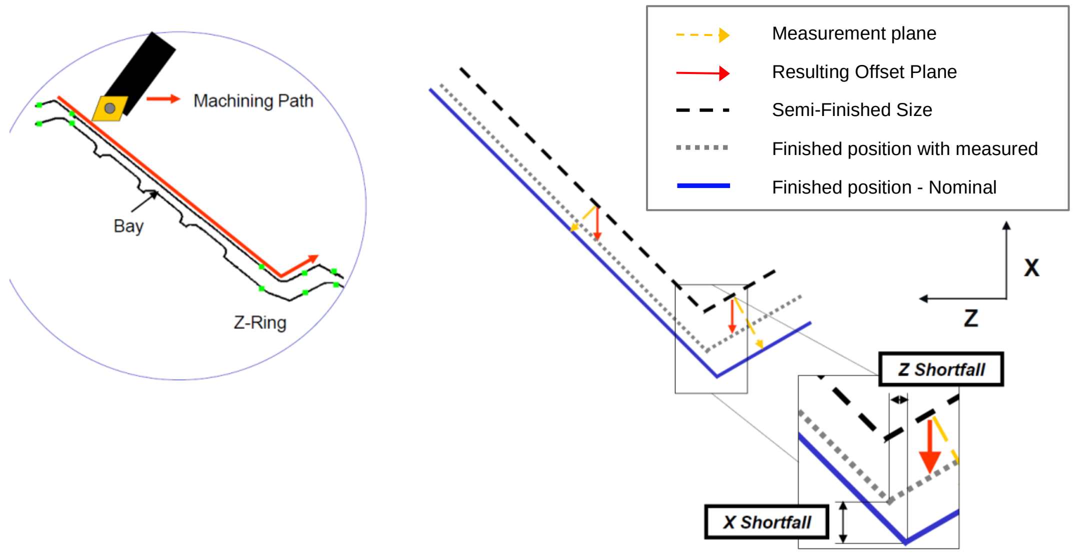


Figure 4-24: Bay and Z-ring relationship shortfall

4.14 Finish cut turning iterations

In order to overcome this difficulty, in translation of in-process measurement into machine offset, the operators will machine to finished size in incremental steps. Offsets in the machine will be made (usually in the X-axis) by approximately half the measured value. The section is then re-machined and then measured again. This process will continue until the machine operator believes they are as close to finish size as possible. This process therefore also involves many rework loops on each section. As expected, the process is highly susceptible to operator skill and therefore undoubtedly introduces a significant amount of variation.

In addition to this the turning of the 1st profile also causes problems. This is because this profile is turned using an X-axis machine offset. This offset has a direct effect on the angled surfaces of the component, as indicated by Figure 4-25.

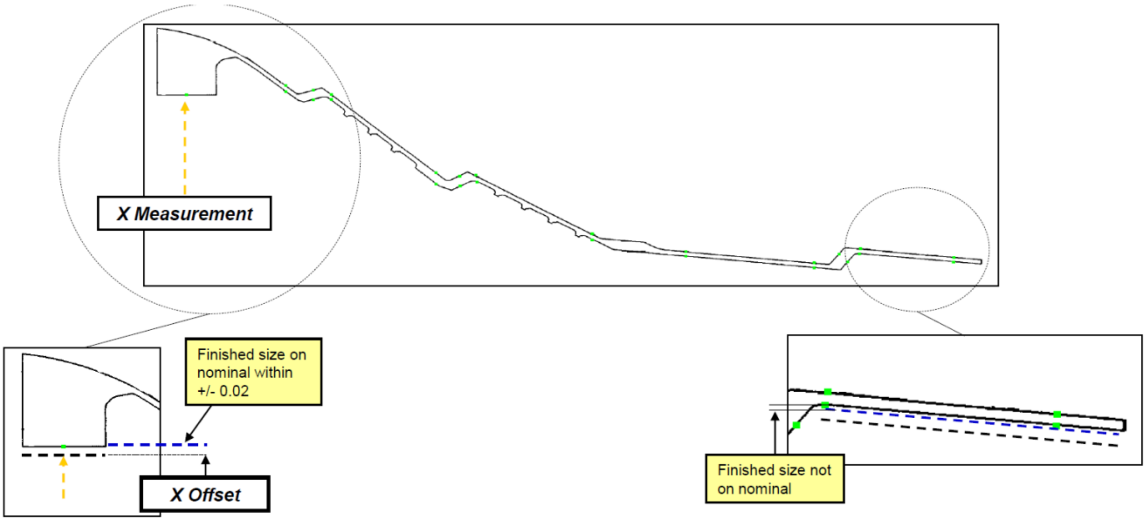


Figure 4-25: Issue with manual measure-cut iterative process

Figure 4-25 illustrates that the X axis measurement and offset error will have an effect on both the 1st and 2nd profile thicknesses. In addition to the complexity in defining the correct offset in X is that inconsistency in the machining of the 1st profile will cause eccentricity issues. As the wall thickness is not just determined by the first operation, but also by the operation that machined the first diameter. Therefore, for example, if Operation 1 machines a slightly out of round diameter then it is likely that Operation 2 will produce variation in wall section. This means that errors in Operation 2 may be introduced not by poor machining or poor measurement but by poor set up for Operation 2, or poor machining in Operation 1. This is illustrated by Figure 4-26

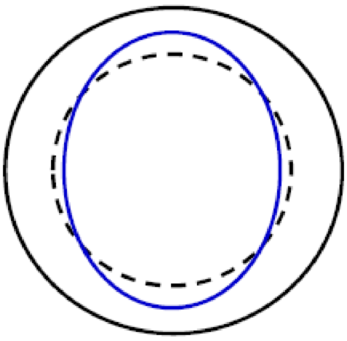


Figure 4-26: Eccentricity on the 1st profile can have an impact on thickness

The issue of eccentricity variation severely constrains the operator, in that they can only offset the machine by the smallest deviation, otherwise they run the risk of going undersized. As a result, this issue is a likely cause to the inconsistent wall thickness around a given bay and z-ring, as seen in results presented in earlier section of this chapter.

4.15 Need for automated on-machine inspection

The preceding sections have identified significant factors in the following two categories: 1) Method and 2) Measurement.

Further to this the PFMEA highlighted the in-process measurement operation as being the high-risk area for a potential failure to occur. Therefore, the focus of the root cause analysis was on the in-process measurement operation in terms of the method and the measurement equipment. The process variation was identified by analysis a series of run charts plotting the wall thicknesses and their corresponding diameters. These run charts showed significant amounts of part-to-part and within part variation.

4.16 In-process measurement via OMP – Method

The root cause analysis was split into two areas of focus: 1) The turning of the 1st profile; 2) The Bay & Z-ring relationship.

4.16.1 Turning of 1st Profile

It was found that on the turning of the 1st profile, the method involved only measuring one diameter and from that establishing an X offset for the whole of the profile. The main reason for this is that the rest of the profile is made up of several angled bays and therefore difficult to gain an accurate measurement using a manual micrometer. This meant that the offset being established was on a flat diameter and only in one axis (X axis). This results in a shortfall in finished size from nominal as illustrated in the previous section.

4.16.2 The Bay & Z-ring relationship

When finishing the 2nd profile to a defined wall thickness, it was found that trying to establish the exact offset required was difficult because the measuring was carried out in a different plane to that of the machine axis. To get the exact offset the operator would have to try and translate the measured value into a two-axis offset. This was further complicated due the angled nature of the bay and Z-ring, and therefore the method was significantly dependant on the operator skill level.

These two issues combined were identified as being the significant factors to the part-to-part variation and some of the within part variation that was seen in the run charts. These two major process issues can be eliminated by introducing on-machine probing.

4.17 Validation of hypothesis

4.17.1 X and Z-ring relationship

In order to establish the exact offset for any given bay and Z-ring, the relationship for the X & Z axes had to be determined. The first task is to try and visualise the interaction between the two axes for a given bay and Z-ring by modelling the component in Siemens NX Unigraphics [234]. The model allowed for the component to be shown in a semi-finish state and therefore also show how far away from nominal the component was. From this, for any given semi-finished condition, one could directly measure off the model, what the exact X & Z offsets should be.

From this it was concluded that the exact offsets were dependant on the interaction between the bay and the Z-ring and their respective angles. It was found that the bay and the z-ring should be treated as a fixed shaped, as dictated by the CNC machining strategy (Figure 4-27).

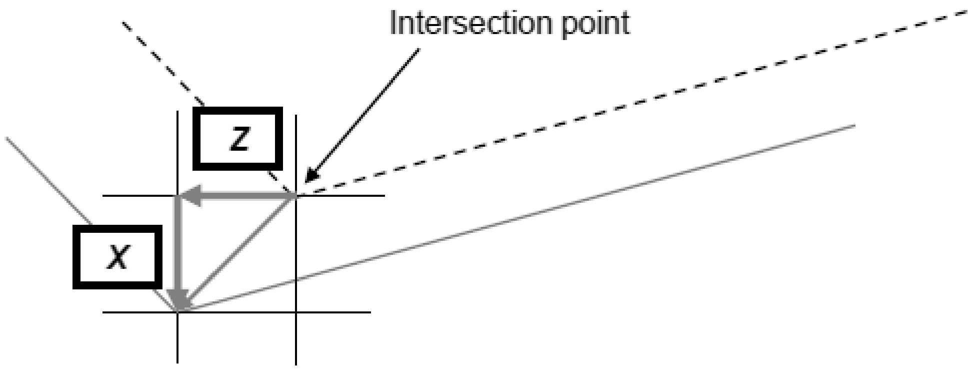


Figure 4-27: Intersection point calculation via Siemens Unigraphics

Figure 4-28 shows how the Z-ring and bay are modelled as two angled lines that intersect. From this intersection point one can then determine the required movement to the nominal position. This movement can then be translated into required movements in the X & Z axes. Therefore, what needs to be established is the position of the intersection point of the Z-ring and the bay. From this the nominal intersection point can be established, and then the offsets can be established.

To try and establish where the intersection point is, positional information about each of the bay and Z-ring is required. This information can be taken from the specified engineering drawing. This is shown in Figure 4-28; where the angular position of the Z-ring and bay and the diameter at a given gauge length can be determined.

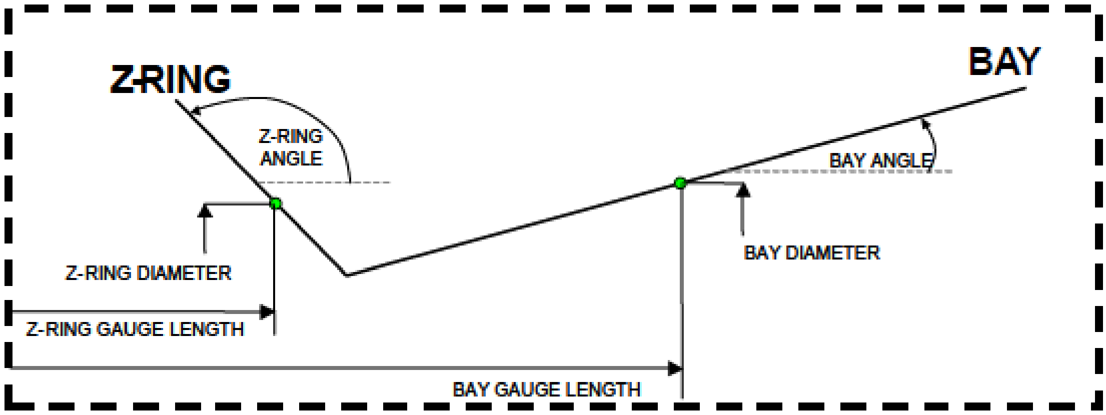


Figure 4-28: Z-ring and Bay angle intersection

4.17.2 The definition of the X and Z-ring relationship – establishing the exact two axis offset

To define the position of the intersection, point the bay and z-ring must be identified as individual lines. The path of each line can be determined by finding their equations. Each line will follow the standard equation:

$$y = mx + C \tag{1}$$

Figure 4-29 illustrates a part being overlaid on cartesian axes; this helps visualise how the required information to generate the equation of line for each of the bays and z-rings can be established.

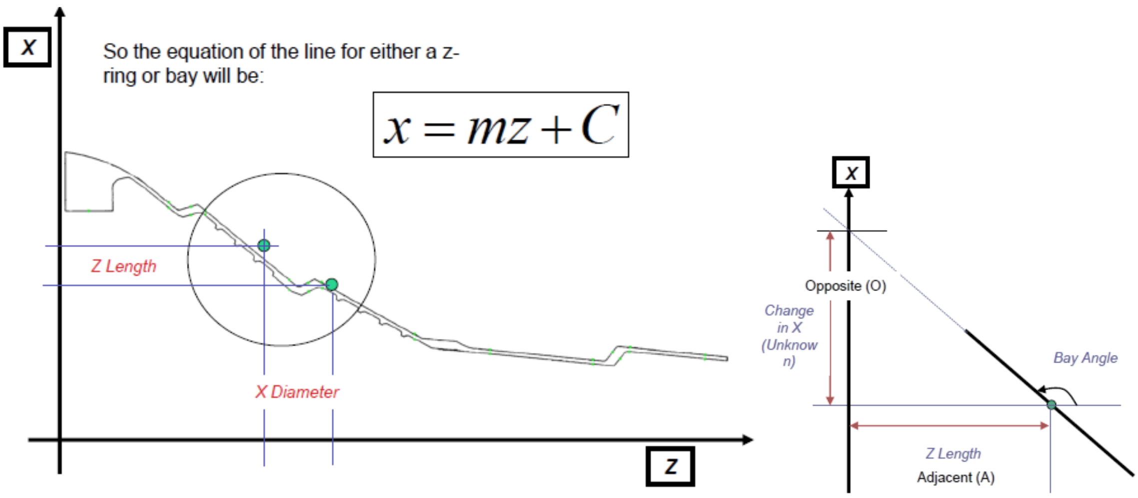


Figure 4-29: Z-ring to Bay linear equation

Therefore, the first stage is to establish the gradient of each of the two lines. With the known intersection point and angle of the line, the following right-angled triangle, as shown in Figure 4-29, can be constructed. From this using the following equation the unknown length X is calculated:

$$\Delta O = \tan(BayAngle) \cdot A_{z-length} \quad (2)$$

Hence the gradient is:

$$m = \frac{\Delta O}{A_{z-length}} \quad (3)$$

Once the gradients for each of the lines have been calculated, one can then establish C (constant), when X is equal to zero, i.e. the Y-intercept:

$$C_{x-intercept} = X_{diameter} + \Delta O \quad (4)$$

Therefore, solving for X:

$$X = \left(\frac{\Delta O}{A_{z-length}}\right) \cdot z + (X_{diameter} + \Delta O) \quad (5)$$

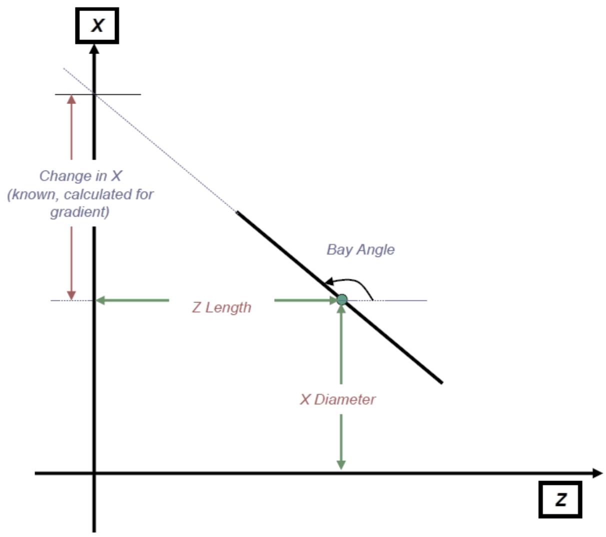


Figure 4-30: Solving Bay angle Z-ring relationship linear equation

With the equation of the line for the bay and the Z-ring then their intersection point needs calculating. In order to calculate the intersection point, the two lines can be solved simultaneously. This will then give the X and Z positions of the intersection point (Figure 4-31):

$$m_{z-ring} \cdot z + C_{z-ring} = m_{bay} \cdot z + C_{bay} \tag{6}$$

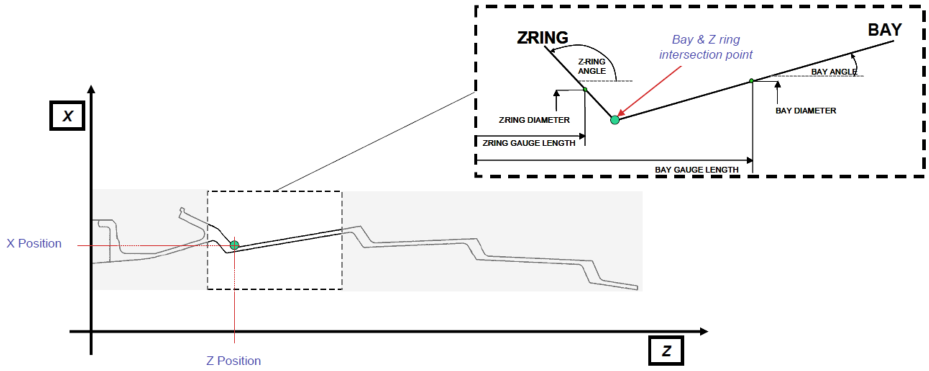


Figure 4-31: Bay- and Z-ring intersection point calculation

To subsequently solve for z, to establish both the z and x offset required for the finish cut:

$$z = \frac{(C_{bay} - C_{z-ring})}{(m_{z-ring} - m_{bay})} \tag{7}$$

And substitute into (1) to solve for x:

$$x = m_{bay} \cdot \left(\frac{(C_{bay} - C_{z-ring})}{(m_{z-ring} - m_{bay})} \right) + C_{bay} \tag{8}$$

Having now established the x and z positions for the intersection point of a given Z-ring and bay combination. The exact x and z offsets for any given z-ring and bay combination can now be established. Therefore, machinists can now take a semi-finish cut, followed by an in-process measurement utilising an on-machine probe and subsequently automatically calculate and implement the exact x-axis and z-axis offset to complete the finish cut (Figure 4-32).

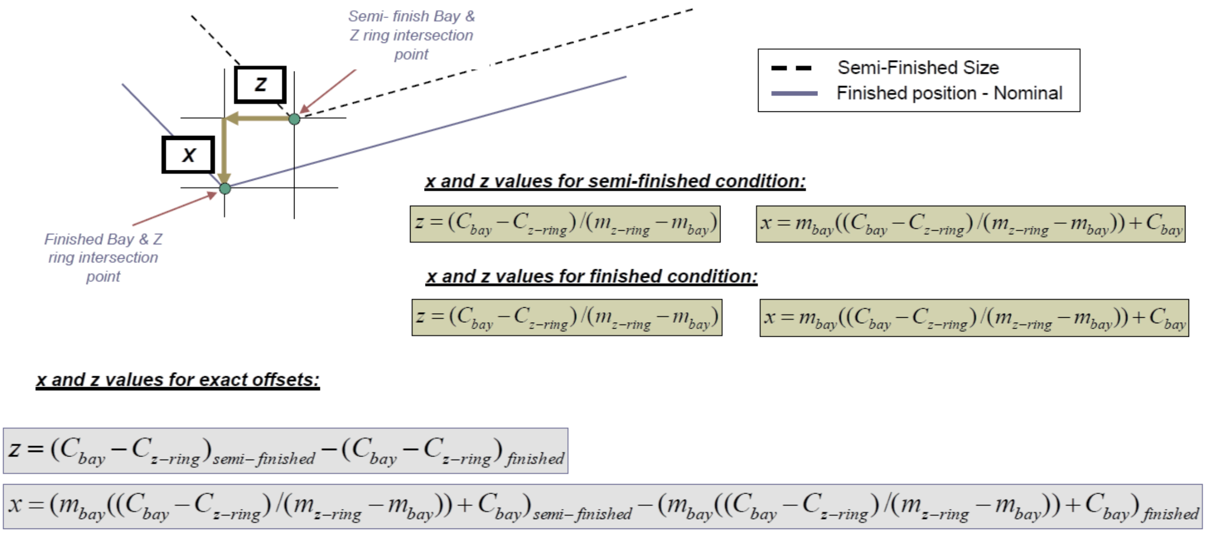


Figure 4-32: Automatic calculation of x-axis and z-axis offset for finish cut with OMP

4.18 Implemented solution

When looking at new methods of manufacture, it was decided, as a result of the current poor capability of the current in-process measurement equipment, that any new method would include a significantly more capable means of in-process measurement. This would not only allow one to reduce the amount of variation attributed to measurement but also provide one the capability to accurately measure diameters on angled bays and Z-rings.

A Renishaw OMP in-cycle probing system was selected and installed into the machine to perform in-process measurements. However, the gauge repeatability and reproducibility still had to be established. A gauge R&R was subsequently installed carried out on the probing system (Figure 4-33).

Gage R&R

		Study Var	%Study Var
Source	StdDev (SD)	(6 * SD)	(%SV)
Total Gage R&R	**0.0016813**	**0.010088**	**1.83**
Repeatability	0.0016813	0.010088	1.83
Part-To-Part	**0.0920179**	**0.552108**	**99.98**
Total Variation	0.0920333	0.552200	100.00

Number of Distinct Categories = 77

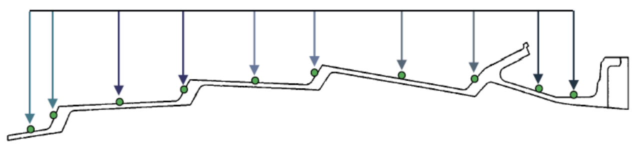


Figure 4-33: On-machine probing Gauge R&R

Figure 4-33 presents a summary of the gauge R&R carried out on the probing system. It shows that when using the probe to measure on angled planes on the part, the probe has a total gauge repeatability of approximately 2%. Therefore, it was decided that the probing system provides the capability of measuring the required diameters on the component to the required accuracy.

4.19 New method of manufacture – OMP system

With the introduction of an on-machine probing system a number of new processes needed to be introduced into the manufacturing process. These were:

1. Qualification of the probe

The qualification of the probe was highlighted as being the critical step in implementing a probing solution. This is because this is the process which establishes the position of the probe in relation to the machine axis zero.

2. Machining strategy change

As the prospect of using a probing system would give us a greater capability in terms of measurement, the current machining approach would be redundant.

3. Automatic calculation of offsets

In terms of addressing the root cause of the non-conformance, this step would integrate the worked-out calculation from the analyse stage into the probing solution.

4. Control of machining system

The measures and controls that must be put in place to sustain the process are crucial. Therefore, the identification of these, based on the above actions, is essential to ensure a production ready process.

4.20 Qualification of the probe

The qualification of the probe within the machine was highlighted as being the most important task to get right. This is where the probe’s position in relation to machine zero is established. Through the session, it was identified that three key values had to be established and verified against:

- X Position
- Z Position
- Electronic Probe Size

In order to qualify the probe and identify these values, an artefact was required. Through a series of trials, it was decided that such an artefact would be part of the fixture. As there are two machined profiles per part, there would be two sets of features on the fixture. These features would create the datum for the qualification of the probe, and therefore establish the probes position in respect to the machine zero (Figure 4-34).

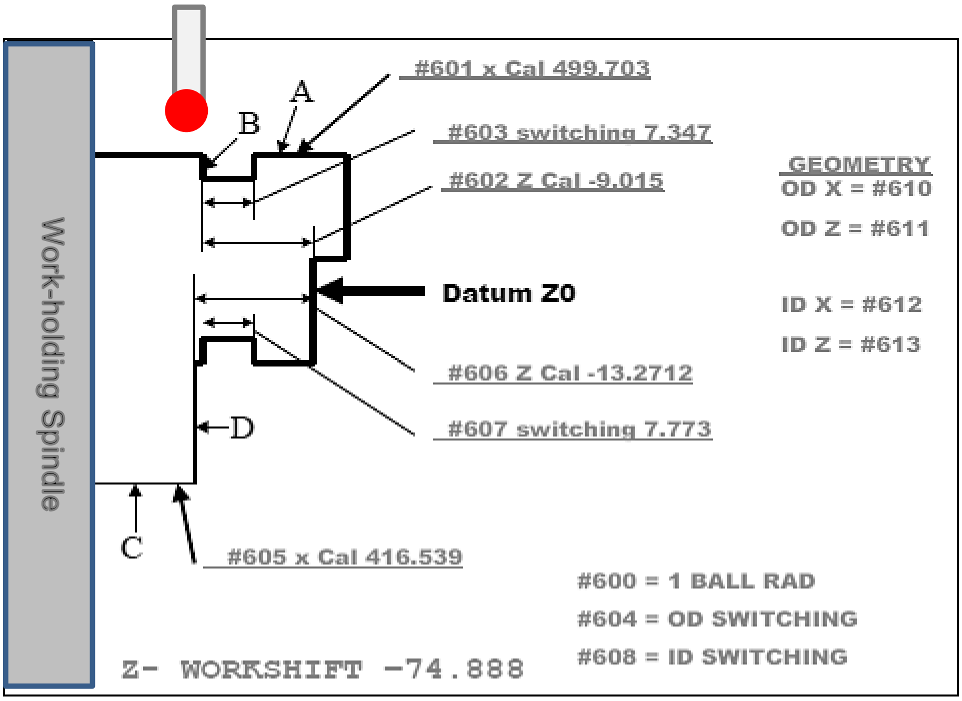


Figure 4-34: Probing qualification artefact integrated in workholding fixture

Figure 4-34 shows the probe set-up and measurement strategy, where:

A – X Calibration Diameter (Outer Profile)

B – Z Calibration Length (Outer Profile)

C – X Calibration Diameter (Inner Profile)

D – Z Calibration Length (Inner Profile)

The electronic size of the probe is also calculated by using the groove feature (Figure 4-34), this is extremely important when using a probe to measure on angled surfaces. The electronic size is the effective size of the probe stylus ruby, allowing compensation for delays between the trigger moment, bending of the stylus and the processing time.

In order to prove the repeatability of the calibration process, a repeatability study was carried out and showed that the probe was repeatable to within 9 microns in the X axis and 5 microns in the Z axis (Table 4-2). This is no more than 1/10th of the tightest tolerance being measured.

Table 4-2: On-machine probe repeatability testing

Run	Calibration Type			
	8 Points + Highest & Lowest Error		8 Points	
	X	Z	X	Z
1	0.040	0.037	0.097	0.060
2	0.038	0.034	0.091	0.060
3	0.037	0.030	0.091	0.058
4	0.035	0.025	0.089	0.057
5			0.089	0.056
6			0.088	0.055

4.21 Machining strategy change

In order to include the probing measurement cycles within the CNC program, a change in machining strategy was required. Currently the process involves turning the 1st profile using a single offset from a measure cut and then finishing the 2nd profile to a thickness requirement using an ultrasonic gauge. However in order to include the new on-machine probing, both profiles will be machined by bay and Z-ring section to given diameters, and as result the thickness requirements will be achieved.

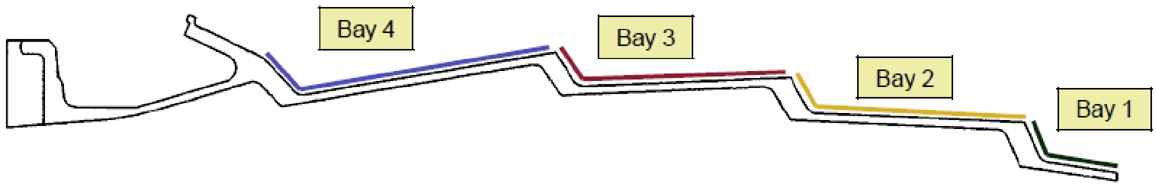


Figure 4-35: New measurement strategy driven by on-machine probing

Figure 4-35 shows how each wall will be broken down into the sections. These sections will then be machined to a semi-finished condition. The probe will then be used to measure the position of each section. Using the measurement information from the probe an offset will be calculated and finally the section will be finish- machined to required dimensions.

As a result of adopting this machining strategy and the inclusion of calculating exact offsets, the requirement for rework is removed. Hence, a section is semi-finished and then finished in two steps. This is a significant improvement, in comparison to the previous method, where previously on average 3-5 attempts were required. This due to not being able to accurately calculate the offsets, as such, the finished size could only be formed gradually.

4.22 Probing strategy – automatic offsetting

Once the machining strategy has been established, the next step was to include the probing routines. Through several development trials, it was decided that the probing routines would be included as part of the CNC program. This would allow for the offset calculation to be also included as part of the CNC program.

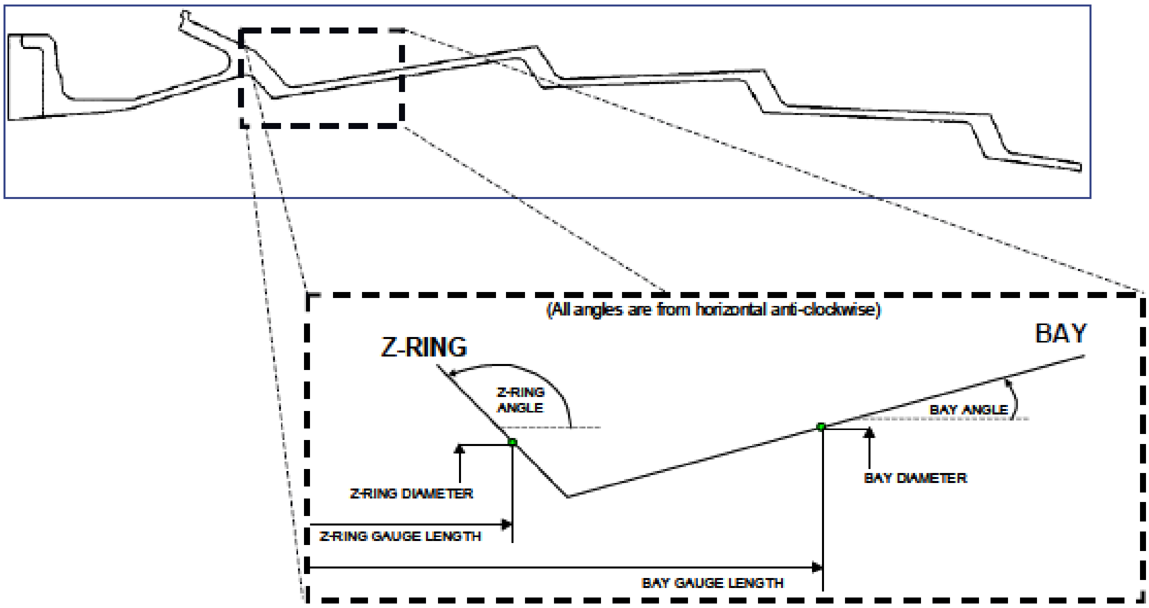
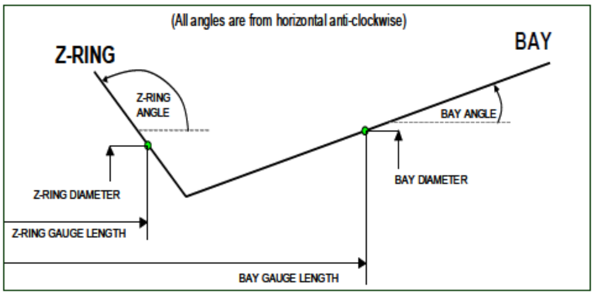


Figure 4-36: Automatic offsetting using OMP

The diagram above shows the two measurement points required to calculate the required offsets. The two diameters, one on the z-ring and the other on the bay, will provide enough information for the offset calculation to be used. In order to incorporate the measurement routines and offset calculations in the CNC programs, several programming trials were carried out in order to establish if the machine's CNC controller had the capability to do so.

The trials that were carried out were based around creating custom macros that would contain the probing cycles and then using that measurement information and running it through the calculations. The trials proved to be successful, the custom NC-codes used the controller's macro variables to store the measurement information and the calculation would pull the information from these macros Figure 4-38.



Part Profile:	
z-ring STOCK gauge point Dia	588.4776
Bay STOCK gauge point Dia	580.0868
Z-ring Length	118
Bay Gauge Point Length	136.42
z-ring angle	119.75
Bay Angle	357.709
Stock on Profile:	
Z-ring stock in x on dia	0.15
Bay stock in x on dia	0.3
Measured z-ring gauge point Dia	588.6853
Measured Bay gauge point Dia	580.2572
Offsets to nominal:	
z Offset	-0.010909
x Offset	-0.169477

Z-ring Line:	y value	-206.4572	120
	Gradient	-1.749637	121
Bay Line	y value	-5.45773	122
	Gradient	-0.040007	123
Intersection Point in z	122.47692		124
Intersection Point in x	580.64462	580.6446	125
Intersection Point in z	122.49874		126
Intersection Point in x	580.8141	580.8141	127

Variables	Macro		Calculations
Z ring measured Dia	118	=	Probe measured Diameter
Bay measured Dia	119	=	Probe measured Diameter
Z ring y value	120	=	(Z-ring Gauge Point Length*(TAN[Z-ring Angle])
Z ring Gradient	121	=	120/Z-ring Gauge Point Length
Bay y value	122	=	(Bay Gauge Point Length*(TAN[Bay Angle])
Bay Gradient	123	=	122/Bay Gauge Point Length
Part Intersect z	124	=	((Bay STOCK Gauge Point Dia-122)-(Z-ring STOCK Gauge Point Dia-120))/(121-123)
Part Intersect x	125	=	(123*124)+((Bay STOCK Gauge Point Dia-122))
Stock Intersect z	126	=	((119-122)-(118-120))/(121-123)
Stock Intersect x	127	=	(123*126)+(119-122)
Z Offset	128	=	(124 - 126)/2
X Offset	129	=	125 - 127

```
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#122=[165*[TAN[173.991]]]
#123=#122/165
#124=[[[344.8337-#122]-[341.6203-#120]]/[#121-#123]]
#125=[[#123*#124]+[344.8337-#122]]
#126=[[[#711-#122]-[#713-#120]]/[#121-#123]]
#127=[[#123*#126]+[#711-#122]]
#2106=[#124-#126]/2
#2006=#125-#127
```

Figure 4-37: Custom macros created to combine probing and offset calculations

Therefore, using the macro variables as storage for all the values that are measured and calculated, provides the ability to: 1) automatically update the tool offsets and 2) monitor the measured values and control them as input variables.

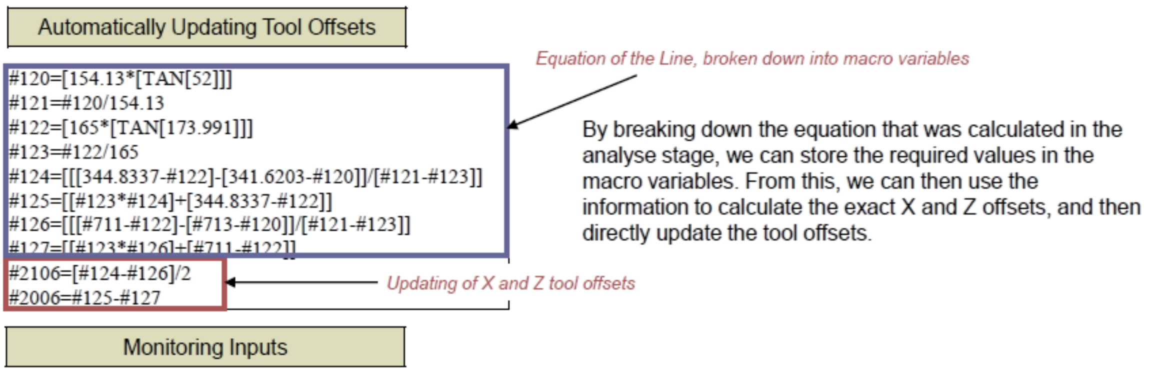


Figure 4-38: G-code sample for finish cut tool offset

4.23 Control of the manufacturing system

Figure 4-39 illustrates a table where all the probe measurement data and subsequent offset are recorded and monitored. By monitoring this information, machine maintainers can identify when a machine needs checking, a tip has not been correctly inserted or the Automatic Tool Setting Unit (ATSU) requires recalibrating. All these possible actions make up the overall control plan.

Probe & Machine																								
Part	Calibration		Bay - Hook					Bay - 1					Bay - 2				Bay - 3				Bay - 4			
			0.25 Stock Offset (Tool 9)			Finished Size		Offset Tool 10	0.25 Stock Offset (Tool 3)		Finished Size		0.25 Stock Offset (Tool 3)		Finished Size		0.25 Stock Offset (Tool 3)		Finished Size		0.25 Stock Offset (Tool 3)		Finished Size	
	X	Z	X (Mic)	X	Z	Z (118)	X (119	Z	X	Z	Z (118)	X (119)	X	Z	Z (118)	X (119)	X	Z	Z (118)	X (119)	X	Z	Z (118)	X (119
HU0437756	0.073	0.047	-0.100	-0.116	0.010	-0.007	0.029		-0.115	0.019	0.063	0.008	-0.169	-0.011	0.010	0.029	-0.191	-0.006	0.011	0.024	-0.165	-0.040	0.021	0.021
HU0437755	-0.003	-0.003	-0.080	-0.078	0.041	-0.002	0.000		-0.069	0.078	0.022	0.007	-0.037	0.057	0.001	0.012	-0.115	0.071	0.086	0.028	-0.116	0.046	0.026	0.026
HU0438048	-0.004	0.001	-0.090	-0.114	0.044	0.008	-0.001		-0.087	0.038	-0.005	0.080	-0.147	0.009	0.047	0.003	-0.177	0.029	-0.001	0.008	-0.205	-0.014	0.008	0.029
HU0439596	0.019	0.025	-0.110	-0.136	0.035	0.016	0.002	0.008	-0.010	0.051	0.018	0.001	0.001	0.069	0.050	0.032	-0.021	0.062	0.016	0.040	-0.021	0.049	0.011	0.029
HU0439632	0.020	0.028	-0.070	-0.095	0.049	0.023	0.008	0.017	-0.061	-0.035	0.010	0.011	-0.093	-0.018	0.035	0.016	-0.134	0.005	0.003	0.020	-0.074	0.000	0.019	0.036

Figure 4-39: Recording and monitoring of tool offset data

In terms of sustaining this new process intervention a ‘measurement matrix’ was constructed (Figure 4-40). This matrix mapped out the requirements for continuous monitoring and optimisation of the OMP system.

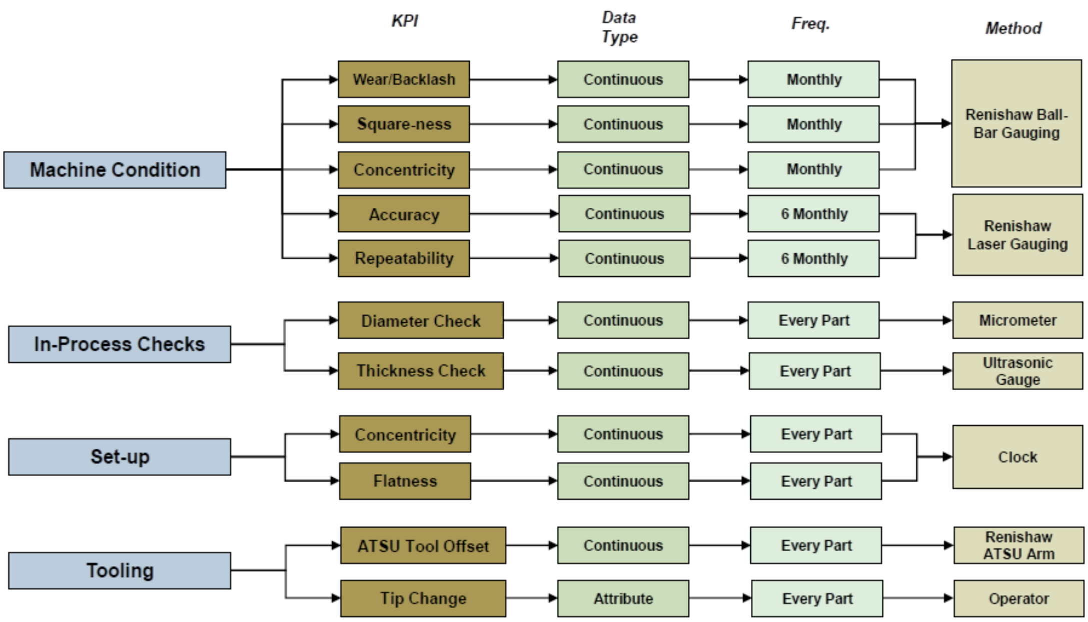


Figure 4-40: ‘Measurement matrix’ for new process

As the probing system had developed into a closed looped system, the control phase of the system was one of the most important issues to be addressed.

4.24 Results & Conclusions

The initial trials consisted of only turning one profile of a combustor wall using the probing and finishing the other profile using the ultrasonic gauging. This method was used to prove out all the steps and the capability of the new OMP offsetting process.

Figure 4-41 presents results from a correlation study carried out between the probe results and the CMM, the variation between the results seen was put down to the part being restrained whilst being probed and unrestrained whilst being CMM. In order to prove this, a series of studies were performed where component walls were scanned to understand how out of round they were. It was found that the out of roundness values were up to 0.15mm different between the two measurement systems. Based on product tolerances the difference between the CMM and OMI results was deemed as acceptable.

Part 1			Part 2			Part 3		
CMM Error	Probe Error	Difference	CMM Error	Probe Error	Difference	CMM Error	Probe Error	Difference
-0.010	0.023	-0.033	-0.008	0.029	-0.037	-0.027	-0.011	-0.016
0.244	0.249	-0.005	0.248	0.265	-0.017	0.244	0.227	0.017
0.608	0.679	-0.071	0.590	0.673	-0.083	0.511	0.655	-0.144
0.343	0.438	-0.095	0.208	0.304	-0.096	0.215	0.321	-0.107
0.715	0.829	-0.114	0.724	0.803	-0.079	0.717	0.868	-0.151
0.299	0.381	-0.082	0.220	0.315	-0.096	0.229	0.333	-0.105
0.782	0.878	-0.096	0.913	1.011	-0.098	0.872	0.999	-0.127
0.246	0.326	-0.081	0.162	0.286	-0.124	0.178	0.307	-0.130
1.051	1.039	0.012	1.136	1.276	-0.140	1.163	1.282	-0.119
0.229	0.354	-0.125	0.004	0.180	-0.177	0.099	0.183	-0.085

Figure 4-41: Correlation between CMM results and OMI results for combustor wall inspection

Figure 4-42 presents the diameter results of the first 3 off walls turned completely using in-cycle probing. All the features on the part were 100% conforming. This demonstrates that the introduction of on-machine probing, as part of a holistic intervention, has been successful.

562.01/562.81mm Diameter At Gauge Height Of 161.42	DIAMETER	0.258	0.329	0.363	0.343	0.3	0.37	0.216	0.141	0.157	0.208	0.338	0.141	0.006	-0.051	-0.07	-0.071	-0.123
564.33/565.13mm Diameter At Gauge Height Of 153.42	DIAMETER	0.246	0.319	0.33	0.351	0.265	0.319	0.224	0.045	0.185	0.225	0.304	0.066	0.067	-0.07	-0.137	-0.112	-0.158
576.22/577.02mm Diameter At Gauge Height Of 143.42	DIAMETER	0.254	0.386	0.413	0.32	0.312	0.362	0.229	0.209	0.349	0.296	0.309	0.272	-0.018	0.098	0.035	0.039	0.05
576.24/577.04mm Diameter At Gauge Height Of 7.92	DIAMETER	0.286	0.427	0.31	0.266	0.276	0.175	0.214	0.369	0.262	0.333	0.109	0.213	0.138	0.20	0.079	0.068	0.09
576.98/577.78mm Diameter At Gauge Height Of 12.42	DIAMETER	0.273	0.416	0.291	0.269	0.27	0.17	0.203	0.368	0.258	0.33	0.117	0.202	0.103	0.1	0.041	0.028	0.062
577.94/578.74mm Diameter At Gauge Height Of 121.92	DIAMETER	0.197	0.344	0.365	0.254	0.275	0.314	0.17	0.201	0.261	0.214	0.26	0.188	-0.023	0.006	0.023	-0.047	-0.032
581.60/582.00mm Diameter In View AU	DIAMETER	0.019	0.044	0.078	-0.001	0.021	0.033	0.007	-0.027	-0.019	-0.041	0.08	0.009	0.048	0.01	-0.001	-0.014	-0.018
583.70/584.50mm Diameter At Gauge Height Of 27.42	DIAMETER	0.205	0.347	0.198	0.171	0.18	0.088	0.104	0.302	0.184	0.233	0.071	0.165	0.04	0.12	-0.019	-0.032	-0.012
583.82/584.62mm Diameter At Gauge Height Of 46.42	DIAMETER	0.299	0.501	0.39	0.331	0.366	0.323	0.2	0.443	0.409	0.5	0.294	0.347	0.034	0.19	0.066	-0.005	0.019
586.11/586.91mm Diameter At Gauge Height Of 86.92	DIAMETER	0.21	0.425	0.422	0.252	0.365	0.306	0.323	0.366	0.254	0.351	0.249	0.246	0.045	0.09	0.074	-0.018	0.002
588.16/588.96mm Diameter At Gauge Height Of 108.42	DIAMETER	0.21	0.415	0.398	0.27	0.341	0.32	0.276	0.362	0.252	0.361	0.26	0.268	0.023	0.076	0.046	-0.028	-0.017
592.39/593.19mm Diameter At Gauge Height Of 71.42	DIAMETER	0.265	0.441	0.37	0.279	0.313	0.301	0.132	0.376	0.318	0.449	0.248	0.306	0.002	0.13	0.016	-0.044	-0.013
598.04/598.84mm External Diameter At Gauge Height Of 36.42	DIAMETER	-0.053	0.098	0.254	-0.015	0.011	0.104	-0.094	0.019	0.061	0.045	0.022	0.05	-0.062	-0.01	-0.1	-0.043	-0.032
601.50mm External Diameter	DIAMETER	-0.157	-0.001	-0.062	-0.068	-0.08	-0.041	-0.086	-0.104	-0.211	-0.172	0.011	-0.033	-0.06	0.00	-0.103	-0.034	-0.007
604.57/605.37mm External Diameter At Gauge Height Of 29.42	DIAMETER	-0.041	0.147	0.303	0.034	0.048	0.133	-0.047	0.071	0.1	0.101	0.048	0.069	-0.048	0.03	-0.096	-0.039	-0.037

All 3 components 100% RFT

Figure 4-42: Diameter results of the first 3 off walls turned completely after the in-cycle probing system has been implemented

Once this was established, a plan was put together to roll out the probing technology across the three remaining part numbers within the cell and then the remainder of the machines in the cell.

4.25 Time savings

Along with the improvement in quality, the need for rework was also eliminated and therefore achieved the cost benefits highlighted in the ‘Define’ stage. The process also removed the significant reliance on the operator and therefore provided the opportunity to multi-man machines. The new process involving the usage of on-machine probing devices is indicated by Figure 4-43.

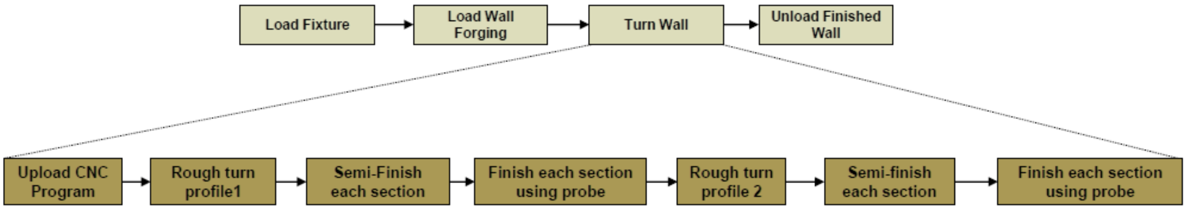


Figure 4-43: New machining process flow incorporating OMI

Figure 4-44 presents a capability of the improvements seen on a typical thickness feature before and after OMI intervention was made.

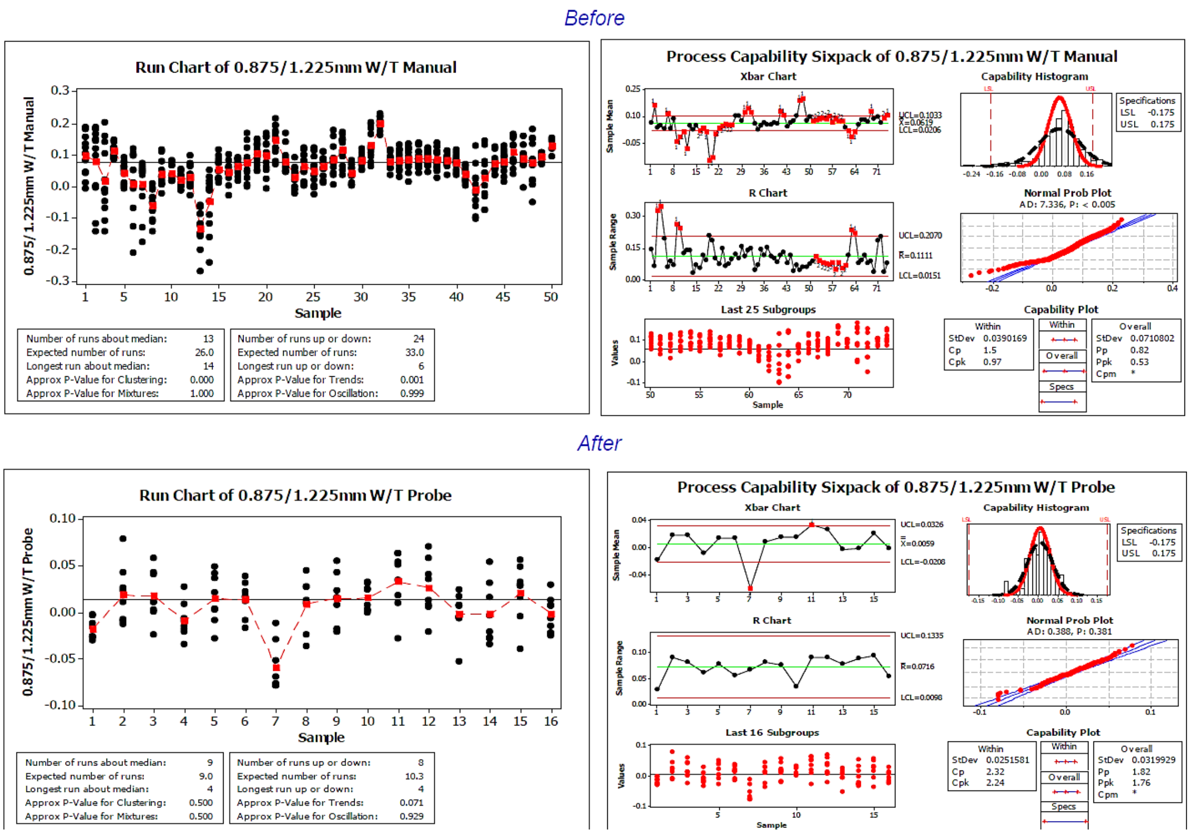


Figure 4-44: Capability on thickness – Before and After OMI intervention

Figure 4-44 shows an improvement of Cp and Cpk from 1.5 and 0.97 respectively to 2.32 and 2.24. As can be seen, variation has been reduced significantly.

Similarly Figure 4-45 shows a summary of the improvements seen on a typical diameter feature.

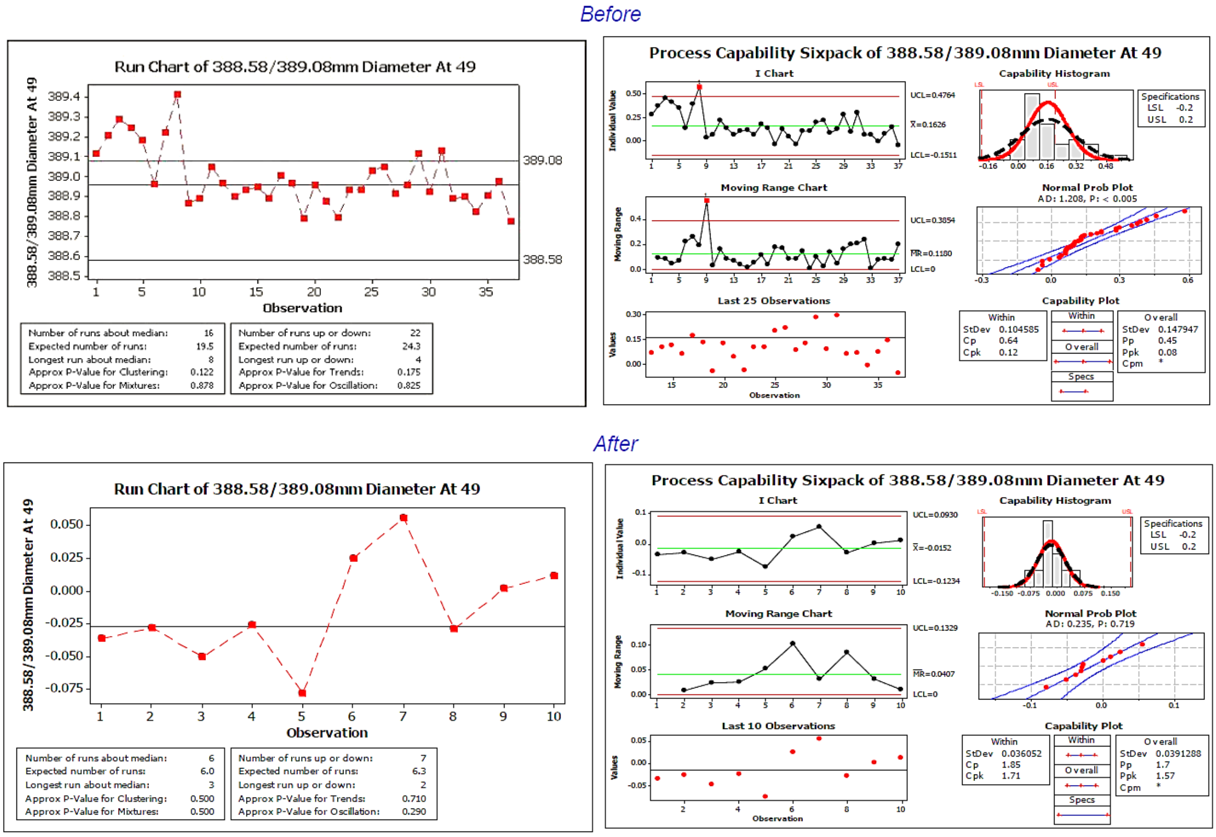


Figure 4-45: Capability on diameter – Before and After OMI intervention

Figure 4-45 shows capability improvements were made from a before Cp = 0.64, Cpk = 0.12 to after: Cp = 1.85, Cpk = 1.71.

Additionally Table 4-3 indicates the improvement in terms of average non-conforming features, post implementation of on machine probing. Here the average number of features that are non-conforming per part drops from over 2 to less than 0.7 at worst case.

Table 4-3: Product RFT after OMI intervention

Parts through turning machines (After in-cycle probing)					
Part No.	Conforming	Non-conforming	Total	Part RFT	Average Non-conforming features per part
Product A	22	1	23	95.65%	0.310
Product B	61	5	66	92.42%	0.160
Product C	37	3	40	92.50%	0.175
Product D	36	3	39	92.31%	0.660

The non-conformance that has been seen since implementing the in-cycle probing (Figure 4-42), has been around special causes such as machine issues where there were faults with the repeatability of the turret and position of tool tips. All these issues would not have been identified if it were not for the probing system and the controls that have been put into place. All these issues were captured in the PFMEA and any future issues will be continued to be logged in the PFMEA.

4.26 Summary

Machine probing can be used for multiple functions; machine and tool setting, part/fixture setting, datum offsets, rotary axis offsets, product measure-cut functions and inspection. In this study the researcher has applied a structured approach via a DMAIC process, to introduce on-machine probing systems onto industrial CNC equipment not originally purposed for such technology. Through a holistic application of this technology a dramatic improvement in terms of product right-first-time and throughput has been achieved. Key enablers for success were the use of both quantitative and qualitative methods for building the economic and technical case, as well as proving and de-risking the conversion of machines to measurement systems. Another key enabler was the engagement and involvement of site staff, their support for this process change was brought about using a structured and traceable approach as well as via multiple engagement workshops.

In this chapter the researcher has demonstrated that the potential of OMI is very real and possible. With such capability implemented and now being consistently proven via CMM capability metrics it is not presumptuous for site manufacturing engineers to consider moving to a reduced-inspection basis on this and other machinery on site. However, despite a strong business case due to the number of socio-technical pitfalls, as indicated by earlier chapters and the study in Appendix A, there is high risk of potential problems. In this case study a key enabler for success was the ability to be able to identify, measure, understand and control the key machine tool errors, for a 2+1 axis machine producing features to tolerances in the region of ±0.100mm this was a relatively straightforward task; this is not expected for machines with more axes producing components at higher tolerance specifications as geometric and kinematic effects are likely to be greater and more severe.

Chapter 5

The ‘Machine Tool Metrology Index’

5.1 Introduction

There are a multiplicity of machine tool types and configurations. The influences of axis stack up makes defining correct measurement protocols a challenging exercise. With manufacturers ever seeking to maximise asset utilisation and minimising production downtime, reducing wasted activities and increasing efficiency is a priority. With previous chapters it has been identified that there is a fundamental need that should a machine be used as a measurement device it needs to be measured itself. The objective of such measurement activities however can vary, in that machines can be measured for purposes of audit, calibration, verification and optimisation. There is therefore no surprise that within industrial environments many are confused or misinformed about the calibration status or true condition of machines. This is due to not being aware of what, how and where each machine error is being measured and controlled. Without such clarification, businesses run the risk of firstly assuming performance in terms of both machining and measurement i.e. machine users make the assumption that a machine is capable for OMI based only on limited error profile information. Conversely, efficiency can be lost via expending unnecessary resource on measuring, correcting and controlling machine tool errors which are not relevant.

This chapter thus illustrates that there is a need for a novel system to create a ‘Machine tool Metrology Index’ for each machine type. This is to be created before measurement, calibration and re-verification can be carried out on any particular piece of measurement equipment. In this chapter the researcher explores and highlights deficiencies in standards and original equipment manufacturer protocol sheets to highlight the need for such intervention. Subsequently the researcher develops and tests this novel approach. Finally, this chapter discusses how software could be created to enhance Machine Tool Metrology Index creation for any type of multi-axis machine tool.

5.2 Machine tool variability

A machining system consists of multiple mechanical, electrical and electronic modules integrated together to generate movements and forces necessary to execute a physical process on a material [194]. A machining process can often be associated to one or more of the categories as indicated by Table 5-1.

Table 5-1: Typical machine tool processes

Physical Action	Examples
Material Forming	Forging (Hot or Cold, Rolling (Hot or Cold), Extrusion (Hot or cold), Tube and wire drawing, Deep drawing, Spinning, Spline Production
Material Separation	Laser Cutting, Water-jet Cutting, Die Cutting/Shearing incl. Lancing, Perforating, Notching, Nibbling, Shaving, Trimming, Cut-off, Fine Blanking
Material Removal	Defined Cutting Edge Machining, Undefined Cutting Edge Machining, Non-conventional Machining
Material Joining	Mechanical Fastening, Ultrasonic Assembly, Metal Inserting, Snap and Press, Heated Welding, Induction Welding, Friction Stir Welding, Solvent & Adhesive Bonding
Material Deposition	Rapid Manufacturing, Casting, Sintering, Electroplating, Sputtering, Evaporation, Physical Vapour Deposition, Chemical Vapour Deposition

Irrespective of function all machining systems operate as an open feedback loop often containing the machine tool structure and axes, tooling, material manipulation process, workpiece and fixturing as indicated by Figure 5-1.

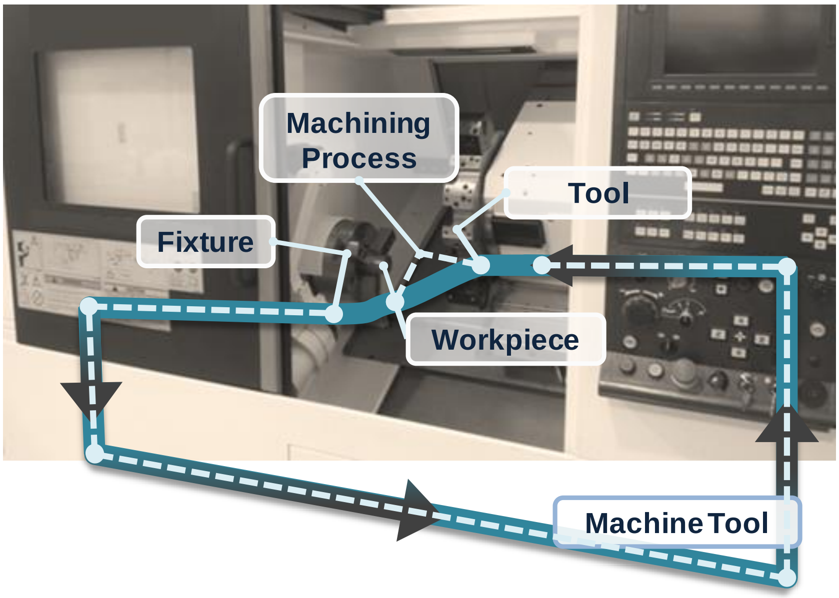


Figure 5-1: Machine tool kinematic chain (Open Loop System)

To close this loop, independent measurement systems are called upon to assess, calibrate and re-verify geometric and kinematic errors and their contributors on a regular basis. As machine tools become increasingly complex in terms of size, task and configuration, the reliance on specialist machine tool maintenance and measurement technology increases.

5.3 Current issues with machine tool metrology

Maintenance teams are ever increasingly under production pressures to maintain asset uptime and capability, where there is already little time available. Should machine tools be repurposed for the dual task of manufacture and measurement this requirement and the associated complexity increases. Therefore, the optimal application of machine tool metrology is required to efficiently control the necessary key performance variables associated to such tasks. However, in practice this often does not happen. Causes of this include:

5.3.1 'Fire fighting' culture

With maintenance teams under continuous pressure to maintain asset uptime, there is often not enough time for them to design and develop efficient measurement, maintenance and control strategies. This often leads to situations whereby assets are corrected and compensated by resolving symptoms of problems without addressing the root-cause of them. Such a strategy for asset maintenance often leads to issues such as an overabundance of data, often at great expense, which is stored and not utilised without thought given to its future use [88]. Additionally, with such an approach due consideration cannot be made with regards to: using correct and suitable measurement procedures; data recording and storage; correct analysis and diagnosis of errors to identify optimum repairs; suitable measurement practice being used. As a result, knowledge regarding machine tool errors and their behaviour stagnates. Many of these issues could be considered as a result of a shortage of skills in the area of machine tool metrology. However, if asset maintainers had visibility of all errors that were critical to the machine, and the most optimum ways to assess them, these burdens could be reduced. Hence the maintenance of high precision machine tools could be more efficiently managed.

5.3.2 Plethora of measurement systems

As presented in Chapter 2 (The Literature and State-of-the-Art Review) there is a plethora of measurement technology available for measuring machine tool errors. As identified by this study no one piece of equipment can measure all errors and there are a number of pieces of equipment which cover multiple-errors. Therefore, it is very common for machine tool maintainers to profile machines based on the equipment they have available i.e. a Ballbar and laser interferometer, rather than fully understanding what errors the equipment is covering and which errors are not being covered. If an index of errors could be provided to asset maintainers, for each of their machine tools, they could identify whether they had all the necessary equipment available to measure them. Or if not, they would be fully aware of what they could control and could not. On a plant level this would bring significant advantages in terms of building the case for purchasing and selecting new measurement equipment.

5.3.1 Multi-axis configurations

Multi-axis machines are commonly used in the manufacture of high-precision aerospace parts, as parts with complex sculptured surfaces are becoming increasingly required. Multi-axis machine tools have the significant advantage of being able to machine geometrically complicated components in single set-ups. However, multi-axis machines have their drawbacks. This is due to the wide variety and complexity of machine configurations. These multi-axis machines are likely to suffer from accuracy issues more than three-axis machines as the simultaneous usage of multiple axes increases the likelihood and severity of volumetric errors [235]. This also poses a challenge for asset maintainers as the measurement of these errors is much more complicated than for three-axis machines. As such, unlike the recognised 21 parametric errors for a three-axis machine, more error components require measuring for a multi-axis machine. These often arise in the form of additional squareness, parallelism, offset, and rotary axis errors. Hence, if the researcher could comprehensively and confidently index all errors for any given multi-axis machine tool these could be better measured and managed.

5.3.2 Limitations of machine measurement standards

To combine all machine tool error information into a simple manual is a difficult endeavour; as illustrated between versions of ISO 230-1 (1996) at 80 pages to ISO 230-1 (2012) at 170 pages long [14], [236]. Despite various methods, guidelines, procedures and technologies being described, the standards tend to not favour any particular measurement equipment manufacturer or focus on any particular machine configuration. Although attempts are being made in a new ISO 230-12 standard [79]. This therefore leaves machine tool users to rely on original equipment manufacturers to understand the strengths and shortcoming of their particular machine, and to supply the procedures and documentation to sustain their capability; this of course is subject to bias. When dealing with special purpose machine tools, these procedures are the only way to measure certain aspects of the machine geometry and performance. Where these procedures may be relevant for maintaining machining performance, it is unlikely that these can be referred to in order to sustain OMI, should it be implemented.

5.3.3 Differing requirements between machine tool users and builders

The requirements of the machine manufacturer and the user/customer often differ when it comes to machine tool metrology. Customers/users are often only interested in whether the machine tool is sufficiently capable of making their parts. If the machine is not sufficiently capable for this task then it is seen to be the job of the machine builder to remedy it. The machine tool manufacturer therefore has a desire to know a lot more about how to measure the various elements of the machine in order to identify and then fix any problems associated to precision and reliability. Where factory and site acceptance tests are performed these are often heavily weighted towards whether or not the machine can make parts as specified, rather than on machine errors and their stack-up. For example, if the machine has out of square axes but it has excellent compensation software, then the customer will rarely reject the machine for axes not being square. As such the machine tool manufacturer often negates the need for such an error to be measured and/or reported at this time.

Where performance measurement tests are requested by the machine tool buyer, these are normally based on ISO 230-2 and ISO 230-4, or equivalent, standards [81], [83]. In this case the customers focus is still relatively simplistic, whereby the request is fundamentally for a demonstration that the machine is adequately accurate throughout the available machine working volume. The machine configuration or error stack-up is of lesser or no interest. As discussed in previous chapters, this approach is not robust enough should the machine tool be used as a measurement device. As such, a requirement exists for all critical machine tool errors to be defined, specified and measured at numerous stages of a machine tool lifecycle.

5.4 Renishaw plc. Productive Process Pyramid™

Developed by Renishaw plc., via its own manufacturing processes, and through solutions developed for its global customer base, the ‘Productive Process Pyramid™’ is used as a commercialised process for which many manufacturing and maintenance engineers turn to; in order to better understand and sustain their machining systems [120], [237]. In whole the full ‘Pyramid’ represents a ten stage systematic approach to reducing waste and variation in manufacturing processes - “*making the process right, and keeping the process stable*” (Figure 5-2). Although many stages can be implemented individually and in various orders; to gain the maximum benefits, all stages are recommended to be addressed. The ten stages of the pyramid break down into four distinct areas:

- Machine calibration and geometry
- Setting processes
- Adaptive machining and process control
- Part verification and measurement uncertainty

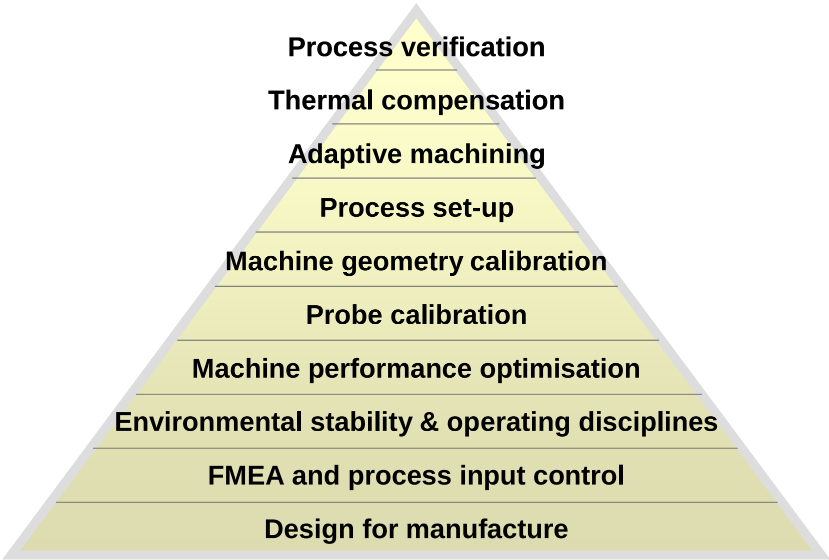


Figure 5-2: Renishaw plc. Productive Process Pyramid™ [2][3]

Machine condition measurement and optimisation is clearly a fundamental element to the Renishaw's Productive Process Pyramid™ (Figure 5-2). In line with academic literature (Chapter 2) a robust implementation of machine performance assessment, calibration, and optimisation can bring a new or existing machine's performance better in-line with the process requirements [238]. As described, machine tool positional errors are therefore one of the most common causes of dimensional rejects. Such errors originate from:

- Geometric, dynamic and scale errors within the machine tool
- Wear and tear in use and machine collisions
- Thermal drift

It is widely accepted that if machine performance is known and controlled, investigations into non-conformance can be focussed on the process and not the machine. However, in practice, simply understanding what errors need to be measured and controlled is a challenging endeavour due to the complexity and variability of machine tools and the products in which they make.

5.5 Industrial challenge

As machine tools become increasingly advanced, so have the maintenance and measurement engineering standards which are relied upon to assess them. Machine tool metrology standards are becoming ever more numerate and voluminous, as their necessity is increasing [72], [73], [239]. Adequate reference to recognised standards and procedures is a critical requirement for the reliability of captured data; where without them decisions based on untraceable data can easily be brought into question.

A major gap that presents itself with machine tool measurement standards is the inability to transform measurement data into sensible maintenance and repair decisions [88]. This is due to standards being written to be generic and as independent as possible. It would be near impossible to propose machine correction suggestions for every machine type and configuration. Currently machine tool builders, specialists and or decisions by committee are often required [77], [238]. Before any assessment of capability; or recommendations for repair, optimisation, or refurbishment can be made; the first challenge is often to question and debate whether all relevant errors have been collected or not. This effectively complicates any decision to continue or interrupt the production process, both potentially costly decisions.

5.6 Academic gap

As discussed in earlier chapters, the kinematics of a machine tool and their associated error parameters i.e. pitch, roll, yaw etc. are explored from either an error reduction perspective or an error compensation perspective. The majority of recent research is focused on error compensation methodologies based on machine tool kinematics and machining process information [240]–[242]; however very few of them consider the machine tool users perspective in terms of understanding and sustaining the capability of their particular equipment i.e. from a maintenance and optimisation perspective. Some will claim that this is inferred by national and international standards associated to machine tool metrology. Therefore, the researcher investigates this claim this in this chapter.

5.7 Critique of current machine tool measurement standards

Machine tool measurement standards have been introduced in Chapters 1 and Chapter 2. Creating standards describing performance tests for all types of machine tools is an enormous challenge. In the future, should new standards be used widely, it will enable users to accept and verify the stated performance of a machine tool and compare performances of different machining systems. Currently standards do not enable the one-to-one comparison of the metrological performance of two machines. An explanation to this is that there will always be risk when comparing performance statements, even when these statements are generated via adherence to international standards. However, on-machine measurement conditions, for example: temperature range of the room, measuring speed, axis configuration, probing system type, volumetric size etc., are seldom imposed by standards, where they will be determined by the manufacturer or the user. When determined by the manufacturer, they are likely to be lax for the normal operation of the machine (i.e. for easy acceptance), when determined by the user they are likely to be too over- or under-estimated due to lack of technical knowledge. This is an issue which therefore needs to be mitigated.

5.8 Critique of machine tool builder acceptance process

A machine tool builder will produce "build" test sheets to ensure quality of work during the assembly and commissioning stages of the machine. In addition to, or in place of, the standards the original equipment manufacturer (OEM) will perform several in-house tests designed specifically for their machine in line with the equipment and skills available to them. Since the end goal is to produce a machine as efficiently as possible, this can sometimes lead to deviations from testing to a particular standard.

For commercial and competitive reasons machine tool builders do not often illustrate the full error profile of their machine. There is little advantage in highlighting the errors that do exist, especially during any warranty period. Therefore, it is only the data from the pass-off stage, which only includes the items demanded by the customer, which is likely to be released.

The typical machine tool measurement and acceptance process is often split into two parts, as per Table 5-2:

Table 5-2: Machine tool acceptance process

Location	Activity	Quality Control
Manufacturers Site	Sub-assemblies	80% of final OEM tolerance
	Process control	80% of final OEM tolerance
	Machine assembly	80% of final OEM tolerance
	Head build	80% of final OEM tolerance
	Pre-delivery inspection	100% of final OEM tolerance
Customer Site	Construction and alignments on site	Tolerances often at OEM discretion
	Error compensation (Linear, rotary and/or volumetric)	Tolerances often at OEM discretion
	Final pass-off	Tolerances based on contractual agreements

Based on Table 5-2, a typical example for a moving column horizontal ram machine [243], would be:

5.8.1 OEM measurement and calibration at site

- Pre-build any sub-assemblies such as 2-axis head and headstock to procedures as per own specification.
- Install machine beds and guideways to own specifications
    - Align and check relevant aspects of alignment
        - Level beds to gravity
        - Align and confirm bed axis guideways straightness (horizontal and vertical plane)
        - Align and confirm base bed guideways for parallelism
        - Align and confirm drive system to bed axis guideways
    - Continue to erect remaining machine structure from bed axes to spindle
        - Fit column base to bed
        - Mount column onto column base (with driving systems)
        - Fit headstock sub-assembly to column
        - Establish machine co-ordinate system
- Complete 'final inspection' quality checks before dispatch to customer
    - Alignments and checks to manufacturers own protocol
    - ISO standards, national standards or hybrid versions
    - These tests are often witnessed by the customer

5.8.2 OEM measurement and calibration procedure at customer site

- Carry out static tests on foundations prior to machine installation
- Install machine to OEM procedures and tolerances
- Perform electronic compensation activities (Linear axis or volumetric)
- Final pass-off the machine to tests as agreed contractually
- Depending on knowledge and experience of the customer pass off test is often just the production of a 'gold' standard part or artefact

As can be seen through this process, although robust in the customer's eyes, this will not support the enabling and sustainment of on-machine measurement. This is as it has not been considered at any point during the machine acceptance process.

5.9 OEM adherence to standards

As described in 5.5, the machine tool manufacturer will perform measurements and calibrations at various stages of the build process. A particular example would be stacked rotary axes which are measured at the build stage, often in a clean-room environment, using special jigs or fixtures. This means that, unlike when the axes are installed on the machine, various geometric errors can be isolated and measured without contamination from other sources. Subsequently these tests cannot always be replicated on the fully installed machine at the customer’s site. As such asset maintainers will not have visibility or the ability to measure these underlying machine tool error sources or know of their symptoms.

5.10 Limitations to standards

As described earlier, a key limitation of standards is that they themselves are a compromise brought about from a wide variety of possible machine configurations. Additionally, varying academic and commercial challenges and changes to these standards are a lengthy process [244]. Since successful machine tool builders are committed to gaining a competitive edge, new configurations of machines and additional ancillary equipment are likely to be introduced before an appropriate industry-wide standard has been set [245].

The in-depth knowledge of any new developments or enhancements that are made by the machine tool builder are likely be retained by the OEM for commercial intellectual property reasons. This can lead to situations where the method of tests of systems on a machine is unclear. A good example of this is the application of electronic compensations, perhaps in the PLC, for which outside agent or end user have no knowledge.

5.10.1 Application of standards

A problem for metrologists and asset maintainers is identifying, and applying, the multiple applicable standards for a measurement of a machine. During a test exercise, four people with experience of both machine tools and coordinate measuring machines were canvassed to specify the exact standards to classify a generic industrial machine tool as a traceable measurement system. No two returns were the same. One comment was that the selected machine-specific standard was “the nearest to that machine”, another provided only the machine-specific standard, but not the general ones and a third provided only the ISO 230 series of general standards for all machines.

5.11 The 'Machine Tool Metrology Index'

This chapter has highlighted a clear need and ambition to define, establish and sustain a machine's required characteristics according to the rigours of the production requirements. A co-written conference paper (Paper I) has been written to propose a novel framework, which applies this thinking to machine tool metrology [238]. Although this paper proposes the concept of machine tool metrology indices' it does not investigate or propose valid methods for their creation.

An index by its definition provides a list of items which can be used to point to a greater volume of information or knowledge. Such a list can be created and used for the specification of machine tool errors. With this list in place, it can act as a frame of reference for specifying tolerances, understanding inter-relationships and primarily be used to identify which errors are relevant to machining and on-machine inspection. Once key errors are identified machine tool users can specify which require calibrating, measuring and controlling for any given task. Additionally, necessary equipment can be selected and optimised to map as many errors in the index as possible. Alternatively, measurement equipment can be specifically chosen and focused upon to measure certain key errors, critical to process, as best as possible. With a complete metrology index, where all errors have been measured, this can be used to provide a comprehensive benchmark of any machine tool. This concept is illustrated in Figure 5-3.

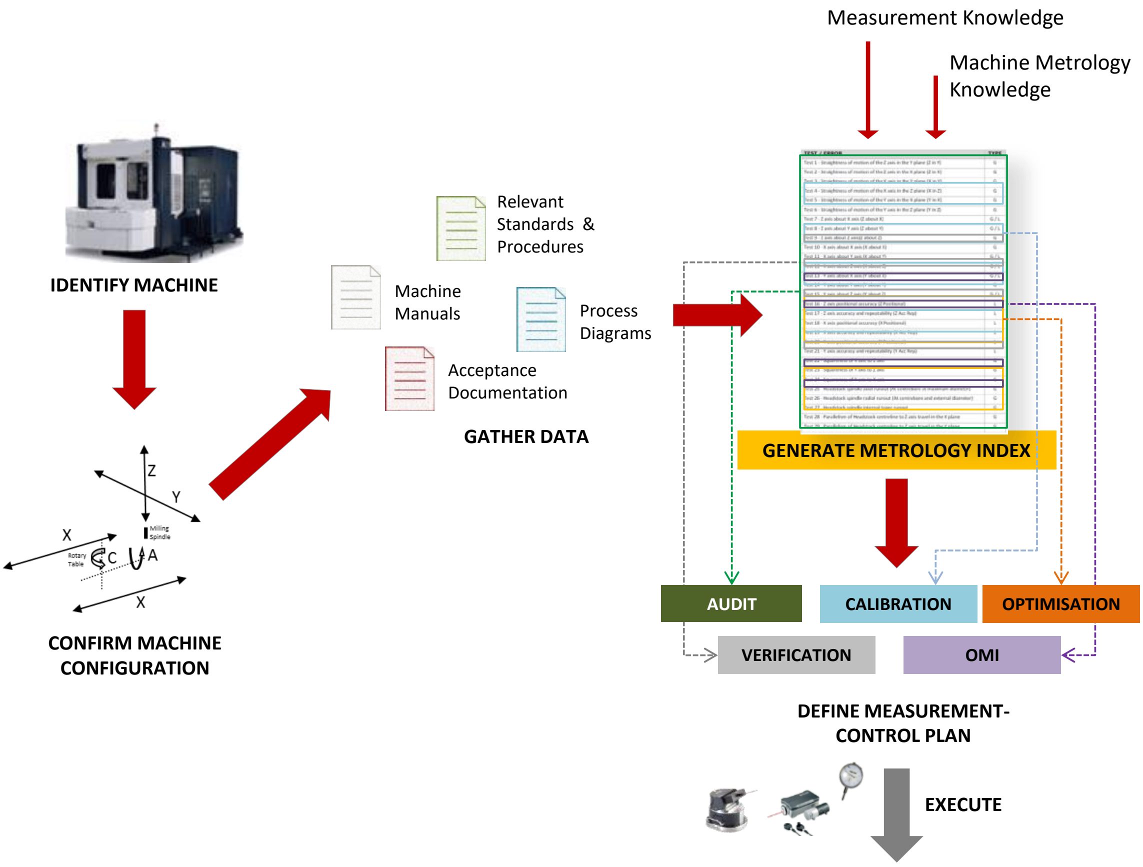


Figure 5-3: 'Machine Tool Metrology Index' process

Figure 5-3 from the left shows a multi-axis machine tool which is of known configuration. This machine is then broken down as a skeleton diagram which indicates interactions of all containing axes and their configuration. From this an index can be created, based on the combination of knowledge from OEM protocol sheets, machine tool standards, expert knowledge and understanding of production requirements. This list now forms a reference point for machine auditing, calibration, verification and sustainment. Hence this can form a vital part of a control plan, which can be used for both optimising a machine both for machining and on-machine measurement capability.

One strategy which machine tool users could employ is to utilise as many different techniques, procedures and measurement methods from the standards whilst combining them with any specialist methods and tolerances from the OEM specification; this often occurs at machine site acceptance stage when equipment is in commission and therefore not yet live. This strategy enables the largest amount of data to be captured for later comparison or analysis. This process however may never be repeated again in its entirety during the life of the machine tool, due to the amount of downtime and skilled resource required.

5.12 Creation of a 'Metrology Index'

The researcher postulates that by performing a critical and taxonomic review of a machine tools' configuration whilst considering: 1) its axes kinematic chain, 3) its auxiliary systems, 3) machine tool build principles and 4) relevant standards; an 'index' containing all key machine tool errors sources can be created. Often created by expert machine tool calibrators, but can also be constructed by group consensus [238], this index will be reviewed for its suitability as a useful and transferable list for the measurement and assessment of a chosen machine tool. Linking traditional measurement techniques with newer state-of-the-art systems can ensure that either all machine tool errors are considered both individually and holistically, therefore the data collected can be sampled by parties interested in machine acceptance, optimisation and/or sustainment at any time. This combination of all such elements creates consistent business knowledge in terms of a particular machine tool under scrutiny as well as all other machine tool equipment the facility utilises. The researcher hypothesises that this approach is more robust than any process machine tool builders are currently using. Alternative approaches are discussed in the following sections.

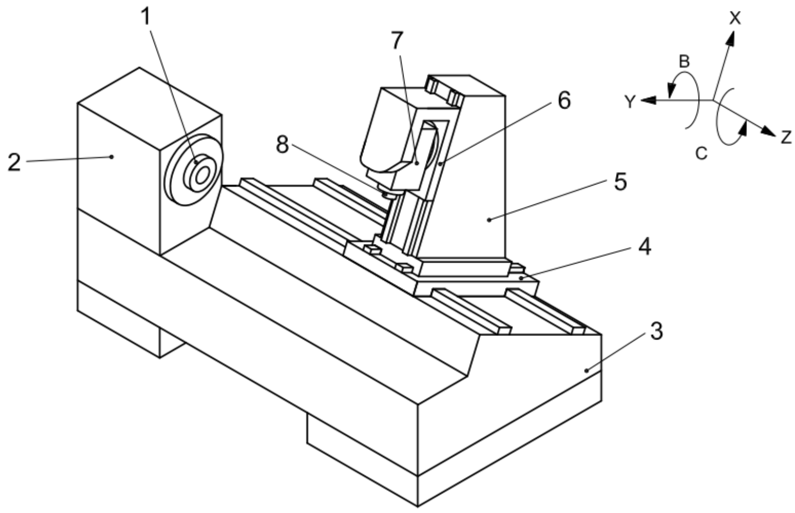
5.13 ISO 230-1 (2012) attempt at a 'Metrology Index'

The ISO 230-1 (2012) standard has been updated within the period of this research work. Amongst several new sections, the majority describing new machine tool measurement techniques, the standard includes a new 'informative' annex section discussing the characterisation of machine tool geometric error. The standard concedes that ISO 841 [34] is not adequate enough to characterise machine tool geometric errors; and therefore presents a potential methodology to perform such a definition.

The standard proposes that from the definition of the positions and orientations of all axes of motion for any machine tool; when represented as a coordinate system; a list of all alignment errors can be defined. In addition to this redundant alignment errors can be automatically removed, in order to facilitate faster and more efficient measurement. Three examples of the methodology are given:

- 3-axis machine - 5 orientation errors, 3 squareness + 2 spindle
- 5-axis machine - 23 positional and orientation (incl. squareness and spindle errors)
- Multi-task turning machine – 23 positional and orientation (incl. squareness and spindle errors)

As stipulated by the new ISO 230-1 standard, choosing the origin and primary and secondary axes for the machine tool coordinate system differently will result in a different set of geometric accuracy parameters. The following example of a ‘Metrology Index’ is given for a multi-tasking machine (Figure 5-4):



Key
1 work spindle (C′-axis)
2 work spindle head
3 bed
4 column saddle (Z-axis)
5 column (Y-axis)
6 cross slide (X-axis)
7 swivel spindle head (B-axis)
8 tool spindle (A-axis)

Figure 5-4: Multi-tasking machine configuration – ISO 230-1:2012 [14]

5.13.1 Minimum number of error parameters to fully characterise a multi-tasking turning centre

As per ISO 230-1 (2012): If the coordinate system for the machine tool (Figure 5-4) is chosen in the following way (Method 1):

- The Z-axis is chosen as the primary axis.
- The X-axis is chosen as the secondary axis.
- The origin is chosen to be along the B-axis average line at the Y coordinate, where the (A)-axis average line intersects with the YZ plane when all axes are commanded to zero.

The alignment error parameters are generated as per Table 5-3.

Table 5-3: Multi-tasking machine tool error characterisation ‘Metrology Index’ as per ISO 230-1:2012

C axis	Z axis	Y axis	X axis	B axis	Spindle(A)
E_{X0C}	-	-	(0)	(0)	-
E_{Y0C}	-	(0)	-	-	0
-	(0)	-	-	0	$E_{Z0(A)}$
E_{A0C}	0	E_{AOY}	-	E_{A0B}	-
E_{B0C}	0	-	E_{B0X}	(0)	$E_{B0(A)}$
-	-	E_{C0Y}	(0)	E_{C0B}	$E_{CO(A)}$

E_{X0C}	X offset error from C to B in reference to XY
E_{Y0C}	Y offset error from C to A in reference to XY
E_{A0C}	Parallelism error of C to Z in YZ plane
E_{B0C}	Parallelism error of C to Z in ZX plane
E_{AOY}	Squareness error of X to Z
E_{COY}	Squareness error of Y to Z
E_{BOX}	Squareness error of Y to X
E_{A0B}	Squareness error of B to Z
E_{C0B}	Squareness error of B to X
$E_{Z0(A)}$	Z offset error from (A) to B in reference to YZ plane
$E_{B0(A)}$	Squareness error of (A) to Z
$E_{CO(A)}$	Parallelism error of (A) to X in reference XY plane

Table 5-3 represents what a ‘Metrology Index’ would look like if it was created using the ISO 230-1:2012 methodology. Commentary within the standard stipulates that functional distances must also be measured i.e. multi-axis centre-point offsets. However, these are not considered as “machine position parameters” and hence not included in the list. This indicates a clear deficiency in the approach, in that there is a heavy reliance on in-depth skill and knowledge to identify this requirement for other multi-axis machine tools.

5.14 Critique of ISO 230-1 (2012) ‘Metrology Index’ methodology

Despite the ISO 230-1 (2012) standard identifying the ‘Metrology Index’ as an issue and providing a robust and valid approach for specifying all alignment errors for any machine tool; it concedes that to fully evaluate the performance of the machine is a specialist task for the machine tool builder. Crucially, as seen from the example given, it does not specify which functional point distances of the machine tool should also be measured i.e. the distance along the spindle axis from the B axis to the functional point of the tool. This is critical for on-machine measurement. However, the ISO standard argues that the consideration of machine position parameters is also the responsibility of the machine tool builder. The researcher accepts this is a valid comment; however the researcher proposes these parameters need to be known and understood and controlled by machine tool users for reasons of maintaining capability as well as improving OMI performance.

The ISO 230-1 (2012) ‘metrology index’ method therefore needs to specify and generate an order in which measurements need to be made; which may be relevant for identifying and optimising root-causes of compound errors. It also needs to provide this in a format in which both OEMs and machine users can understand; which currently it does not. Additionally, whilst the methodology the standard provides is suitable and efficient, it is not straightforward for non-academics to follow. As such, it cannot give machine tool users the guarantee that all critical alignments are covered. Therefore, machine tool users are still heavily reliant on experienced machine tool metrologists to consult and specify this full metrology index. This is proven with the following test cases.

5.15 ‘Metrology Index’ test cases

The researcher has examined the requirements and policies of standards, OEM build and installation practices and measurement experts from academia and industry to benchmark the current methods of measuring machine tools. In particular, four machines typical for Rolls-Royce manufacturing operations have been identified as test cases for the creation of ‘Machine Tool Metrology Indexes’. These indices have been created via several information sources including:

- The University of Huddersfield – Centre for Precision Technologies
- Machine Tool Technologies Ltd.
- The British Standards Institute
- Machine tool builder information
- Machine tool measurement specialists

5.15.1 Makino 5-axis machining centre ‘Metrology index’

The first machine selected for machine tool metrology index creation is a 5-axis Makino MCD2016 – 5XA located at the Advanced Manufacturing Research Centre (AMRC) in Sheffield, UK (Figure 5-5).

Figure 5-5: 5-axis milling machine – Makino MCD2015-5XA illustration

The axis configuration for the machine is as shown in Figure 5-6.

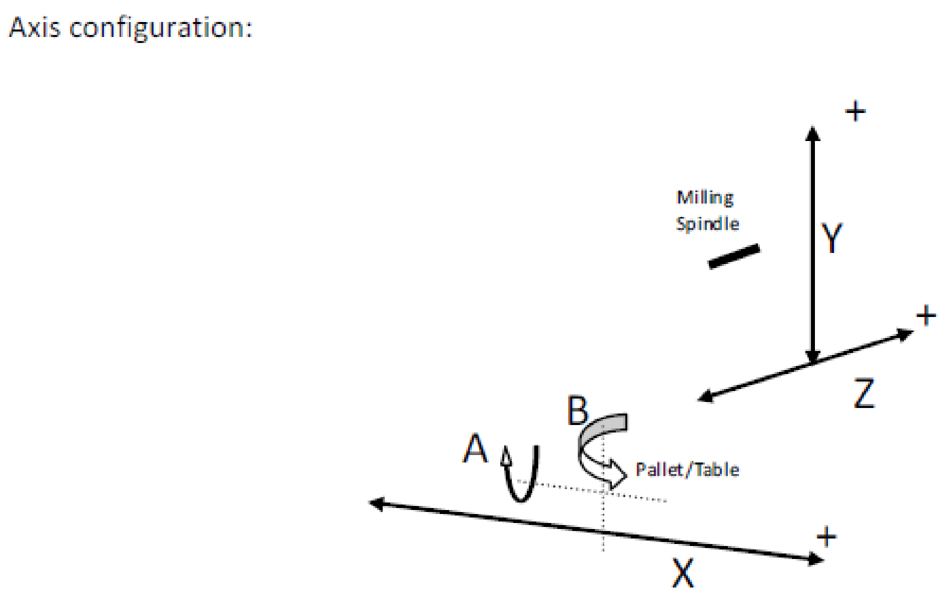


Figure 5-6: Axis configuration diagram for Makino MCD2015-5XA

Additional machine tool features include a pallet and tool changer.

This machine can be considered either in its entirety as a five-axis milling machine, or by ignoring the rotary axes as a three-axis cartesian machine for basic OMP.

Applicable standards for this configuration of machine are:

- ISO 3070-3: 2007 - Machine tools — Test conditions for testing the accuracy of boring and milling machines with horizontal spindle — Part 3: Machines with movable column and movable table

- ISO 10791-1: 1998 - Geometric Tests for Machines with Horizontal Spindle and with Accessory Heads (Horizontal Z-axis)

Metrology index as per user consensus indicates 50 tests given (Appendix B.1).

According to ISO 230 standards 42 measurement parameters are expected to have been specified for this machine. When comparing against the researchers generated index (Appendix B.1) this is an accurate number as the measurement of linear and rotary axes have been accounted for twice: once as a single bi-directional run and then once as an ISO 230-2 test. Additionally, the consortium also took into consideration that this machine is fitted with a pallet changing system.

5.15.2 Mazak Integrex 35 4-axis mill-turn ‘Metrology index’

The second machine selected for machine tool metrology index creation is a Mazak Integrex 35 4 axis Mazak located at Rolls-Royce Bristol site (Figure 5-7).

Figure 5-7: Horizontal Mill-turn (Mazak Integrex 35) illustration

The axis configuration for the machine is as per Figure 5-8.

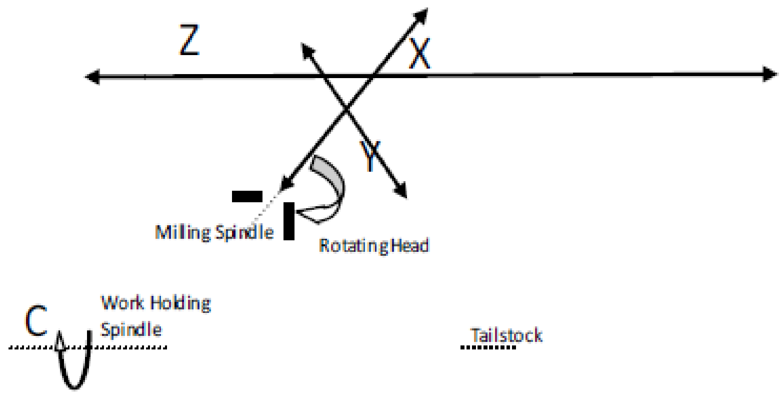


Figure 5-8: Axis configuration diagram for Mazak Integrex 35

Additional machine tool features include a rotating head (non-interpolating) and tailstock system.

Applicable standards for this configuration of machine are:

- ISO 6155: 1998 Machine tools - automatic lathes – Testing of the accuracy
- ISO 13041-1:2004: Test conditions for numerically controlled turning machines and turning centres: Part 1: Geometric tests for machines with a horizontal workholding spindle

Metrology index, again build from consensus, generated 46 tests, presented in Appendix B.2

According to ISO 230 standards 30 measurement parameters are expected to have been specified for this machine. The reason for the discrepancy is due to the ‘double-accounting’ of positional error tests as well as the consortium also taking into consideration that this machine is fitted with a nodding head system. Although not entirely relevant for OMI these are important omissions for machine capability optimisation reasons.

5.15.3 Okuma V55R 2-axis vertical turning lathe ‘Metrology Index’

A common machine utilised in the manufacture of aerospace components, an Okuma V55R 2-axis vertical turning lathe (VTL) was chosen for metrology index comparison (Figure 5-9).

Figure 5-9: Vertical Lathe (VTL) Okuma V55R illustration

The axis configuration for the machine is as per Figure 5-10.

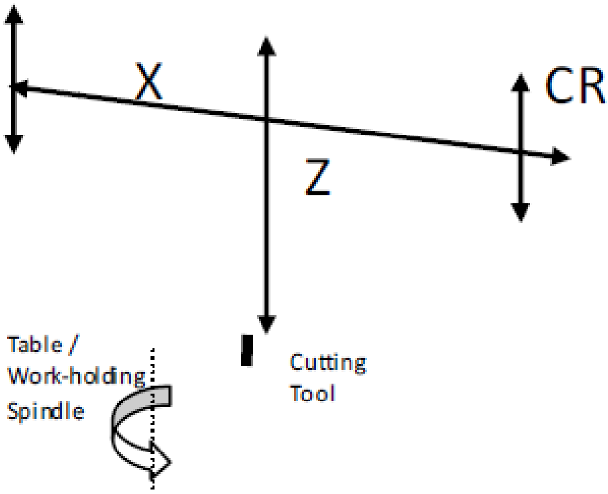


Figure 5-10: Axis configuration diagram for Okuma V55R

A key additional machine tool features include a cross-rail.

VTLs are a very common machine tool configuration in Rolls-Royce plc. due to a consistent need to manufacture cylindrical components. Geometric errors can often dominate due to requirements for rotary axis geometry and the need for capacity for tall workpieces. It is also important to recognise the need to repeat tests at different cross-rail positions.

Applicable standards:

- BS 4656-22: 1988 - Accuracy of machine tools and methods of test. Specification for vertical boring and turning lathes, single and double column types

- ISO 3655: 1986 - Acceptance conditions for vertical turning and boring lathes with one or two columns and a single fixed or movable table - General introduction and testing of the accuracy
- ISO 13041-2:2008 - Test conditions for numerically controlled turning machines and turning centres: Part 2: Geometric tests for machines with a vertical work holding spindle

Metrology index: 25 tests given in Appendix B.3.

According to ISO 230-1 standards 18 measurement parameters are expected to have been specified for this machine. There is no evidence that the ISO 230-1 method will specify the requirement to take measurements at different cross-rail positions. As seen with the manufacture of cylindrical aero-engine components, this is a significant source of geometric error.

5.16 Machine manufacturer acceptance sheets vs. user defined metrology indices

Site acceptance sheets from nine different machine tools have been collected from multiple sites across the Rolls-Royce manufacturing supply chain. All such machines have been recently installed within the last three years. Skilled machine tool measurement engineers, including from the University of Huddersfield and Machine Tool Technologies Ltd. were invited to create ‘Metrology Indexes’ for these different machine tools. Table 5-4 shows the results when compared to the expected metrology index for each of the machines.

Table 5-4(*a*): Comparison of metrology index items between OEM specification and stakeholder consensus

Machine Supplier	Number of items on metrology index †	% of items missing from OEM test sheet	Notable error parameter omissions include:
6-axis machining centre **Supplier A**	79	70%	• Linear axis straightness • Linear axis angularity • Linear and rotary axis squareness • C axis • Milling spindle • B axis • Tailstock • Reference position • Ballbar circularity
5-axis machining centre (with swivel head) **Supplier B**	61	64%	• Linear axis straightness • Linear axis angularity • Linear axis positional accuracy and repeatability (ISO 230-2) • Linear and rotary axis squareness • Milling spindle • B-axis / Swivel Head • C axis • Ballbar circularity • Reference tests i.e. pivot length and rotary axis alignments • Pallet changer
5-axis machining centre **Supplier C**	60	63%	• Milling spindle tests • C axis tests • A axis tests • Reference tests i.e. pivot length and rotary axis alignments • Ballbar circularity

Table 5-4(*b*): Comparison of metrology index items between OEM specification and stakeholder consensus (*cont.)*

Machine Supplier	Number of items on metrology index †	% of items missing from OEM test sheet	Notable error parameter omissions include:
5-axis machining centre **Supplier D**	56	51%	• Linear axis straightness • Linear axis angularity • Milling spindle • A axis (Tilt Table) • B axis (Rotary Table) • Reference tests i.e. pivot length and rotary axis alignments • Ballbar circularity
5-axis machining centre **Supplier E**	61	61%	• Linear axis angularity • B axis checks • C axis checks • Reference tests i.e. pivot length and rotary axis alignments • Ballbar circularity checks
5-axis machining centre **Supplier F**	55	61%	• Linear axis angularity • B axis • C axis • Reference tests i.e. pivot length and rotary axis alignments • Ballbar circularity checks

Table 5-4(*c*): Comparison of metrology index items between OEM specification and stakeholder consensus (*cont.*)

Machine Supplier	Number of items on metrology index †	% of items missing from OEM test sheet	Notable error parameter omissions include:
5-axis machining centre (twin-spindle) **Supplier G**	86	43%	• X, Y and Z angularity • A axis straightness • A axis angularity • A axis squareness • A axis parallelism • B axis alignment • Linear axis positional accuracy and repeatability (bi-directional) • X, Y ,Z, C1, C2 & B axis Reference tests • Ballbar circularity checks
5-axis mill turn **Supplier H**	55	66%	• Linear axis straightness • Linear axis angularity • Linear axis positional accuracy and repeatability (bi-directional) • Reference tests i.e. pivot length, rotary axis alignments, zero setting • Ballbar circularity checks
6-axis mill turn **Supplier I**	69	49%	• Linear axis straightness • Linear axis angularity • Linear and rotary axis squareness • B axis • Tailstock • Reference tests i.e. pivot length, rotary axis alignments, zero setting • Ballbar circularity checks

† as created by consortium

From Table 5-4 the following summary statements can be made:

All nine machine tool builders failed to present the same list of tests as per specified by the researcher’s user defined ‘Metrology Indices’. In some cases, up to 70% of measurement tests were omitted from OEM factory and site acceptance sheets. When considering the nature of the omitted items, any one omission could have an impact on the accuracy/performance of the machine in question. More significantly there is no benchmark of machine other than the machine’s ability to produce components. It was also found that 6 out of 9 do not reference any national/international standard. Where the standard was referred to, all 9 did not adhere to the standard requirements i.e. equipment utilised is not disclosed, methods of test are not detailed or presented and/or data presentation is not consistent with standard requirements etc.

Although not included in the user defined ‘Metrology index’ lists, environmental temperature variation error (ETVE) machine tests and mechanical and thermal displacement tests of both the work- and milling- spindles to be performed to the relevant ISO standard are never specified. Where the researcher can argue that these errors can be mitigated by machine warm-up, these tests would be more relevant for on-machine inspection validation and control.

5.17 Improving the process of ‘Machine tool metrology index creation’

The discussion and examples in previous sections has shown the need and importance of creating a comprehensive error index for industrial machine tools. Where many machine tool metrologists have identified this need there is still no go-to solution for creating such indices for any machine tool. Although attempts have been made to resolve this issue, mainly through ISO 230-1 (2012), this methodology is unlikely to be adopted by industry. The researcher therefore concludes that, the most important reasons for this are:

- *Unlimited machine tool configurations*: The almost infinite variety of machine tools due to the factorials of axes configurations and auxiliary systems; this is a significant challenge facing machine tool users who wish to better understand the capability of their machining systems. A one size fits all may never be found.

- *Missing error parameters:* It is very difficult to validate a ‘Metrology Index’ for a new machine without some sort of validation and peer review. Therefore, users are likely to always have much doubt that they are missing something and therefore default to relying on the OEM to provide such information.

Additionally, there is ambiguity in which parameters need to go onto an index or not i.e. probe calibration, thermal influences, dynamic tests, spindle tests.

- *Generating interest from machine tool manufacturers and industry:* Everyone that has interest in or affected by machine tool capability in some way or form can be convinced that the creation of a metrology index for each and every machine tool is of great importance. This is especially the case for OMI implementation. However, OEMs are not eager to provide a full index of tests in which their equipment should be assessed on. However, with regards to machine acceptance, many machine tool buyers may not want additional complication other than pass and fail i.e. having a metrology index with specified tolerances can likely delay acceptance of a machine tool despite a proven ability to manufacture the product.

- *Development of CAD-CAM packages*: Users are requesting 3D kinematic models from OEMs more than ever to meet needs of their CAD-CAM solutions [246]. Here full virtual kinematic models are available to simulate the machining process and are often necessary for generating and post-processing NC code as well as detecting machine collision points. With this technology becoming more readily available the next step is to perhaps link measurement information to kinematic details. As such, their systems can be used to define all errors based on known configuration, freedoms of movement and kinematics.

5.18 Conclusion

In this chapter the researcher has explored and proposed the novel concept of the 'Machine tool Metrology Index'. An index created for any particular machine tool can be used to confirm and categorise machine tool parametric errors which are fundamental to machine tool on-machine inspection. This form of identification enables machine tool users to choose, and be in control of, the most appropriate solutions and opportunities to measure them. The ISO 230-1 (2012) standard has made an attempt to provide a methodology for the creation of such metrology indices. However, the researcher has illustrated that the process presented requires considerable skill and knowledge to implement it. Additionally, it has been shown that this approach is not robust enough for industrial application. The alternate solution, to follow machine tool builder specification sheets, has also proven to be flawed.

As machine tool users drive to repurpose their equipment as traceable measurement systems they also aim to understand and improve their true capability. Following this, they eventually wish to define capability values for their equipment i.e. classify machine tools by a grading system. This is becoming more and more relevant since metrologists familiar with CMM equipment and dimensional metrology are unlikely to understand the principles of machine tool design, capability and metrology as well. This is primarily because this is an environment and situation, they are not familiar with, especially with regards to how multi-axis machine tools are calibrated and maintained.

The researcher believes that those who are writing machine tool standards are aware of this challenge and thus endeavour to work towards a robust solution. However, the current solutions; 1) to rely on the ISO 230-1 (2012) system; 2) rely on OEM intervention; 3) create metrology indices by committee are potentially not viable solutions in the long term. A more likely solution may be perhaps to make the most of virtual machine tool models often found within commercial CAD-CAM software packages [246]. This is therefore an area for potential future study.

Chapter 6

Rapid machine tool calibration to enable industrial OMI

6.1 Introduction

The regular calibration of machine tools is a key requirement for manufacturing companies, especially those who wish to maintain their assets to a high level of precision. More often this function is performed on an annual basis. To enable capable on-machine inspection there is a core need for measurement to be performed more frequently and robustly. Chapter 2 has shown that there is a wide body of knowledge and array of technology associated to the measurement of machine tools. Chapter 5 has presented and demonstrated a method for the creation of error indices for machines of different configuration. It has been demonstrated that it is critical to measure and understand these errors as the configuration and variation of these have a direct impact on a machine's overall capability, and hence OMI performance. It has been shown that a 5-axis machine can potentially have in the region of 50 error parameters, all of which may have an impact on OMI performance.

As highlighted in Chapter 2, it is recognised by industry that all machine tool errors need to be fully understood, in terms of impact on machining or measurement task, and either corrected or compensated for to guarantee task-specific performance. Additionally, chapter 2 has presented several commercially available devices that have been used to measure machines for many years. However, in practice, using these devices it is found that it typically takes up to five days to fully measure an industrially based multi-axis machine. The amount of downtime necessary to fully profile a typical multi-axis machine tool is considered too expensive, resource intensive and not generally acceptable by industry. This indirectly presents a major block preventing OMI being enabled on production machine tools.

Although maintenance engineers strive to reduce measurement time for machine tools located within a particular manufacturing facility, it is found that this is no straightforward task. This is due to:

- the variability of machine tools in terms of their control systems, sizes, configurations and nuances;
- the plethora and technical complexity of available 'off-the-shelf' machine tool measurement equipment;
- the limited availability of skilled measurement equipment operators;
- the limitations of current standards and guidance in terms of improving measurement efficiency;

As indicated by the literature review there is little academic work done on investigating the total process of machine tool measurement (i.e. from machine hand-over to hand-over) with a focus on process optimisation.

In order to gain commercial advantage, it is normal for measurement system equipment providers to make exaggerated claims about the speed of their systems. However, the experience of the researcher and anecdotal evidence suggests that these are optimistic at best and almost certainly do not reflect the start-to-finish time of a typical measurement; which must include time to unpack, setup, thermally stabilise equipment, measure, process data and equipment re-packing and handover.

In this chapter, the researcher considers and investigates the entire process of calibration within an industrial environment. Subsequently, proposals are made in terms of new next generation measurement systems, which are likely to enable a step change in machine tool measurement time. These systems are subsequently tested in an industrial and academic setting. The work contained within this chapter has been supported and validated by the University of Huddersfield – Centre for Precision Technologies, Machine Tool Technologies Ltd. and Rolls-Royce plc.

In this study the term 'calibrate' is defined as the correlation of readings (of an instrument) with those of a standard in order to check the instrument's accuracy [247]. In this case the instrument is the machine tool. The adjustment of machines post measurement (i.e. applying physical and/or electronic corrections) is considered as out-of-scope, as this is likely to vary considerably from machine-to-machine, due to factors such as age, location, type, size, cost etc. Hence, this decision has been made to ensure external validity of this study.

6.2 Selected machines

The machines as per Table 6-1 have been selected for this study. These machines have been chosen as they are considered ‘representative’ for the production of high precision aero-engine components. For consistency these are the same machines as chosen for investigation in Chapter 5. As such metrology indices have been produced for the machines, as presented in Appendix B.

Table 6-1: Chosen machine tools for case study

Machine Type	Manufacturer	Controller Type	Axis Count	Axis Travel (mm and degs)				
				X	Y	Z	B	C
Machining centre	Makino MCD2016	Fanuc Pro 5	5	2000	1600	1300	115°	360°
Horizontal Slant-bed Lathe	Puma 400	Fanuc 18i-T	2	725	110	-	-	-
Horizontal Mill-Turn	Mazak Integrex 35	Mazatrol T Plus	4	900	1100	1600	-	360°
Vertical Turning Lathe	Okuma V55R	OH-OSP-LG II	2	680	635	-	-	-
5-axis Router	Geiss	Siemens	5	2450	1300	800	120°	360°

6.3 Categories of calibrators

Current best industry practice in time required for calibration will vary with different providers. To reflect this, span the study considered the calibration being performed by four different classifications of people, with different training levels, equipment and familiarity (regularity of use).

Timings are predicted for:

- Regular service engineer
- Factory maintenance engineer
- Machine builder (OEM)

- Academic who is experienced in machine measurement in both academic and industrial settings

The rationale for these categories is provided in

Table 6-2 and is largely influenced by the regularity with which they conduct calibration of machine tools. This is reflected in the estimates made in the remainder of this section.

Engineers having completed advanced training courses will show a high level of aptitude and skills. However, if they do not have the opportunity to use these skills on a regular basis they soon suffer appreciable drop-off in speed. This phenomenon is particularly prevalent in the use of laser interferometry.

Another factor to note is the level of uncertainty management. The timings for the academic category take into account at least two bi-directional runs for each piece of data since experience has shown that measurement drift and non-repeatability results are not possible using only a single run [81]. A typical example of this is an electronic level which requires time to stabilise, but for which manual measurements are time-consuming. The academic is likely to have produced an automated solution to make the capture more convenient, permitting multiple runs.

Table 6-2: Capabilities and characteristics of typical machine tool calibrators

	Machine Tool Service Engineer	Factory Maintenance Engineer	Machine Tool OEM	Experienced Academic
Equipment Skill	Maintains good level of industry standard equipment able to perform a number of measurement tasks	Has a basic stock of measurement equipment, typically bought against a specific process	Owns measurement equipment required to perform machine installation tasks	Often has access to latest technology
Familiarity with machine tool calibration	Familiar with a wide range of machine tool configurations and controllers	Very familiar with equipment due to nature of job	Very familiar with machine, also has access to proprietary information	Experience with using measurement technology. Will be unfamiliar with specifics of new machinery
Experience	Measurements are conducted on daily basis due to nature of job	Measurements are performed less frequently due to production pressure. Less experience with using equipment	Typically, measurements are made to apply linear compensations. Full calibration is rare	Calibrations conducted frequently on own equipment time and lack of pressure allows for extensive familiarity with equipment
Skill level	Good understanding of principles of measurement and application of	Trained personnel will have good understanding of principles of measurement. Infrequent application likely to reduce competence.	Has been trained to use equipment as a tool. Often does not have thorough background knowledge of equipment.	Has thorough understanding of measurement principles
Motivation	Makes measurement as efficiently as possible, due to nature of job. Has systems in-place to ensure traceability for repeating work or allowing hand-over to colleagues	Owner of the measurement process, often interrupted due to other calls on time	To ensure the machine is seen to be capable	Interest in data collected and understanding. Likely to take extra time for unnecessary measurements and on-site data analysis,

6.4 Research method

Data, experience and testing has been sourced from providers of metrology equipment, measurement experts, machine tool service engineers, international standards and leading practitioners. In addition, several timing studies were conducted as part of the process.

A workshop was conducted to capture the time estimates for each group detailed based upon the experience of suppliers and customers of this type of service. The study is based upon the assumption that there is a team of two carrying out the measurements. This is typical both from a health and safety requirement and from an efficiency point of view.

It was decided to break the calibration task down into three broad areas:

- Those generic aspects that apply to all machines, such as programming the controller, described below as “Procedural items”
- Timings for running the tests on the target machines described below as “Machine configuration-specific tests”
- Other items out of the scope of the timing analysis were also captured as “Additional items”, to be later considered in a Process Failure Mode Effects Analysis (PFMEA) and Strengths Weakness Opportunities Threat (SWOT) analysis.

6.5 Non-machine specific items

“Fixed” timing costs for a calibration are an estimate based on an average machine. This is derived from experience of a wide number of machines and configurations measured in a wide variety of environments and companies. This aspect is particularly difficult to capture since experience shows that on the worst of machines some tasks, estimated as thirty minutes, can take several hours.

The analysis breaks down those items that require the machine (downtime) and those which must be undertaken but would not require the machine to be out of production – for example, taking the equipment to the machine does not require a halt in production. Writing part programs can be largely achieved offline but does require some interaction with the machine: at a minimum dry running, but often some element of debugging.

6.6 Machine specific items

The tests detailed in Appendix B.1-4 constitute the measurements required for the specified Rolls-Royce example machines, these have been generated by consortium as described in Chapter 5. Additionally, Appendix B.4 of this document details the list of measurements required for a Geiss 5-axis machine at the University of Huddersfield.

Timings for each test were estimated based upon the equipment each category of engineer would be likely to use, skill levels, previous set-ups, etc.

6.6.1 An example: Straightness of the vertical Z-axis in the horizontal X-axis direction

The service engineer would use:

- a laser to measure Z-axis positional error,
- a granite square to measure squareness and use the side of the square to measure the Z straightness in X

The academic would use:

- a laser to measure Z-axis positional error,
- a granite square to measure squareness but a laser to measure the Z straightness in X

Both parties have to line up the laser for positioning and the square for squareness, but the setup cost for the academic to take Z straightness in X is higher because the time to adjust the laser and take the measurements is longer than the time to measure from the square.

However, the laser is likely to give more repeatable results and can cover more of the axis stroke.

6.7 Site specific items

Such items are those procedural items that either could have a particularly wide range of times or would add too much uncertainty to the timing results. For example, reinstalling a manufacturing fixture on a machine can take anywhere from five minutes to an entire shift, depending upon the requirements for lifting equipment, alignments, etc. From experience, the use of Manual Data Input (MDI) mode on the CNC instead of automatic mode is particularly prevalent among OEMs but adds a 20% uncertainty to the timing estimate for the measurement run. Table 6-3 contains some examples of such items.

Table 6-3: Machine tool calibration activity considerations

Consideration	Notes
Machine covers/guarding removal	Only needed if measuring ballscrew/scale temperature. In principle, the cover should then be replaced (with sensor in situ) during test
Machine covers/guarding replacement	Only required if the cover has been taken off
Fixture removal/replacement	Variable, and sometimes not possible
CNC backup	Required if the true mechanical accuracy is needed (healthcare), but not if only interested in the present state of the machine
Safety interlock by-pass	If there is a requirement (often due to measurement equipment cabling) to have the machine doors open whilst testing
Programming the test in MDI rather than Automatic mode	Setup time is reduced (i.e. no requirement to write-prove part programs), but measurement time can be increased
Data collation and report writing	Highly dependent upon the quality of information, IT proficiency of the calibrator and depth of analysis. This can be from 5 minutes (for automatic output) to several days.

6.8 Further considerations included in the analysis

When calculating the downtime, it is important to look at the length of time the machine would be out of service in terms of working days. Calibration work is often double-shifted as good practice. Therefore, an estimate of lunch breaks and tea breaks is also included.

Furthermore, a normal shift of eight hours has been assumed for each category except the service engineers who are assumed to work a ten-hour day. Within this analysis, the travelling time of all off-site individuals is included in the calculation, while that for factory maintenance is assumed as zero, ignoring any required inter-site travel.

6.9 Downtime estimations

Figure 6-1 presents estimations of the total time required for the calibration to take place on each of the machines using contemporary measurement methods. The chart also indicates expected measurement times depending on the operator of the measurement equipment, being: an experienced academic, machine tool OEM, factory maintenance staff, or a regularly practicing machine tool service engineer. The Makino and Geiss machines are estimated to take the most time, due to them being relatively large 5-axis machines. The Puma lathe is expected to take the least amount of time due to it being only a 2-axis machine. For each machine type, it was estimated that maintenance engineers and machine tool OEMs would take longer to measure machines tools. This for reasons stated in Table 6-2.

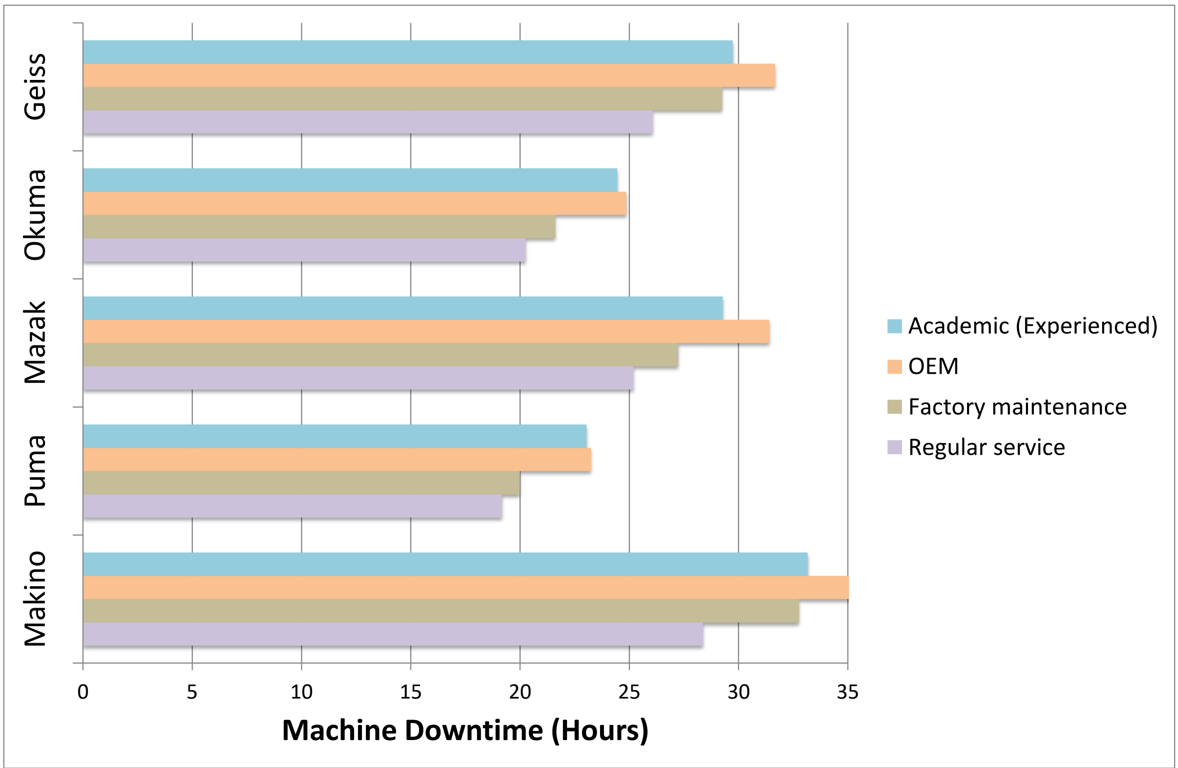


Figure 6-1: Estimated total time for measuring the target machines

Table 6-4 presents the raw data from Figure 6-1. It is clear from these estimates that the familiarity of the dedicated service engineer produces the quickest results, with the advantage being greatest on the most complex machines. The 5-axis Makino has a range of eight hours between different groups, equivalent to a half or full operational shift.

Table 6-4: Estimated machine downtime for target machines (hours)

	Regular Service Engineer	Factory Maintenance Engineer	OEM Engineer	Academic (Experienced)	Average	Range
Makino (5-axis)	22.5	30.5	30.1	27.2	27.6	8
Puma (2-axis)	13.3	17.7	17.6	17.1	16.4	4.5
Mazak (5-axis)	19.3	25.0	25.8	23.3	23.4	6.5
Okuma (2-axis)	14.4	19.4	19.2	18.5	17.9	5.0
Geiss (5-axis)	2.6	27.0	26.0	23.8	24.3	6.8

Figure 6-2 presents, to the same scale, estimates of machine tool downtime only, for each machine. The downtime only figures are mirrored in Table 6-5 but converted as shifts.

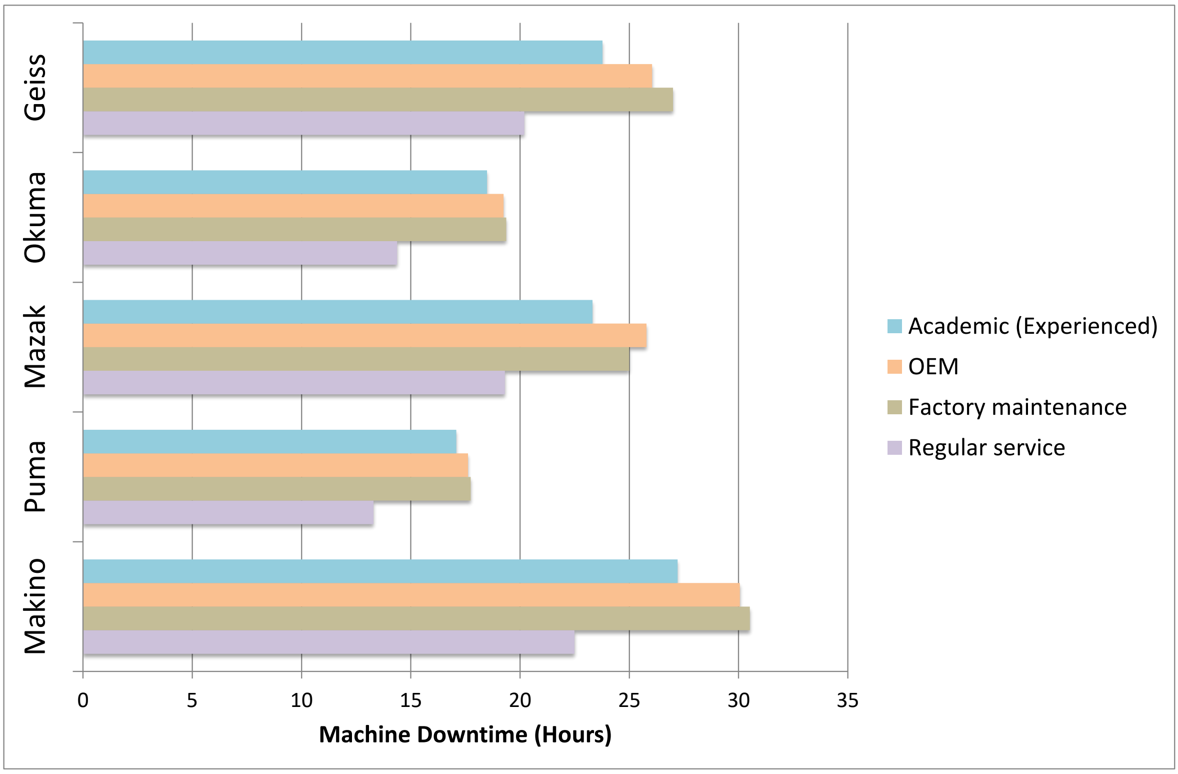


Figure 6-2: Estimated downtime for measuring the selected target machines

Table 6-5 indicates that regular service engineers are likely to cause the least downtime, whereas factory maintenance engineers and machine tool OEMs are likely to be more disruptive. Again this is likely to be due to equipment skill levels, measurement system and machine tool familiarity, as well as experience and motivational aspects.

Table 6-5: Estimated downtime (shifts) for target machines (8 hour shifts)

	Regular Service Engineer	Factory Maintenance Engineer	OEM Engineer	Academic (Experienced)	Average	Range
Makino (5-axis)	2.9	3.9	3.8	3.5	3.5	1
Puma (2-axis)	1.7	2.3	2.3	2.2	2.1	0.6
Mazak (5-axis)	2.5	3.2	3.3	3.0	3.0	0.8
Okuma (2-axis)	1.8	2.5	2.5	2.4	2.3	0.7
Geiss (5-axis)	2.6	3.4	3.3	3.0	3.1	0.8

Table 6-5 shows that, depending on machine and measurer, the amount of machine tool downtime required ranges between two and four 8-hour shifts. Assuming that a single two-person team undertakes the calibration for continuity, this effectively requires up to four days of downtime. Table 6-5 also indicates that, irrespective of measurement equipment used, the equipment operator can influence machine downtime to the extent of a full or half machine shift.

6.10 Hypothesis validation – University of Huddersfield 5-axis machine

Validation of the time study was undertaken by monitoring the time required to measure a 5-axis machine tool by a senior, highly experienced engineer within a machine tool service company. It can be considered that the engineer undertaking the exercise represents the quickest that it could be expected to take the data with the present technology.

6.11 Limitations of validation

Although the validation was conducted in as scientific a manner as possible, some limitations need to be acknowledged.

Within this study, the engineer did not perform the tests shown in Table 6-6 largely because manufacture of suitable brackets would have been economically or technically unviable. For example, the uncertainty of the A-axis positioning measurement would have outweighed the benefits. For those elements that were not measured, the value used in the analysis was that of the estimate. There is also some potential cumulative error on the uncertainty of timing each measurement.

Table 6-6: Tests omitted during timing validation on the 5-axis Geiss machine

Test	Reason for omission	Estimated time for Service Engineer (mins)
Test 15 – Z axis about Z axis (Roll)	No suitable equipment available (Requires two laser straightness measurements)	60
Test 37 – A axis positional accuracy	No suitable bracket for mounting	70
Test 38 – A axis accuracy and repeatability	No suitable bracket for mounting	40
Test 39 – C axis positional accuracy	No suitable bracket for mounting	70
Test 40 – C axis accuracy and repeatability	No suitable bracket for mounting	20
	TOTAL	260

6.12 Results of validation study

The service engineer utilised in this study was very familiar with the machine, having used it a number of times for research work, demonstrations during training courses, etc. This meant that the procedural items and the tests themselves were carried out perhaps more efficiently than might normally be expected.

Table 6-7: Comparison between estimated and actual times for procedural items

Item	Estimated **(mins)**	Actual (mins)	Contributors to downtimes
	Fixed Costs		
Break out equipment	60	30	0
Align laser linear 1 (Horizontal)	10	8	1
Align laser linear 2 (Horizontal)	10	8	1
Align laser linear 3 (Vertical)	15	12	1
Fixture off	30	0	1
Tidy up equipment	30	0	0
Offsets and handover	30	8	1
	Variable costs		
Part program writing	30	7	0.25
Part program transfer and test	30	60	1
Machine 'features'	60	0	1
Awkward set-up premiums	30	0	1
Misfire/Lost reading during test	10	10	1
Investigation	15	8	1
	Conditions		
Cool down	0	0	1
Cleaning machine	60	0	1
Travel time	240	360	0

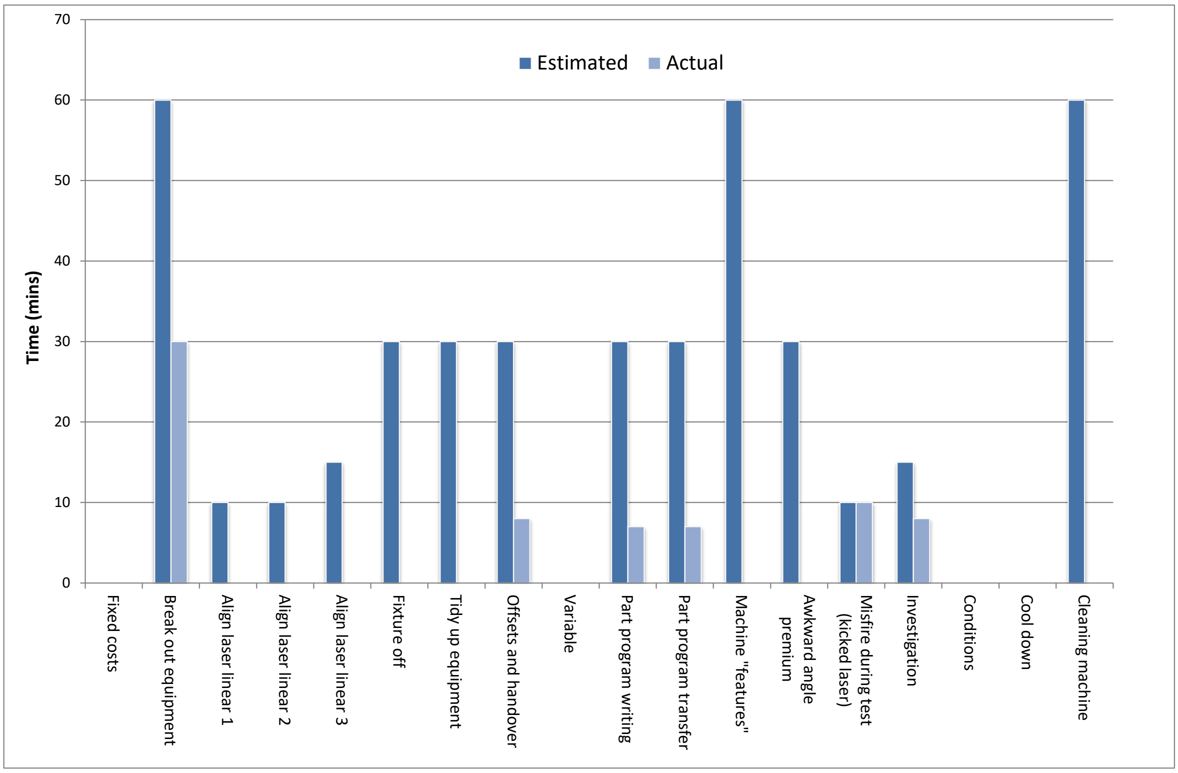


Figure 6-3: Comparison between estimated and actual times for procedural items

Similarly, the tests (detailed in Appendix B.4) were each conducted with great efficiency, as might be expected of someone using this equipment on an almost daily basis. Figure 6-4 shows the comparison between estimated and actual time for each test.

The largest anomaly is test 31, "C-axis zero setting" which took more than six times the estimate.

One reason is that the engineer chose to "fix" the problem when first measured. This is outside the scope of the study, but the data remains in the analysis because this sort of outcome is quite common. If an engineer with experience takes the trouble to set up and measure an artefact, and then has the capability to repair a fault (update a parameter in the controller) then the psychology of the job often leads to this type of reaction. Furthermore, the "fix" should only have taken 10 minutes yet took significantly longer because the re-measuring indicated non-repeatable behaviour.

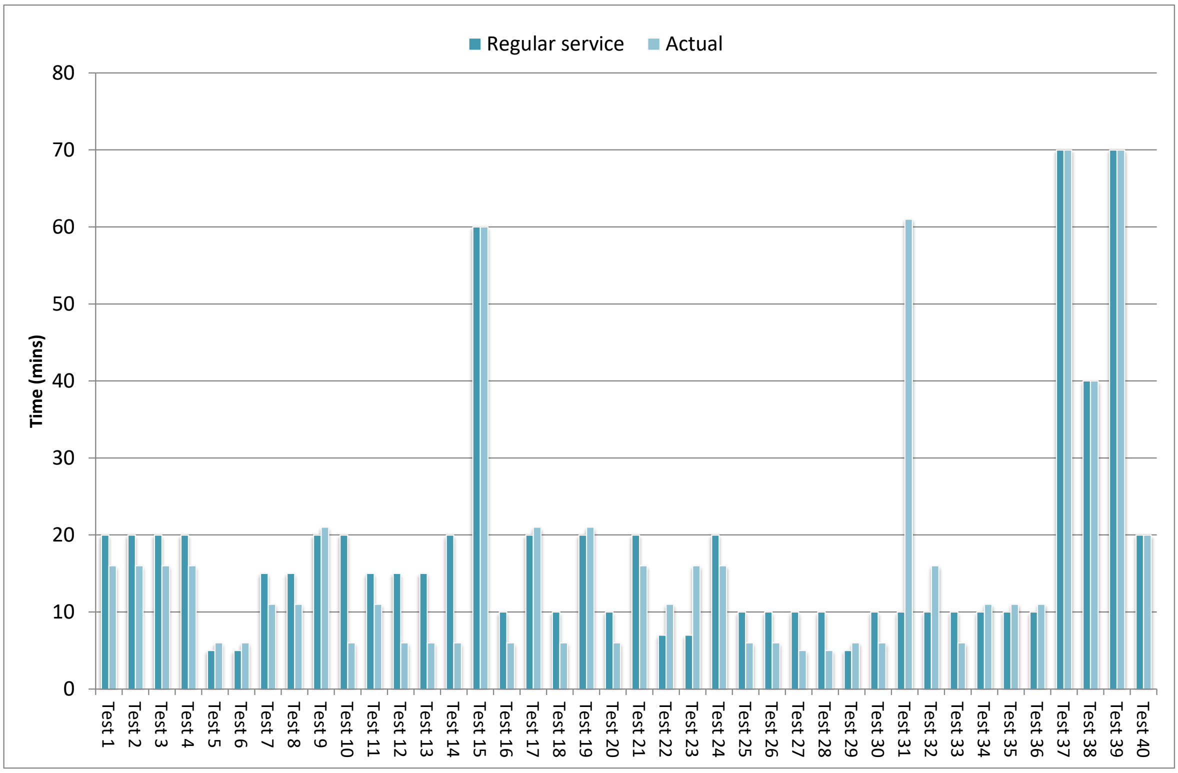


Figure 6-4: Comparison between estimated and actual times for conducting tests as per metrology index for Geiss machine

6.13 Validation study - Discussion

The summary of the main sections for downtime is given in Table 6-5 and more visually in Table 6-8. This clearly shows that the estimation for each test is very close since there is only a difference of 41 minutes between the estimated and actual measurements over the full forty tests.

Table 6-8: Comparison between estimated and actual times for measurement and procedural items for the Geiss machine calibration

	Estimated (mins)	Actual (mins)	Difference (mins)
Measurement	724	683	41
Procedural	308	63	245
Totals	1032	746	286

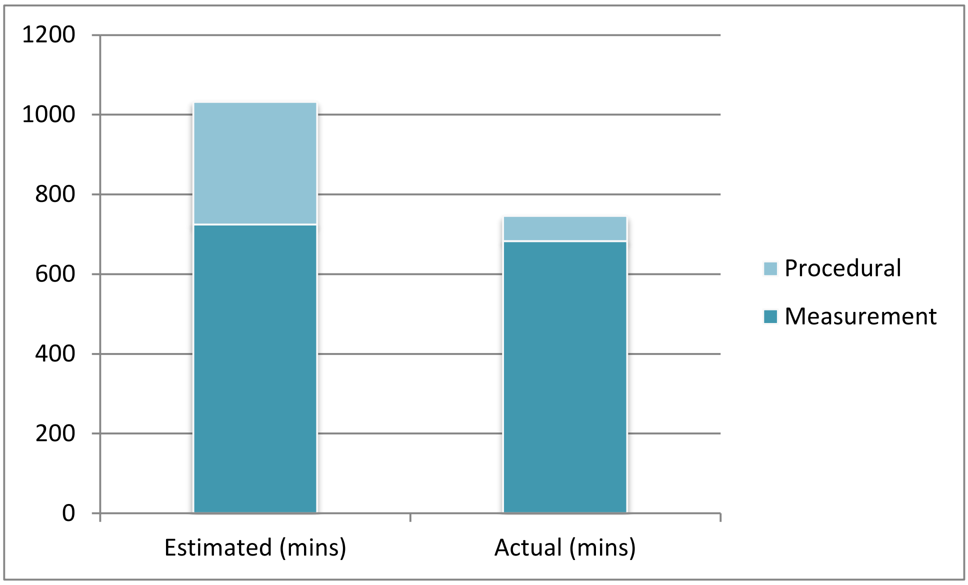


Figure 6-5: Comparison between estimated and actual times for measurement and procedural items for the Geiss machine calibration

The estimation for procedural items was less applicable to this machine, with a large discrepancy of over four hours. This skewing comes from the choice of machine for this exercise. The Geiss 5-axis machine was familiar to the engineer and it is presently being used for research in machine tool metrology. A breakdown of the discrepancies in the analysis is provided by the pie chart of Figure 6-6 which shows the values of the six major contributors which between them account for over 90% of the estimate error.

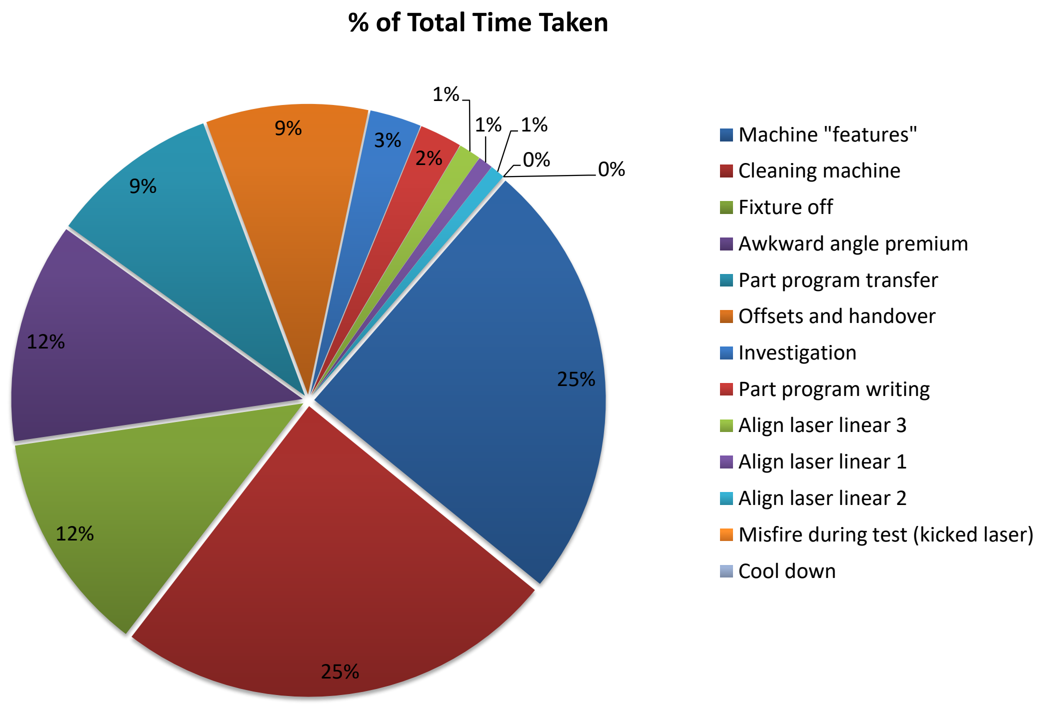


Figure 6-6: Pie chart illustrating time contributions of procedural items

Figure 6-6 illustrates that the half of total time taken is lost through having to clean the machine and dealing with machine tool nuances/features. Other relatively long lead-time items include removing fixtures and dealing with awkward measurement equipment set-ups. Finally transferring measurement part programs is seen to be an issue, and as indicated by the 'Misfire' item, mistakes are costly.

Table 6-9: Major contributors to the shorter times than estimated for the Geiss machine measurement

Item	Difference (mins)	Reason for discrepancy
Machine "features"	60	Engineer was very familiar with this machine, having used it to provide training
Cleaning machine	60	Machine already clean due to measurement activities prior to study
Fixture off	30	No manufacturing fixturing present
Difficult set-up premium	30	A very open machine with good access. Side panelling had already been removed
Part program transfer and testing	23	Modern controller on machine. Programs easily transferred via USB key.
Offsets and handover	22	Not a production machine therefore not relevant

Table 6-9 highlights and presents explanations discrepancies between estimates and actual findings. Such discrepancies have been accounted for by the engineer's familiarity with the machine in question, its cleanliness, and the lack of fixturing and ease of set-up.

6.14 Equipment considered for next generation rapid machine tool calibration

A full list of equipment considered in this investigation is included in Appendix C. A preliminary down-selection was made from this list to identify the most likely technologies to be able to achieve the aim of reducing measurement time to a minimum (Appendix C). This section of the chapter covers the equipment considered after this preliminary down- select which have been investigated in greater depth. All items of equipment are, as claimed by their respective manufacturers, 'upgrades' to previous systems. Therefore, it is expected that measurement precision is better than or equivalent to their predecessors as presented and investigated in Chapter 2.

6.14.1 Linear axis measurement – Renishaw XM-60 (6DoF) Laser Interferometer

The Renishaw plc. XM-60 6DoF (Figure 6-7) has been designed to capture multiple linear axis errors in a single pass. This laser interferometer based system is the expected predecessor to the XL-80 laser interferometer [120]. This system is not yet on commercial sale, but has been used by Renishaw themselves internally to calibrate CMMs. The University of Huddersfield has been testing pre-production versions of the system to assess their suitability for calibrating machine tools. The research engineer, via Rolls-Royce plc., has been granted access to the system.

Advantages of the system are the ability to measure all six axial errors in a single pass and an efficient method of application. In particular, proprietary Renishaw technology enables vertical axis roll to be measured – one of the few systems capable of this. Key features of the technology are presented in Figure 6-7.

Disadvantages of the current version of the system are a perceived lack of robustness in the unit (being addressed by Renishaw) and a range limitation of a few metres. In its present configuration, the system cannot measure squareness.

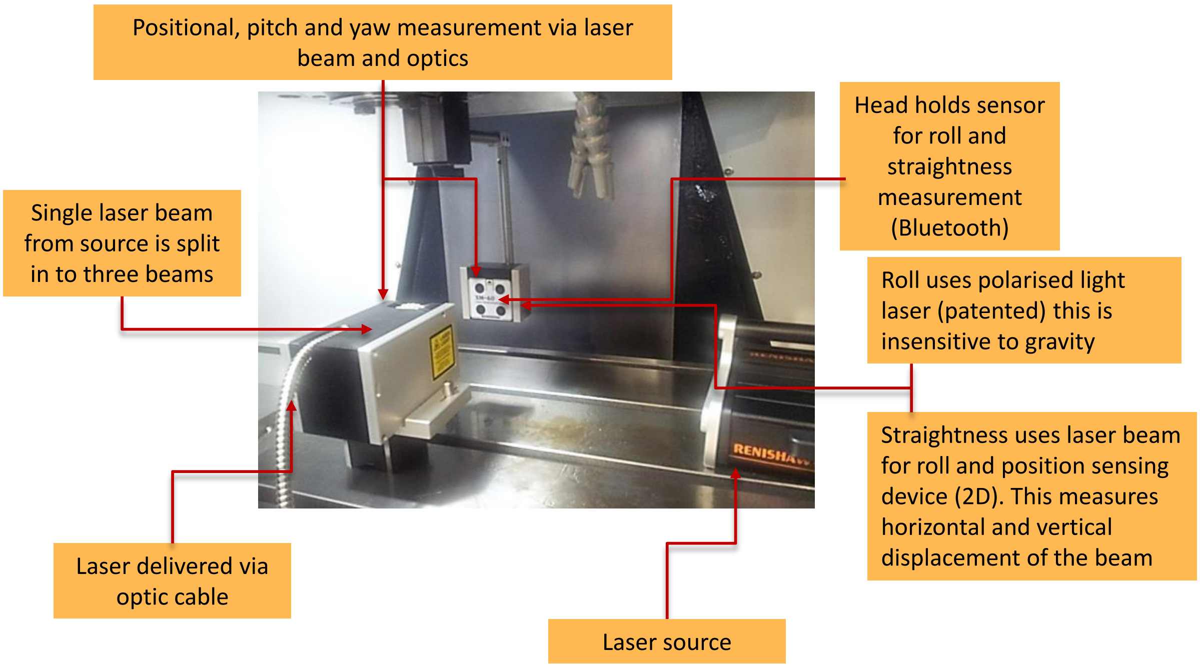


Figure 6-7: Renishaw plc. XM-60 laser interferometer system (not yet released)

6.14.2 Squareness measurement – Renishaw QC20-W Double Ballbar

Ballbar systems have been historically designed for circularity checks providing suitable information for health checking of a machine. Renishaw plc. has taken the opportunity to gain additional calibration data from this technology. For example, the Renishaw QC Ballbar system has the capability to measure axes squareness. The measurement of squareness using a Ballbar has been investigated and verified by Khan *et al.* [112]. In this study Khan *et al.* demonstrate that using such a technology can be equivalent to using a traditional granite square method. A pre-requisite is however given, in that no significant angular errors can be present within linear axes.

The following systems remain possible supplementary solutions to the QC20-W ballbar, as they can measure squareness error in a similar fashion. However, these are not chosen as their measurement times are considered to be much longer.

- Heidenhain KGM grid encoder
- Renishaw QC10 Ballbar
- API Precision Ballbar

One key advantage of this QC20-W system is that it can be operated wirelessly, over a Bluetooth™ connection. This means that engineers can operate the equipment with all machine guards closed and locked. This saves considerable time due to the elimination of the need to bypass safety interlocks on the machine. Additionally, a lack of trailing cables also means that the equipment can be set-up and run with more ease and less likelihood of collision or cable snagging. Finally, the equipment can be used to perform a ‘volumetric measurement’ whereby all three axes can be measured using a single set-up, as such three squareness values can also be measured (Figure 6-8: Renishaw QC20-W Ballbar measurement).

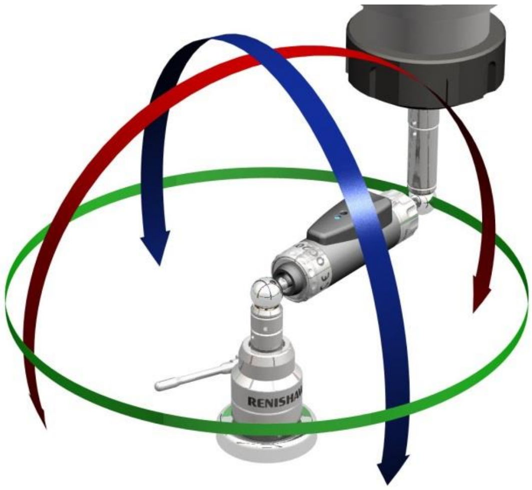


Figure 6-8: Renishaw QC20-W Ballbar measurement system (Source: Renishaw)

6.14.3 Rotary axis measurement – Renishaw XR20-W rotary indexer

The Renishaw XR20-W (Figure 6-9) has been designed and commercialised in conjunction to this research exercise. It follows the same principles of maintaining the direction of a return beam to a separate laser interferometer as per technology described in chapter 2. The motion in the unit is based upon Renishaw’s REVO technology [199], so provides a continuous motion, rather than only indexing. The unit is more symmetrical than its predecessor, significantly lighter and smaller, making it applicable to many more machines. These features enable a significant improvement with regards to equipment set-up time and effort. A major improvement also includes wireless capability and the ability to perform ‘off-axis’ calibrations. This is important as there are many rotary axes, especially on 4-and 5-axis machining centres, where it is difficult to access the point of rotation and where there is no convenient mounting surface, as illustrated by Figure 6-9.

One significant disadvantage with this new equipment is a reliance on an XL-80 laser interferometer to provide the laser source and receiver to take measurements. This means that should the equipment be required, one must also set-up and align a XL-

80 laser interferometer system in addition to the XM-60 laser interferometer, which is chosen as the primary system for performing interferometric measurements. Although it is not anticipated that this will significantly increase machine tool measurement time it will however provide a cost consideration for machine tool calibrators i.e. the requirement to procure a piece of equipment at considerable cost only to perform a narrow scope of measurement tasks.

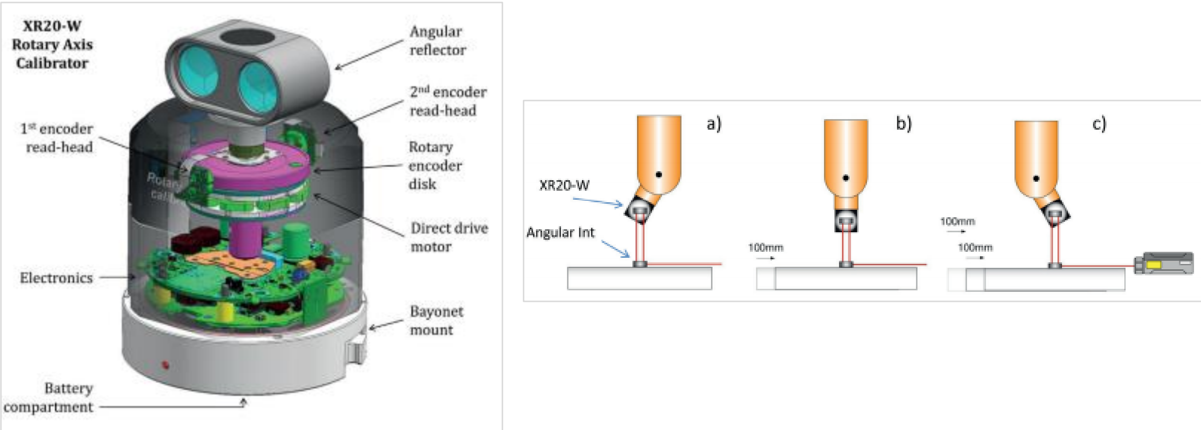


Figure 6-9: Renishaw plc. RX20-W wireless rotary indexing system

6.14.4 Rotary axis measurement – IBS Wireless R-Test

The non-wireless R-Test system has been presented in Chapter 2. In order to improve the performance of the equipment the researcher has worked with the equipment manufacturer and design improvements have been made. Such improvements include the wireless transmission of data, which in combination allows for the system to be installed via the machine tool changer and operated with machine guards closed. The wireless version also dispenses with the delicate contact plates and capacitance probes and replaces them with eddy-current probes that sense the ball surface directly. This means that there are no moving parts so the probe can withstand the forces involved in an automatic tool change. This combination of technology is expected to dramatically improve measurement times.

Figure 6-10: IBS Precision wireless R-Test system

6.14.5 Spindle measurement – IBS Precision Spindle Inspector

The researcher has worked closely with IBS Precision, the University of Huddersfield and the University of Bath to develop a novel spindle error checker device. With this new technology measurement can take place anywhere inside the machining volume; where measurement is taken using a probe ‘nest’ located within the machine. As indicated by Figure 6-11 the target is a high precision ceramic cylinder, which can be manually or automatically loaded into the spindle. When the cylinder is placed near the three capacitance sensors in the probe nest simultaneous radial and axial error measurements can be made on rotation of the spindle. The list of parameters that can be measured are:

- Synchronous radial error in X & Y
- Asynchronous radial error in X & Y
- Synchronous rotating radial error
- Asynchronous rotating radial error
- Fundamental axial error in Z
- Residual axial error in Z
- Asynchronous axial error in Z
- Axis shift in X, Y and Z

Figure 6-11: IBS Precision spindle check system

6.15 Test cases using primary machine tool calibration method

Utilising the aforementioned equipment time studies were conducted on following machines:

- Cincinnati Milacron 3-axis
- Okuma 3-axis
- Okuma 5-axis
- G&L 5-axis
- Mazak 4.5 axis slant-bed

All measurements in this study were performed by University of Huddersfield technicians supported by either on-site maintenance staff or Machine Tool Technologies Ltd. service engineers. In all cases test conditions for machine measurement were compatible with the ISO 230:2012 series specification. Linear and rotary axes were measured using five bi-directional runs to evaluate accuracy and repeatability. A minimum of 6 target points per metre were measured. All error measurements were made pseudo-static where possible, with the exception of linear axis squareness which was measured using a Renishaw QC20W Ballbar. This was to ensure that dynamic measurement results could not be confused with quasi-static results. With the R-Test, the error calculation is at the cardinal points, where the machine is paused.

6.15.1 Cincinnati Milacron 3-axis

Estimated optimum measurement time for this machine tool was 7:02hrs. The machine was measured using the selected technology in a total of 2:40hrs. Figure 6-12 presents the key contributors to machine downtime.

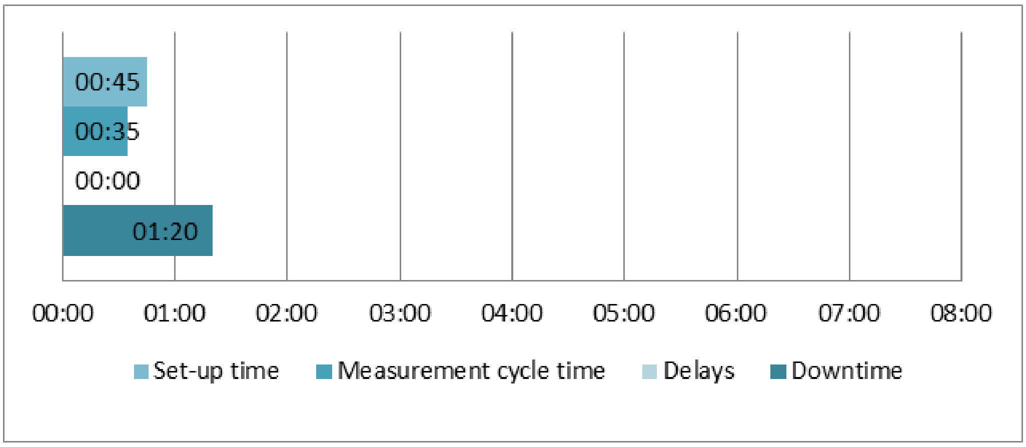
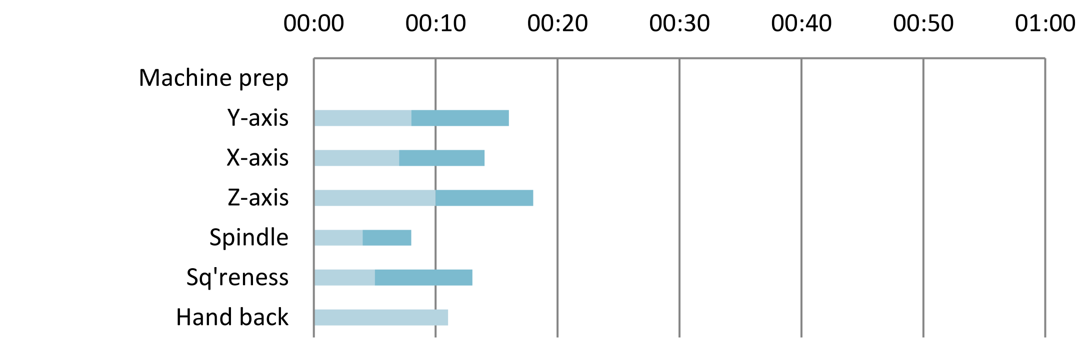


Figure 6-12: Cincinnati Milacron measurement time utilising rapid measurement solution

Figure 6-12, indicates that the equipment was set-up in 45 minutes and all measurements were taken in 35 minutes. There were no un-expected delays in the measurement task. Additional, non-measurement, downtime due to setting up part programmes and de-bugging contributed to 1:20hrs of total downtime. It is expected that this would reduce should the machine be measured again.

As indicated by Figure 6-13 all linear axes were measured in 48 minutes by University of Huddersfield staff.



	Hand back	Sq'reness	Spindle	Z-axis	X-axis	Y-axis	Machine prep
Set-up time	00:11	00:05	00:04	00:10	00:07	00:08	00:00
Measurement cycle time	00:00	00:08	00:04	00:08	00:07	00:08	00:00

Set-up time   Measurement cycle time

Figure 6-13: Measurement activity breakdown for Cincinnati Milacron

Figure 6-13 shows that each linear axis was measured in less than 20 minutes, including set-up time. Axis squareness was measured in less than 15 minutes. As University of Huddersfield staff were supported by on-site maintenance, the handover to and from production was also streamlined.

6.15.2 Geiss 5-axis gantry machine

Estimated optimum measurement time for the Geiss 5-axis machine utilising 'classical' methods were calculated as 24:37hrs. The machine was measured utilising the rapid measurement solution in less than 7 hours. Figure 6-14 presents the contribution of set-up, measurement, delays and downtime associated to the activity.

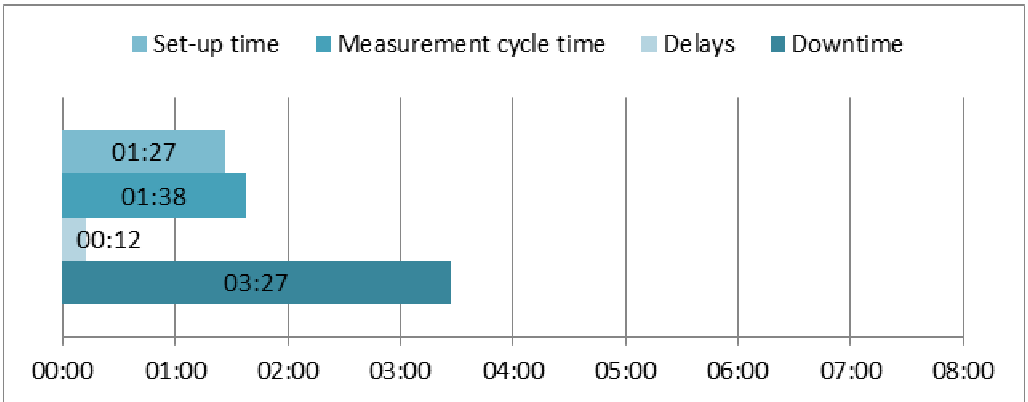


Figure 6-14: Geiss 5-axis measurement time utilising rapid calibration solution

Figure 6-14 illustrates that the combined equipment set-up and measurement times were less than other associated machine downtime activities. Part programmes took more time to write, implement and test due to the CNC controller and machine type. There was also an un-expected delay due to connection issues with the equipment being used.

Figure 6-15 presents a detailed breakdown of the measurement activity for the machine. As can be seen, each linear and rotary axis is measured in less than 30 minutes. The X-axis took the longest time to measure as this axis had the longest travel. The Z-axis linear measurement was more difficult to set-up, due to it being a vertical axis, hence the longer measurement set-up time.

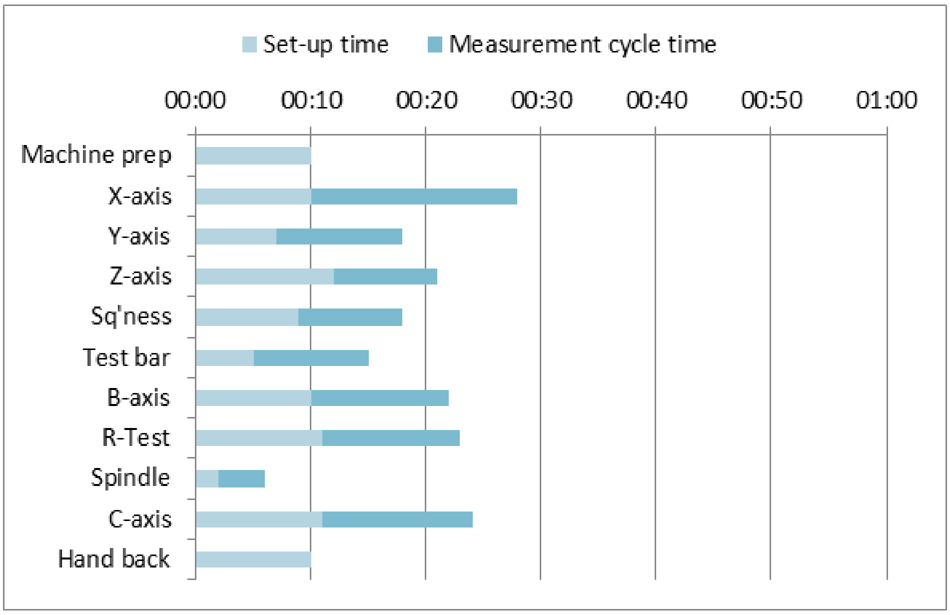


Figure 6-15: Measurement activity breakdown for Geiss 5-axis machine rapid measurement

6.15.3 Okuma 3-axis machine

Previous estimated optimum measurement time for the Okuma 3-axis machine was 7:42hrs. The machine was fully measured to its metrology index in 3:40hrs. This is illustrated in Figure 6-16. Once again activities related to delays and general machine downtime such as fixture removal, NC controller familiarisation and part programme writing took up a significant amount of time. Again, this time would reduce on the next visit to this machine.

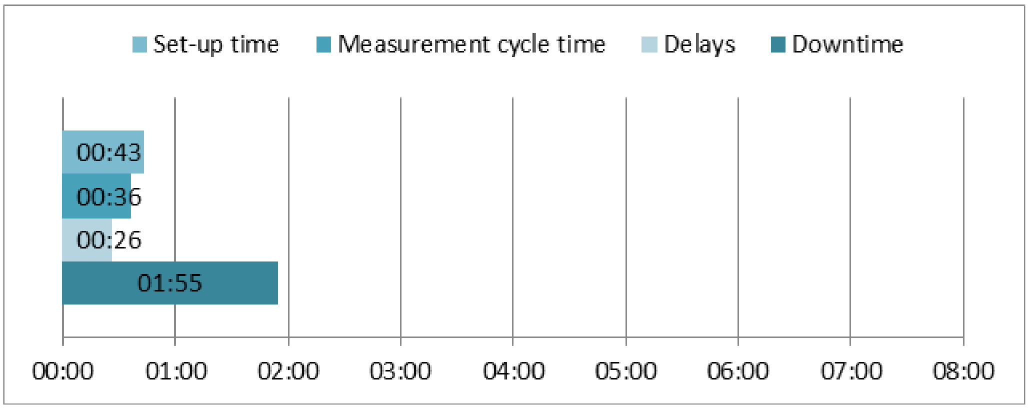


Figure 6-16: Okuma 3-axis measurement time utilising rapid measurement solution

Figure 6-17 indicates that all linear axis and squareness measurements were measured in less than 20 minutes each. The spindle measurement time was negligible as the IBS Spindle Check device was already installed on the machine.

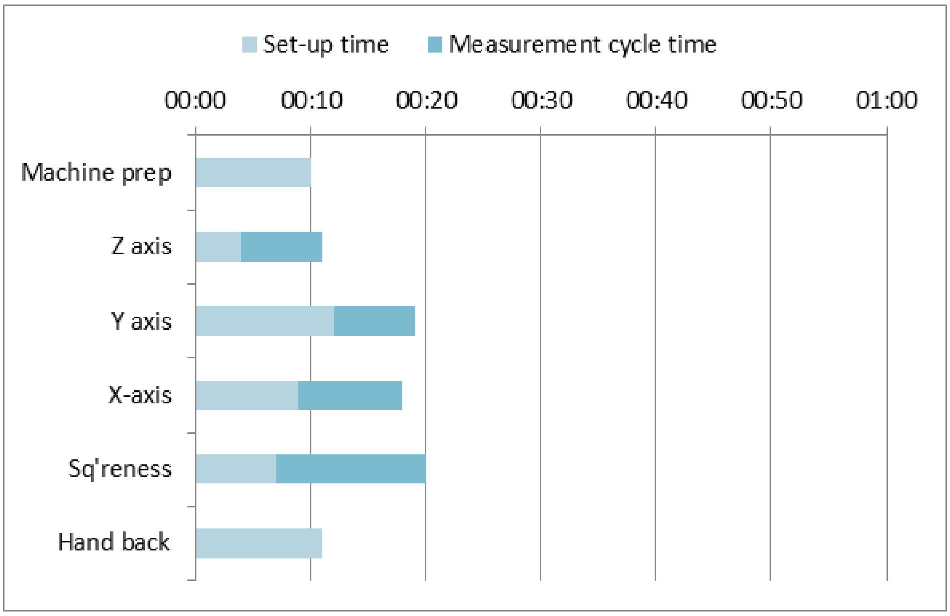


Figure 6-17: Measurement activity breakdown for Okuma 3-axis machine rapid measurement

6.15.4 Mazak Integrex 35 4 axis mill-turn machine

Previous estimated optimum measurement time for the Mazak Integrex mill-turn machine was 23:40hrs. All errors were measured in 10:50hrs by University of Huddersfield and on-site maintenance staff. Figure 6-18 details the breakdown of the entire measurement activity.

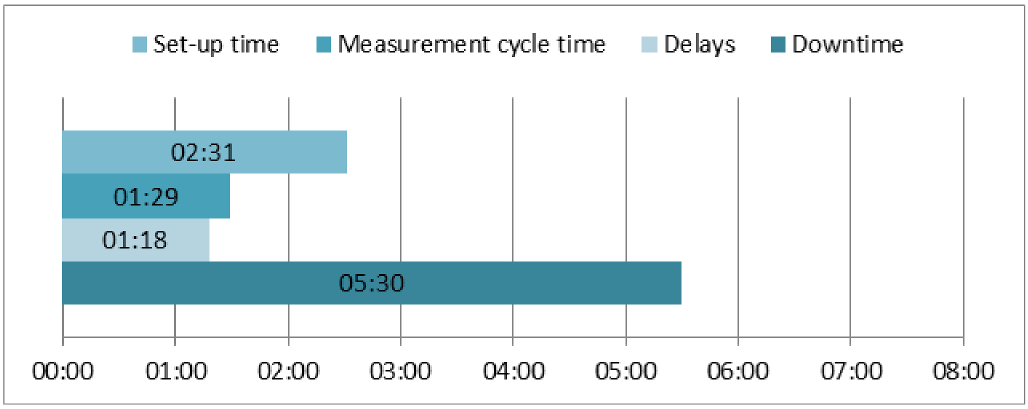


Figure 6-18: Mazak Integrex 35 measurement time utilising rapid measurement solution

Figure 6-18 once again shows that general downtime and delays contributed to a significant amount of the total measurement time. A major factor to this is that the machine in question had just come off a production cycle and therefore significant time was taken removing fixturing and machining swarf from the area. In this case also wireless communication between devices was troublesome and therefore machine guarding had to be removed and interlocks over-ridden. A further reason was that bespoke fixturing to mount measurement systems to machine axes was required, this was not available and therefore had to be created at the time of study.

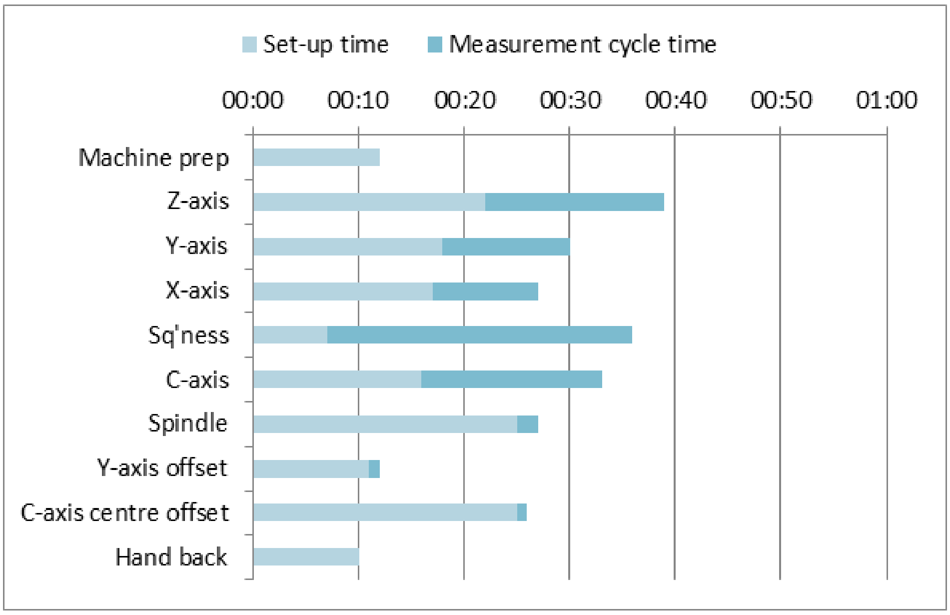


Figure 6-19: Measurement activity breakdown for Mazak Integrex 35 machine rapid measurement

Figure 6-19 indicates that set-up and measurement times were longer than in previous examples. This was attributed to the fact that the machine was of slant-bed configuration, which is a more difficult machine configuration to work-around.

6.15.5 Okuma Millac 5-axis milling machine

Previous estimated measurement time for the Okuma Millac 5-axis machine was calculated as 18:50hrs. All axes measured in less than 14:00hrs minutes by University of Huddersfield and Rolls-Royce on-site maintenance staff (Figure 6-20).

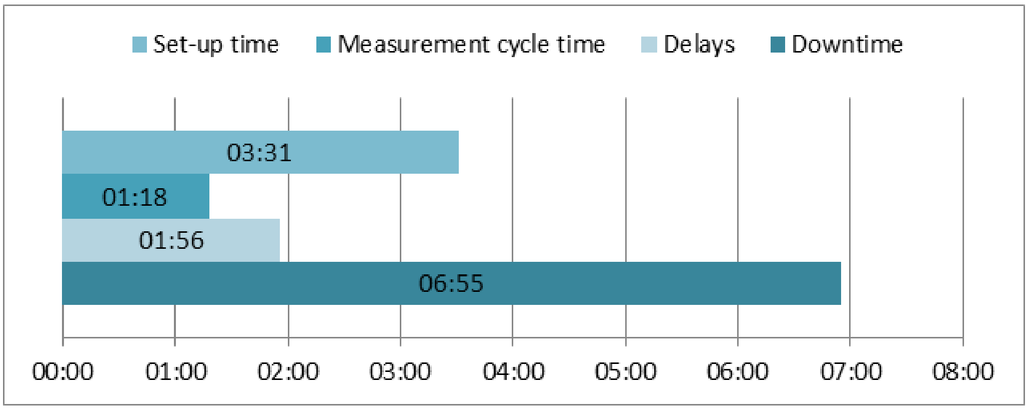


Figure 6-20: Okuma Milac measurement time utilising rapid measurement solution

Figure 6-20 shows that in this case downtime and un-expected delays contributed to a significant amount of the total measurement time. This is a clear illustration that the rapid measurement of machine tools cannot purely be achieved entirely by measurement technology. In this case the equipment was predominantly operated by Rolls-Royce maintenance staff whom were not familiar with the technology and whom only received the machine tool from production at very late notice. Capability with the machine tool NC controller was also a major delaying factor. With the controller being relatively old, this posed significant problems. To operate the R-test equipment synchronous multi-axis movements are required. This was not straightforward task on this machine tool as certain CNC controller settings had to be overridden. Additionally, programming the necessary multi-axis movements directly from the NC control panel was not easy. Such challenges are not expected to be an issue on newer multi-axis machine tools or where NC code can be produced offline.

Figure 6-21 illustrates that the set-up time for all measurement tasks contributed to the majority of measurement cycle time. This was attributed to the fact that Rolls-Royce maintenance staff were less familiar with the equipment being used and its operation. Additionally, there were additional fixturing challenges and there was a production requirement that certain product fixturing could not be removed from the working area. This meant that programs had to be tested thoroughly and at a slower speed to ensure collisions did not occur.

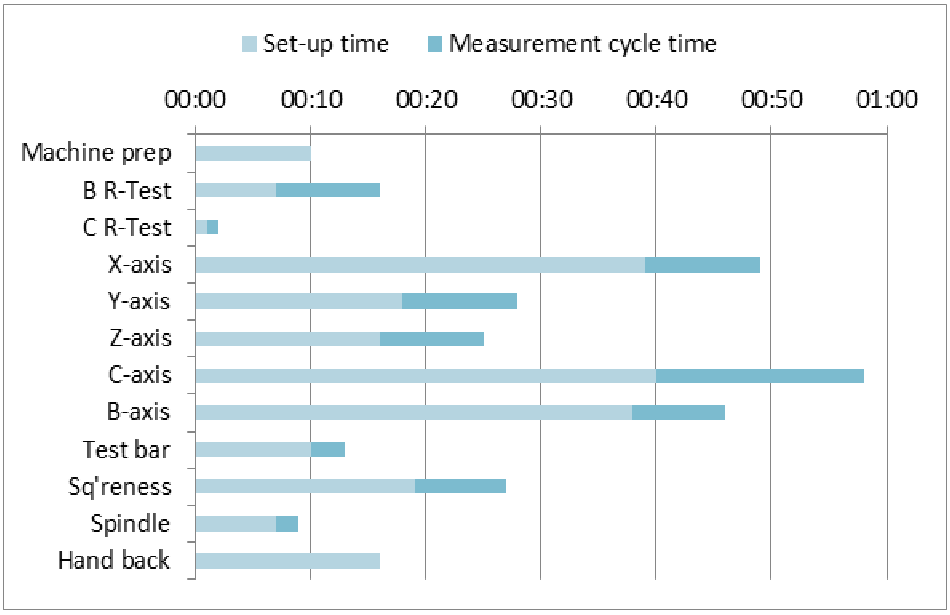


Figure 6-21: Measurement activity breakdown for Okuma Millac 5-axis machine rapid measurement

6.16 Discussion and conclusions

In order in ensure that a machine tool is capable to perform measurements it must be measured itself. Although widely acknowledged as necessary the measurement of machine tools is considered too disruptive activity, due to the amount of machine downtime required.

To enable the full measurement of a machine tool one must generate the full metrology index for the machine in question and procure the necessary measurement equipment to cover all errors. Once these actions have been completed a data gathering process can commence. This often requires the creation of machine specific programmes, fixturing and selection of appropriate measurement locations. Additionally, there may be intrusive actions to be taken such as the removal of machinery panels and guarding and product fixturing.

A hypothesis was made that to reduce total measurement time, without disregarding error parameters as specified by the metrology index, a holistic approach to the measurement process would be required. In this chapter a validation study was performed which compared the measurement processes for various machine tool 'calibrators'. The results showed that although engineer experience can play a major part in reducing necessary machine downtime, many procedural items are in fact machine specific. The disparity of estimates to actual time to complete ‘procedural’ measurement confirmed this. The anticipation is that machine specific and ‘fixed cost’ activities can be optimised by machine tool users when performing regular measurement tasks. The validation study also indicated a 41min difference between estimates of measurement and actual performance for a 5-axis machine. This indicated that estimates for other machines were also likely to be relatively accurate. A further hypothesis was made that by employing a set of new direct and indirect error measurement devices at the same time combining pitch, roll, yaw and positional measurement in a single pass; measurement time could be dramatically reduced.

A number of novel measurement devices were created, developed and tested with the support of state-of-the-art measurement equipment vendors (Renishaw plc. and IBS Precision). This was achieved through collaboration with Rolls-Royce plc., Machine tool Technologies Ltd., The University of Huddersfield and The University of Bath. Key to the success of these devices was the ability to wirelessly transmit data and/or the ability to measure multiple error parameters simultaneously. Key connectivity features of each measurement device employed is illustrated in Figure 6-22.

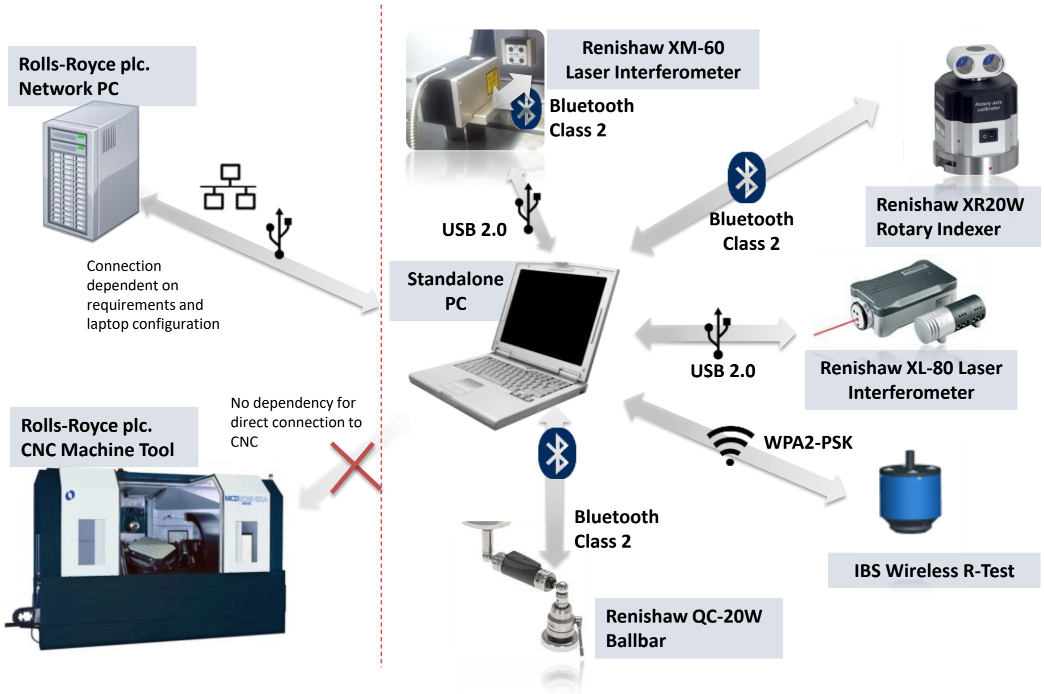


Figure 6-22: Rapid machine tool measurement system IT connectivity requirements

Utilising this new technology and approach a series of validation studies were performed on the targeted machine tool platforms. This demonstrated a considerable improvement in measurement time.

It has been observed from the validation studies that delays and time losses revolve around lack of detailed knowledge of machine behaviour and specific nuances such as the difficulty of removing/replacing product fixturing. This is likely to be mitigated with regular repeated measurement of the machine. Additionally, strong engagement between machine measurement engineers and site production engineers was found to be a necessity; where a robust proven handover process needs to be in place and planned in.

To further improve machine tool measurement time, special measurement equipment fixturing is essential. This can include rotary axis locator systems which would potentially reduce setup time for rotary axis measurement by approximately 25mins.

As laser interferometer systems have become more compact the flexibility of where and how they can be mounted within the machine has improved. This posed the challenge of having to create bespoke fixturing at the time of measurement. Should such generic flexible mounting and fixturing be available this would still require cantering and fastidious setup. Therefore, it is anticipated that future ISO 230 standards will have to consider and prescribe for this.

In this chapter the use of scanning probing technology has not been considered, which has become available on the market more recently. It is anticipated that some error measurements can perhaps be made with such technology via the use of dedicated precision fixturing which can be located in the machining volume. This would also be beneficial in that only the machine tool volume where work is being carried out would be considered rather than a blanket covering of the entire machining volume. This would be far more efficient not just for machine tool calibration but for on-going machine tool verification which is a critical pre-requisite for enabling machine tools as measurement devices.

Chapter 7

An enabling framework for industrial on-machine inspection

The rapid calibration solution created and tested in Chapter 6 provides an efficient and effective means to quickly assess the metrological capability of any multi-axis machine tool. With this new solution, engineers are likely to be less resistant for their machines to be audited and calibrated, due to a significantly reduced downtime requirement. Where such measurement or calibration is likely to occur on a schedule prescribed basis, should machine tools be used as measurement devices, an interval of 6-12 months is still not suitable. If one could measure and trend key process variables, associated to OMI, this data and system could provide flags in terms of when a machine tool requires intervention; in terms of re-calibration, optimisation or repair.

In line with this opportunity, two key research sub-questions are being considered, namely: *“Q3: How can a multi-axis machine tool be measured and re-verified with least disruption?”* and *“Q4: Is there a consistent strategy for utilising machine tools as measurement devices in an industrial environment?”*. This chapter thus focuses on the process of enabling machine tools as measurement systems through the utilisation of on-machine probing devices within an industrial setting.

In this study a novel approach is presented which machine tool users can adopt in order to confidently apply traceable on-machine measurement utilising OMP systems within their manufacturing operations. The methodology is subsequently tested within a live aero-engine manufacturing facility.

The organisation of this chapter is as follows: Firstly, the researcher presents the need for an appropriate industrial framework. Then a proposed framework that can be used is described. Finally, this framework is implemented a live manufacturing cell.

7.1 Need for a framework to enable traceable on-machine inspection

Despite on-machine probing devices being prevalent on most shop floors for many high precision manufacturers their usage is often not clear to all stakeholders. For example, a machine tool may have the utilisation of a touch-trigger OMP device. However, that device can be utilised in numerous ways, including:

1. Process setting
2. Machine datuming
3. Part alignment
4. Machine alignment and verification
5. Tool length setting
6. 5-axis rotary axis alignments
7. Comparative measurement
8. Dimensional measurement
9. Burr detection

Although OMP systems are effective ways to improve the quality and production of machined parts, their integration into existing production systems requires the consideration of a number of stakeholder needs.

Table 7-1: Challenges associated to OMI integration in an industrial environment

Political	Economic
- Regulatory requirements (especially in aerospace) - Lack of industry standards - Who owns the product quality? The machine operator, product owner, CMM operator, quality engineer, manufacturing engineer etc.	- Comparative cost of a machine tool is considerably higher than for a measurement device i.e., unclear business case - Risk of quality issue passing through multiple manufacturing processes undetected increasing risk and waste
Social	**Technical**
- Measurement perceived as non-value adding and a burden. Therefore it is not compatible for many manufacturing engineers - Lack of skilled engineers able to program machine tools as if they were CMM devices	- Metrological traceability challenges. - Machine tool hardware and software limitations - IT Infrastructure challenges

As identified in chapter 2, there is no single coherent methodology, within existing academic or industrial literature, on how machine users should identify relevant information and data to help them confidently implement on-machine probing systems for in-process dimensional inspection; thus mitigating issues as identified in Table 7-1. A structured and complete approach to enable machine tools as measurement systems is required for an industrial setting. This approach would be designed to addresses these political, economic, social and technical challenges. Without this, manufacturers are likely to find it very difficult and high risk to navigate and enable this paradigm change.

7.2 Strategic view to reduce or eliminate CMM inspection

Typically, manufacturers will choose to move to a sample inspection basis when product features or part-feature family process capability can be proven. When doing such manufacturing engineering will abide by the following rules:

- Establish manufacturing process stability and capability
- Establish a sampling frequency and proving sample
- After each significant change event in the manufacturing process measure a number of consecutive ‘proving samples’ to re-confirm process capability
- Operate at a sample frequency provided all operating criteria are met i.e. control chart tests, product conformity, PFMEA analysis etc.

These rules can potentially de-risk the process of moving to sample inspection in a medium-high volume manufacturing environment. Unfortunately, this approach is not fully applicable for reducing final CMM inspection by moving to OMI. As process capability is typically demonstrated on a sample of 30 parts or more, such a strategy is less effective if components are produced as a mix of different smaller batches; or where component sizes are relatively large. It is therefore unrealistic to sample 1 in 25 from a process that produces 5 components per shift due to the fact that many shifts will operate with no product being inspected.

The rule to re-confirm process capability after a “significant change event” also poses a challenge with regards to OMI. In this case, this could include the introduction or change to fixturing, revision to NC code, machine breakdown or collision, machine maintenance, a new batch of raw material, amongst a multitude of different process variables. Additionally, many change events are often un-quantifiable and difficult to track in a machining environment i.e. an operator may make a manual adjustment such as change of feedrate or an undetected collision may occur. This therefore poses a significant barrier to OMI implementation.

Despite shortcomings of this approach the researcher proposes a more appropriate, but complementary, strategy can be designed for low-batch high variability products. Such approach is founded upon the utilisation of a robust in-process verification system. Here measurement technology is employed by the machine tool to self-assess and decide, on a Go, No-Go basis, whether it is capable as a machine tool and/or measurement device. With using such technology, the machine tool is able to self-detect and decide if a ‘significant change event’ has occurred, based on appropriate rules.

7.3 Soft-systems challenges for OMI

The research has covered the hard-systems aspects of enabling machine tools as traceable measurement devices in previous chapters. From this research, indications are that there are also many soft-systems challenges which are preventing OMI being regularly adopted my manufacturers. As found within Rolls-Royce's manufacturing operations, there are a number of unwritten rules which engineers will adhere to. These are as follows:

1. The cost unit value of a machine tool is in the region of 10:1 to a measurement system, and thus should not be used as a measurement device
2. Measurement is already perceived as a non-value adding activity (i.e. it is not manipulating/removing material) therefore this should not be compounded by bringing it to the machine tool
3. The machine tool environment will always be too hostile and uncontrollable to be able to control the measurement process
4. The adaptive management of sampled inspection is too complex and will not be understood by all in the business
5. The enabling of such a 'decision-based' sampling system will require considerable IT investment

Such arguments were uncovered via a study performed in conjunction with the University of Bristol - Systems Centre, resulting in the research paper (Appendix A - unpublished). In this study socio-technical elements of implementing on-machine measurement systems within an industrial environment were explored via soft systems methodologies. This work highlighted that although the economic case for implementing on-machine measurement was present, as well as the technical capability, complexity plays a significant role in its resistance to being implemented. In that, there are a numerous non-technical challenges that are unknown, not understood or which cannot be measured and/or controlled.

It has been identified that there is a need for a total management of such a technology. This can be achieved by clarifying definitions; business expectations; and investing in the appropriate training and equipment. Therefore, in this chapter the researcher aims to address this issue with the creation of a novel framework which machine tool users could use to justify the decision of moving to full on-machine inspection as a gated and hence de-risked process.

7.4 Developing a framework for OMI implementation

All the conclusions made within the paper, presented in Appendix A, infer that a soft- and hard-systems understanding is required to enable capable and reliable on-machine measurement. This indicates that both a quantitative and qualitative understanding is required to complement the introduction of such a significant process change as well as reduce/eliminate stakeholder polarisation. Observing this, in Figure 7-1 an approach is presented which considers these aspects whilst applying a gated approach which stakeholders can ‘buy-in’ to and effectively ‘sign-off’ on. This approach is counterintuitive to a standard approach of change management, whereby it follows systems thinking principles. The researcher hypothesises that this approach can deliver the case for intervention as a robust gated process. This provides manufacturing organisations a traceable decision route allowing for economies of scale, risk-reduction and management of scope. The approach also provides a clear and de-risked exit strategy should requirements not be achieved i.e. intervention is not made on the machine or within the organisation at the wrong point in time, and therefore is costly to undo.

7.4.1 Framework structure

Although no literature exists on the topic of enabling industrial machine tools as measurement systems, Juran (1999) presents a general approach for defining measurement systems and their elements [228]. In his book ‘Juran’s Quality Handbook’, Juran presents practical advice for creating and evolving complex measurement systems. This text presents a theoretical strategy which considers ‘operational level’, ‘tactical level’ and ‘strategic level’ intervention with regards to introducing a new measurement system into an organisation. The strength of this approach is claimed by the empowerment of ‘virtually everyone’ involved. As such the researcher has chosen to consider this theory for the enabling of a machine tool as a measurement system.

The framework presented in Figure 7-1, presents the researchers adaptation of Juran’s theory. The framework presented exposes a series of significant organisational milestones and is designed to complement existing business processes, in this case Rolls-Royce’s ‘Capability Acquisition - Manufacturing Capability Readiness Level (MCRL)’ gates are referred to [223]. MCRL gates are used internally at Rolls-Royce plc. to integrate new technologies into the manufacturing process. This ‘systems thinking’ approach is strongly based on NASA’s Technology Readiness Level (TRL) methodology. This methodology is designed to support the acquisition and development of a total manufacturing solution to deliver a capable and reliable method of production [248]. The researcher chooses to merge these two approaches i.e. theoretical and practical, whilst considering the purpose of converting a machine tool as a measurement system. As a result, this new framework can provide a robust, stable and traceable decision-making approach for such an important and complex organisational change.

Consisting of six 'milestones' this framework (Figure 7-1) follows key principles originally presented by Juran [228]; these are:

1. Manage measurement as an overall system rather than a technology
2. Understand who makes decisions and how they are made
3. Make decisions and measurements as close as possible to the activities they impact upon
4. Select a parsimonious set of measurements and ensure it covers what goes on "between functions"
5. Define plans for data storage and analysis in advance
6. Seek simplicity in measurement, recommendations and presentation
7. Define and document the measurement protocol and quality programme
8. Continuously evolve and improve the system
9. Help decision makers learn to manage their processes and areas of responsibility instead of the measurement system
10. Recognise that all measurement systems have limitations

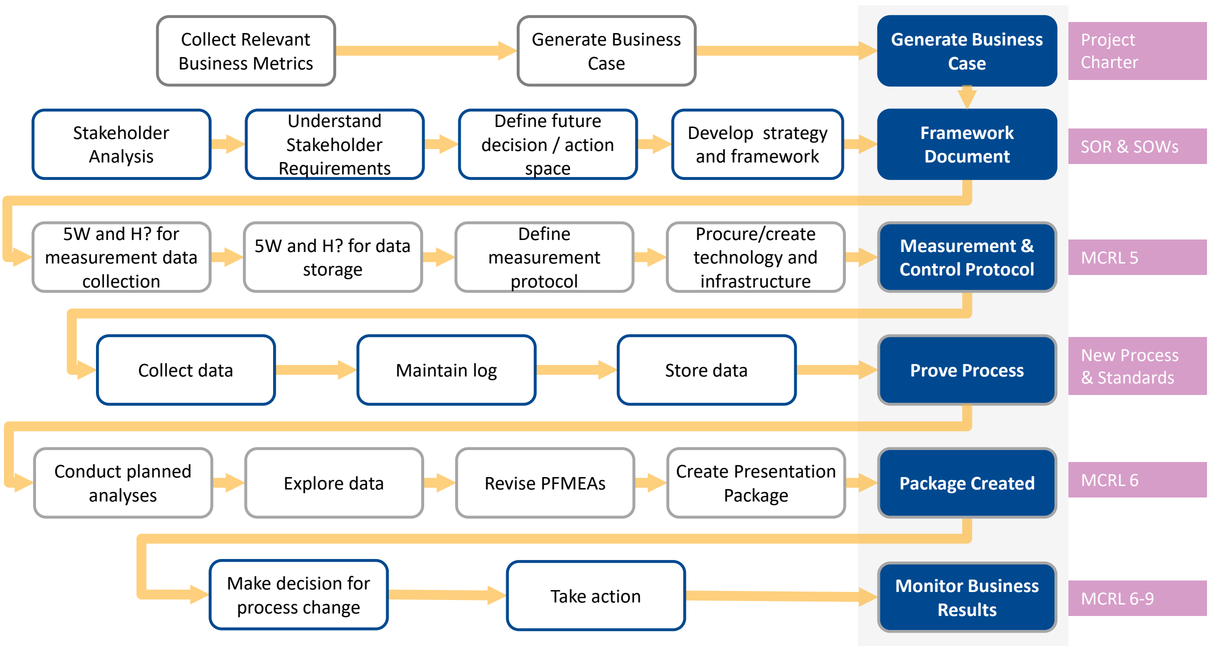


Figure 7-1: Proposed framework for the introduction of OMI adapted from [228] and [223]

The following sections describe the main stages of the OMI implementation framework.

7.4.2 Generate Business Case

Before determining whether an on-machine probing system should be employed on the machine tool for final product inspection it is important to clarify the business case. Such a business case must be both an economic and technical one. Typically, the argument of many is that the cost/hour for a machine tool is significantly higher than for a CMM measurement system. However, this is only looking at the business case from a very local level. This framework proposes that the business case is reviewed from a plant throughput perspective where all assets have an equal cost rate irrespective of purchase price i.e. on a fully-absorbed cost basis.

The technical case can be made with existing capability data where features to be measured on the machine tool can be justified by current product feature Cpk values. For example, a manufacturer could state that the minimum process capability for the application of sample inspection could be:

Category A features: Do not sample

Category B features: 1.33 Cpk

Category C features: 1.50 Cpk

Where:

$$C_p = \frac{USL - LSL}{6\sigma}$$

and

$$C_{pk} = min\left[\frac{USL - \bar{X}}{3\sigma}, \frac{\bar{X} - LSL}{3\sigma}\right]$$

Where required, the level of process capability shall determine the maximum permissible sample frequency i.e.

Cpk<1.3	Cpk 1.33 to 1.5	Cpk >1.5
Use CMM only	Up to 3 in 4 features removed from the CMM and/or moved to the machine tool	Up to 24 in 25 of features removed from the CMM and/or moved to the machine tool

With this knowledge a traceable decision can be made as to whether or not the enabling of on-machine product inspection is feasible. The economic and technical case will also assist in deciding the amount of on-machine inspection that is possible as well as defining a budget for the amount of investment that can be made to implement this manufacturing process change.

7.4.3 Create Framework Documentation

Despite a business case being demonstrated on paper this does not eliminate all risk in deciding whether reducing final product inspection, by bringing it to the machine tool, is achievable. Other socio-technical reasons may prevent this application of OMI some of which may not be quantifiable as well as unknown and unknowable. This can include specific stakeholder needs, such as customer protection, information systems, intellectual property, machine capability and logistical requirements. Therefore, this stage of the framework is important as it leads users to consider stakeholder viewpoints in order to mitigate obvious risk. In this case a typical industrial product introduction business process could be used, such as a R-R MCRL process [223]. Such an approach will also enable stakeholders to be involved in this paradigm change at an early stage.

7.4.4 Create Measurement and Control Plan

As discussed in previous chapters there are a number of key process variables which need to be controlled to enable stable and traceable OMI/OMP. In Chapter 5 the concept of machine tool metrology indices was introduced. Employing Jurans' approach of utilising a 5W and H approach (Who, What, Where, When and How Often) structure can be created around this and subsequently a robust control plan is created [249]. With this approach, manufacturers can define in-process, daily, weekly, monthly and annual measurement tasks to support the traceability of on-machine inspection activities. This element of the framework may involve the creation of on-machine verification artefacts, bespoke probing routines, rapid machine verification technology (Figure 7-2) or other ancillary systems such as tool length measurement devices or visual inspection tasks.

Figure 7-2: IBS Precision Spindle Check – Rapid machine tool spindle measurement and verification system

7.4.5 Prove out the process

With the first three major gates of the framework completed and passed off it is considered prudent to have an element of process proving and optimisation before a full transition to reduced or eliminated final (CMM) inspection is made. At this stage one would want to run both in-process and CMM inspection in parallel. This is to understand bias between gauges and perform capability studies as well as design of experiment analyses [250]. The length of transition phase would be decided based upon business throughput flexibility, capability metrics and product quality risk.

7.4.6 Seal the decision to move to on-machine inspection

On completion of the prove-out stage, a process to collect and correlate data, confirm business case assumptions and revise process control plans is made. After this phase of work is complete a package can be created by the project team which will initiate the change to reduced final inspection. At this point all associated stakeholders are likely to be involved in the decision to proceed.

7.4.7 Control and Continuously Improve

Once the decision to move to a new system of reduced final-inspection and greater on-machine measurement has been made it becomes imperative to sustain and continuously improve the system-wide change. Without consideration of sustaining the system the risk to business becomes higher should the new approach fail. Therefore, an important component of the framework is the constant monitoring and analysis of measurement results for a data-driven Go, No-Go decision system, process knowledge generation and capability sustainment. This section of the framework will be supported by PFMEA and control plans created earlier on in the framework. Relevant key performance indicators are identified for the process. Such data can include measurement, vibration analysis, oil condition monitoring, and artefact probing data.

7.5 Action-case study - Rolls-Royce Hucknall CBCC

Having identified a potential framework an action case approach is taken to explore its validity. This cell was chosen as the manufacturing process had demonstrated capability, a metrology driven maintenance team, the machinery had on-machine probing capable for inspection and site staff were open to piloting this novel approach to OMI and reduced final inspection. Feedback from this case study will be collated and used to improve the framework. There are 12 products impacted by this research activity, the same as those in Chapter 4, again product names are not disclosed for confidentiality reasons. At the time of writing this study is still in progress, therefore it will only consider the first three major milestones of the framework.

7.5.1 Current and Future process flow

At the chosen facility an intermediate CMM inspection operation follows each machining process (Figure 7-3). The previous study (Chapter 4) demonstrated that the use of in-process probing enabled a dramatic improvement in product quality and right-first-time where previously probing concession level was 85% and after probing concession level was 7%. Although it has been demonstrated that in-process measurement can lead to a much more stable process, due to measurement being closer to the machining process, the ultimate aim is to improve, if not, guarantee the on-machine probing process past the need for the CMM. In this case the manufacturing control plan is shifted from solely observing product quality to both observing product and process quality (Figure 7-4).

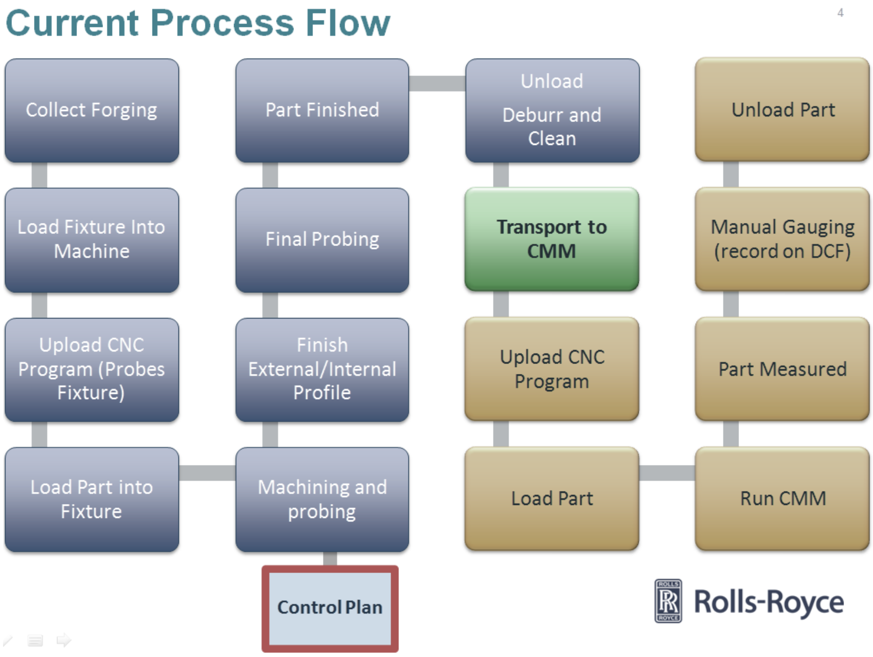


Figure 7-3: Current R-R CBCC manufacturing process flow and control plan without OMI

Figure 7-3 presents the current production strategy for the manufacturing cell. Here a control plan exists which specifies all features which need inspection on the CMM. Following the machining the component is transferred and processed by a CMM to certify the product. As can be seen this consists of several non-value adding processes.

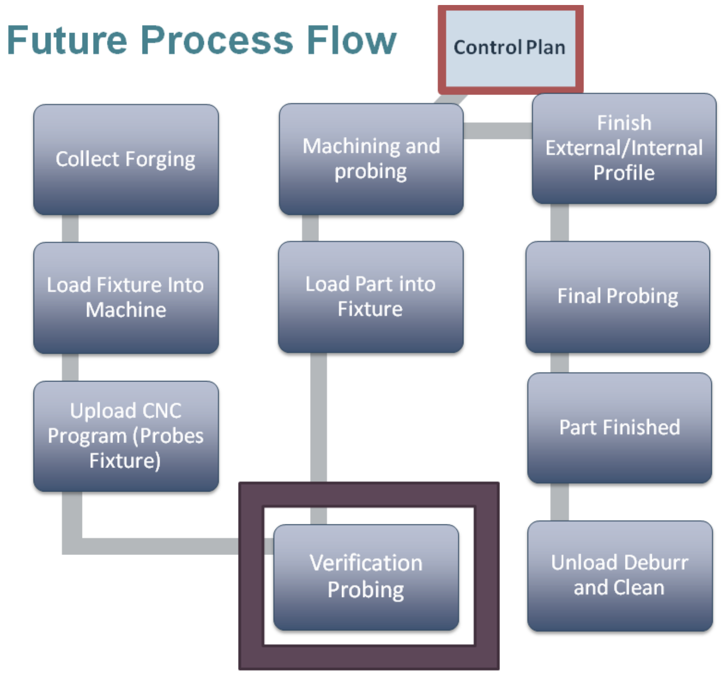


Figure 7-4: Future R-R CBCC manufacturing process flow enabled by rapid machine verification and OMI

As indicated by Figure 7-4 to enable traceable on-machine inspection, this will require introduction of a new 'Verification' manufacturing operation. This is enabled by shifting and adjustment of existing process control plans. With this the CMM inspection route can be eliminated.

7.6 Reduced CMM inspection economic case

To create the economic case for this cell a proposed flow was created to understand potential scenarios of operation (Figure 7-5).

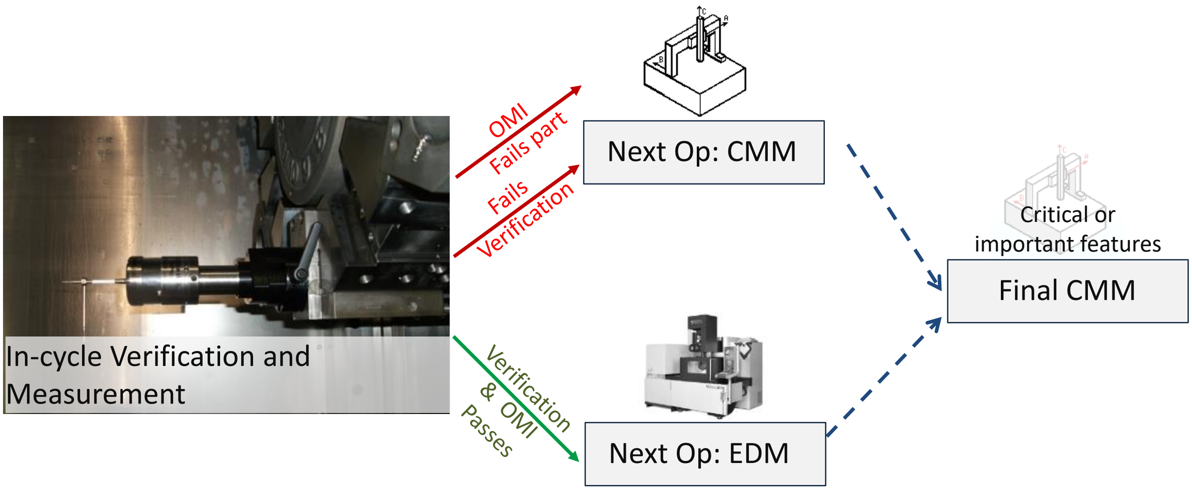


Figure 7-5: Proposed product flow based on Go/No-Go Verification and OMI implementation

As illustrated by the Figure 7-5 the machine tool with its in-cycle measurement system will be responsible for the decision that the product it has just machined should go to the next manufacturing operation (in this case EDM) or the product should be sent to a CMM as there is suspected non-conformance in the product.

Irrespective of option a strategic decision is made that all features are measured at product delivery stage. Therefore the risk of releasing a non-conforming product to the customer is mitigated.

A time study was performed in order to understand the current manufacturing process. Table 7-2 and Table 7-3 present the breakdown of the work content and its different operations for two products. This highlights the percentage of time the product spends at the CMM. There is potential for an improvement of 10-15% on product throughput if the CMM operation is reduced.

Trent TURN		%	Time
Machining	Removal of metal	75.95%	13:00
Preparation	Upload CNC Program	4.19%	00:43
	Load Fixture + Part		
Finishing	Unload Fixure + Part	2.92%	00:30
	Clean/Deburr Part		
Intervention	Inspection	1.95%	00:20
	Tip Change		
Trent CMM Op			
Measurement	CMM part features	10.22%	01:45:00
	Manual Gauge Features		
Preparation	Upload CNC Program	3.12%	00:32:00
	Transport to CMM		
	Load Part		
Finishing	Unload Part	1.66%	00:17:00
	Record CMM/ Manual gauge data on DCF		
CMM Process =	15.00%		

Table 7-2: Potential business opportunity for Product A (Trent Engine Component)

Table 7-2 presents the total contribution of all manufacturing activities with regards to the operation of turning Trent combustor wall features. As indicated, 76% of all activities involve the machine tool and 15% of all activities involve post-machining CMM inspection. Other critical activities are not shown for confidentiality reasons. A cost per hour rate was applied to this data to present to senior manufacturing managers.

BRR TURN		%	Time
Machining	Removal of metal	65.81%	06:00
Preparation	Upload CNC Program	7.86%	00:43
	Load Fixture + Part		
Finishing	Unload Fixure + Part	5.48%	00:30
	Clean/Deburr Part		
Intervention	Inspection	3.66%	00:20
	Tip Change		
BRR CMM Op			
Measurement	CMM part features	8.23%	00:45:00
	Manual Gauge Features		
Preparation	Upload CNC Program	5.85%	00:32:00
	Transport to CMM		
	Load Part		
Finishing	Unload Part	3.11%	00:17:00
	Record CMM/ Manual gauge data on DCF		
CMM Process =	17.18%		

Table 7-3: Potential business opportunity for Product B (BRR Engine Component)

Table 7-3 similarly shows the total contribution of all manufacturing activities with regards to the operation of turning BRR combustor wall features. In this case machining contribution is 66% and CMM contribution is 15%. Again other critical activities are not shown for confidentiality reasons.

With this cost consideration covered the researcher is left with the understanding that there is a cost impact of moving to reduced CMM inspection (by transferring to the machine tool or not). This is done by breaking down the process from machining to CMM and calculating different case scenarios depending on the amount of on-machine inspection that is required.

Table 7-4: Business case calculator for reduced CMM inspection via OMP (Based on internal R-R data)

	Product A	Product B	Product C	Product D	Product E	Product F	Product G	Product H	Product I	Product J	Product K	Product L
Actual Turn Run time (mins)	381	492	321	552	495	915	390	690	390	690	390	690
Total time including loading etc (mins)	480	660	480	660	840	720	390	690	390	690	390	690
Proposed Total Turn time (mins)	510	690	510	690	880	760	415	715	415	715	415	715
Cost/hr	£ 69.51	£ 69.51	£ 69.51	£ 69.51	£ 69.51	£ 69.51	£69.51	£69.51	£69.51	£69.51	£69.51	£69.51
Current Total	£ 556.08	£ 764.61	£ 556.08	£ 764.61	£ 973.14	£ 834.12	£ 451.82	£ 799.37	£ 451.82	£ 799.37	£ 451.82	£ 799.37
Proposed Total	£ 590.84	£ 799.37	£ 590.84	£ 799.37	£ 1,019.48	£ 880.46	£ 480.78	£ 828.33	£ 480.78	£ 828.33	£ 480.78	£ 828.33
Turn Saving	-£ 34.76	-£ 34.76	-£ 34.76	-£ 34.76	-£ 46.34	-£ 46.34	-£ 28.96	-£ 28.96	-£ 28.96	-£ 28.96	-£ 28.96	-£ 28.96
Actual CMM Run Time (mins)	60	45	50	30	228	220	135	120	135	120	135	118
Total time including Set Up etc (mins)	95	80	85	65	263	255	155	140	155	140	155	138
Proposed CMM Run Time (mins)	0	0	0	0	0	0	0	0	0	0	0	0
Cost/hr	£ 69.51	£ 69.51	£ 69.51	£ 69.51	£ 69.51	£ 69.51	£69.51	£69.51	£69.51	£69.51	£69.51	£69.51
Current Total	£ 110.06	£ 92.68	£ 98.47	£ 75.30	£ 304.69	£ 295.42	£ 156.40	139.02	156.3975	139.02	156.3975	136.703
Proposed Total	£ -	0	0	0	0	0	0	0	0	0	0	0
Reduced Inspc Saving	£ 110.06	£ 92.68	£ 98.47	£ 75.30	£ 304.69	£ 295.42	£ 156.40	£ 139.02	£ 156.40	£ 139.02	£ 156.40	£ 136.70
Overall Turn/CMM Savings	£ 75.30	£ 57.93	£ 63.72	£ 40.55	£ 258.35	£ 249.08	£ 127.44	£ 110.06	£ 127.44	£ 110.06	£ 127.44	£ 107.74
Overall Engine Saving	£133.23		£104.27		£507.42		£237.49		£237.49		£235.18	
Load/Year	263	271	91	88	66	65	360	249	133	44	20	9
Total savings for Engine/Year	£35,502.23		£9,366.47		£33,240.84		£73,280.92		£21,791.39		£3,518.36	
Total Yearly Cost Reduction :	£176,700.21											

Table 7-4 indicates an extract from the business case that was produced for this action case. Calculators like these can been used to understand, predict and target the amount of machine tool inspection required, the optimum sampling strategy and best case and worst case scenarios and budgets based on this. In this action case calculated cost savings per product ranged from £3.5k - £73k per year. When considering the amount of investment required to implement such a change, return-on-investment ratios in this case were calculated in the region of 18:1. Details for this ratio cannot be provided for commercial reasons. As such the economic justification for moving to 100% on-machine inspection has been proven.

7.7 Reduced CMM Inspection Investigation

Although an economic case for moving to a sampled inspection basis has been calculated, it does not necessarily mean that there is a technical case for such intervention. In Chapter 4 a technical case for moving to on-machine probing for adaptive machining was made, this was enabled through utilising a DMAIC approach [225]. In this situation the technical case is made by analysing capability data generated by CMM equipment being used to measure conformity post machining.

The CMM measurement of components was investigated. It was found that 587 features were being inspected on the CMM. The total operation on average had a time of 135 minutes. The following approach was then taken to identify which features can be removed / eliminated at CMM measurement stage:

1) Collate the CMM Data from the last 25 components
2) Sub-group the measurements into family of features which are created on the same tool path.
3) Collect the measured difference from nominal for each of the features for the 25 parts
4) Analyse the capability of those features across the 25 parts removing any special causes
5) Use the distribution to calculate the action limits based on 99% confidence of what fits under the distribution curve. If the reduced features fall outside the control limits on measurement, then all the intermediary points are to be measured.
6) Recommend which features to remove from the CMM inspection program and calculate warning limits
7) Recommend changes to the products' inspection plan, on-machine probing and the CMM Program.

Families of features identified during this process mainly consisted of:

1) Diameters
2) Thickness
3) Depth

4) Length

All CMM measurements were grouped into family or features which are created on the same machining tool paths and which have the same specification limits. This grouping is presented in Table 7-5.

Table 7-5: Sub-groups of features – Outer wall and Inner wall

Outer Wall		Inner Wall	
Family	**Feature Numbers**	**Family**	**Feature numbers**
Angles	61, 66, 70, 73	Angles	104, 107, 109, 111
Thickness 1	60, 65, 71, 72	Thickness 1	103, 106, 108, 110
Thickness 2	58, 511, 512, 513, 514	Thickness 2	105, 562, 563, 565
Diameters 1	62, 63, 64, 67, 68, 69, 74, 76, 78, 79	Diameters 1	113, 115, 117, 118, 120, 125
Diameters 2	75, 77	Diameters 2	114, 116, 119, 121, 126
Lengths	47, 48, 49, 50	Lengths	97, 98

Through the collection of CMM data, the measured difference from nominal was calculated for the 25 parts. Process capability studies were also performed. Results of this study are presented in Appendix D. The study confirmed that the Puma turning process was very stable and capable for all features measured. Based this investigation (Appendix D) the proposals were made as per Table 7-6.

Table 7-6(*a*): Proposed Method of OMI (Appendix D)

Feature Group	Investigation Finding
Inner wall – Angles (features No. 104, 107, 109, 111)	Since these features are on a control plan and given a capable process, the inspection can be removed from the CMM program and move to the machine tool.
Inner wall – Thickness 1 (features No. 103, 106, 108, 110):	According to the capability analysis, the CMM programme will only inspect the first and the last thickness. Since all these features are created on the same tool path and then if these features show no non-conformance via OMI, then all the intermediary thicknesses will be conforming.
Inner wall – Thickness 2 (features No. 105, 562, 563, 565)	A full inspection of these features is required on the CMM if OMI inspection results are outside of warning limits.
Inner wall – Diameters 1 (features No. 113, 115, 117, 118, 120, 125)	As the process is very capable and since all these features are created on the same tool path, the OMI inspection programme will only needs to inspect the first and the last diameter (features 113 and 125).
Inner wall – Diameters 2 (features No. 114, 116, 119, 121, 126)	As the process is very capable and since all these features are created on the same tool path, the OMI inspection programme will only need to inspect the first and the last diameter (features 114 and 126).
Inner wall – Lengths (features No. 97, 98)	As the individual values fail the warning limits a full inspection of these features is required on the machine tool. If warning limits are exceeded transfer part to the CMM.
Outer wall – Angles (features No. 61, 66, 70, 73)	As these features are on the control plan and being the process capable, the inspection of the whole family of features can be removed from CMM inspection and moved to the machine tool.
Outer wall – Thickness 1 (features No. 60, 65, 71, 72)	As the process is stable and capable, the OMI program will only need to inspect the first and the last thickness (features 65 – thickness AS and 71 – thickness AT), Since all these features are created on the same tool path and if these features show no no-conformances, then all intermediary thicknesses will be conforming.
Outer wall – Thickness 2 (features No. 58, 511, 512, 513, 514):	A full CMM inspection of these features is required should OMI results fall outside warning limits.
Outer wall – Diameters 1 (features No. 62, 63, 64, 67, 68, 69, 74, 76, 78, 79):	As these features are on the control plan and being the process capable, the inspection of the whole family of features can be removed from the CMM Inspection and moved to the machine tool.
Outer wall – Diameters 2 (features No. 75, 77):	These features are also on the control plan and the process is capable, so the inspection of this family of features can be removed and moved to the machine tool.

Table 7-6(*b*): Proposed Method of OMI (Appendix D) (*cont.*)

Feature Group	Investigation Finding
Outer wall – Angles (features No. 61, 66, 70, 73):	As these features are on the control plan and being the process capable, the inspection of the whole family of features can be removed from CMM Inspection and moved to the machine tool.
Outer wall – Thickness 1 (features No. 60, 65, 71, 72):	As the process is stable and capable, the OMI program will only need to inspect the first and the last thickness (features 65 – thickness AS and 71 – thickness AT), since all these features are created on the same tool path and if these features show no no-conformances, then all the intermediary thicknesses will be conforming.
Outer wall – Thickness 2 (features No. 58, 511, 512, 513, 514):	A full OMI inspection of these features is required. If results are outside warning limits the component is to be transferred to the CMM.

As a result of this investigation (Appendix D), of 155 inner combustor wall measurements being taken on the CMM, 61 measurements could be removed from the CMM and transferred to the machine tool. Additionally, 94 measurements would need to be carried out on the CMM should the adjusted control plan exceed tolerance limits. Similarly, for the outer combustor wall, of the 136 measurements currently being carried out on the CMM, 50 could be moved to the machine tool and 86 could be managed via an adjusted control plan. If non-conformance in the control plan or OMI measurements outside the warning limits is found this triggers a reaction plan in which a full inspection will take place. This would consist of a 100% CMM inspection of all features.

7.8 Implementation

The economic and technical case, as presented, has enabled key Rolls-Royce stakeholders to understand the opportunity of moving to an OMI basis. This has allowed a project team to proceed to move to adjusting the manufacturing process flow. Following the framework, as described, a workshop event was held involving key stakeholders associated to the manufacturing process. Attendees of this workshop were the same as those identified and engaged in chapter 4. The outcome of the workshop event was the confirmation and agreement of the current manufacturing process flow as well as an agreement on what the future manufacturing process would look like (Figure 7-6). It must be noted that the successful outcome of the workshop was attributed to having a presentation for the economic and technical case for this process change pre-made and available for all to agree upon.

Figure 7-6 illustrates the predicted future process framework as described by the group of stakeholders involved. As can be seen from Figure 7-6 the points where decisions are made have been introduced by new processes of on-machine inspection. One new and key requirement is identified as the verification of the machine. Using this framework, the project team moved forward in reviewing current process documentation, including: PFMEAs; Control Plans; Feature Verification Analyses; as well as IT and logistical information. This is to highlight key areas where change was required. A new enabling activity being proposed was the utilisation of Mitutoyo MeasurLink™ manufacturing process control software [210]. This software currently purposed for receiving and reporting shop-floor CMM measurement data is to be connected to the machine tool to directly receive machine tool measurement data. By using this approach manual steps of processing OMI data would be eliminated, hence streamlining the process.

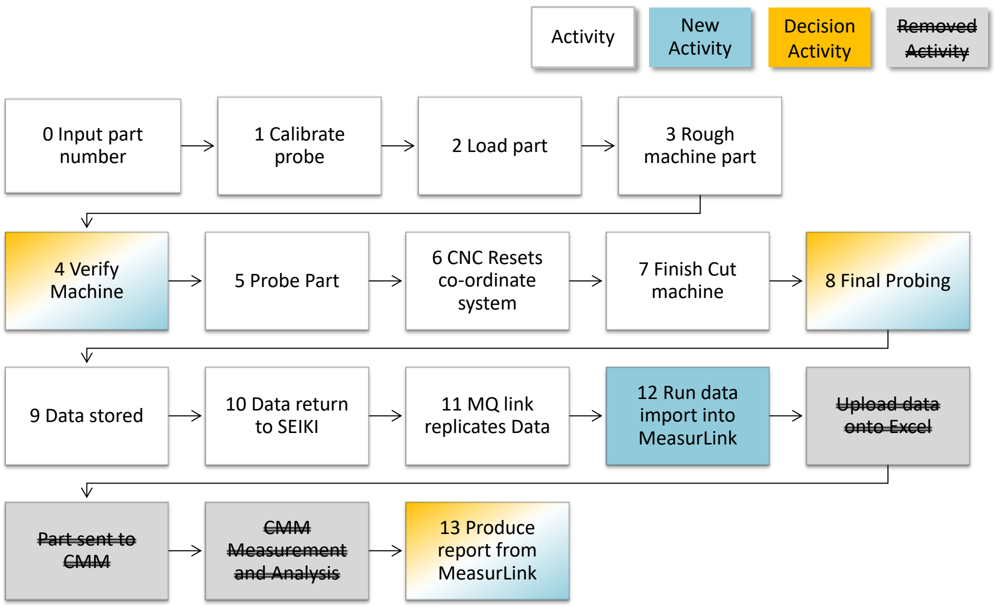


Figure 7-6: Process flow and decision points for 'Future' process

7.9 Rapid machine tool verification process

A consistent agreement, made between all stakeholders involved in this process change, was the need for an independent in-process machine verification system; to confirm that machine tool precision (and calibration status) is being maintained over time. Although a rapid calibration solution was developed in Chapter 6 this was still deemed too intrusive for in-process validation of machine tool condition; due to the amount of skilled human intervention required. A research exercise was completed with the University of Bath – Laboratory for Integrated Metrology Applications (LIMA) to create a 'solution tool kit' sufficient for the rapid verification of a machine tool resulting in Paper V. The contents of this paper will not be repeated in this chapter. However, key new contributions to knowledge generated by the work, including a strategy for developing a suitable machine tool artefact and the logic process for the NC programming of a Go, No-Go system, is utilised.

7.10 Verification artefact development

Utilising learning generated via the research work with the University of Bath – LIMA, a decision was made to create a verification artefact which could be loaded into the machine tool (Paper V). This would happen before, after and/or during the machining process.

In this case study the machines being used only utilise two axes to take measurements (X and Z axes). As such, the proposed artefact solution is required to verify the on-going repeatability of these axes to a resolution of 5-10 microns. This would be within the working range of the machine where measurements are taken. Certain key functional and non-requirements for the verification artefact were as follows:

- The verification process in total lasts less than 15 minutes
- The solution needs to be a 'Green button' process
- The solution must utilise existing on-machine probing and infrastructure
- The solution needs to be proven to be stable in a machining environment
- The solution has a total cost of less than £10k
- It must be easily handled (size, weight)
- Its material must not conflict with the product

With these requirements in mind, the machines were surveyed for suitable mounting points for the artefact to be located within the machines (Figure 7-7). Options included; (1) Mounting the artefact on existing work-holding fixturing; (2) Mounting the artefact on the tail-stock of the machine tool, and bringing it into play when necessary; (3) Utilising the existing ATSU or adding an additional 'ATSU' type system in which the operator could quickly load and unload an artefact. All these options are displayed in Figure 7-7.

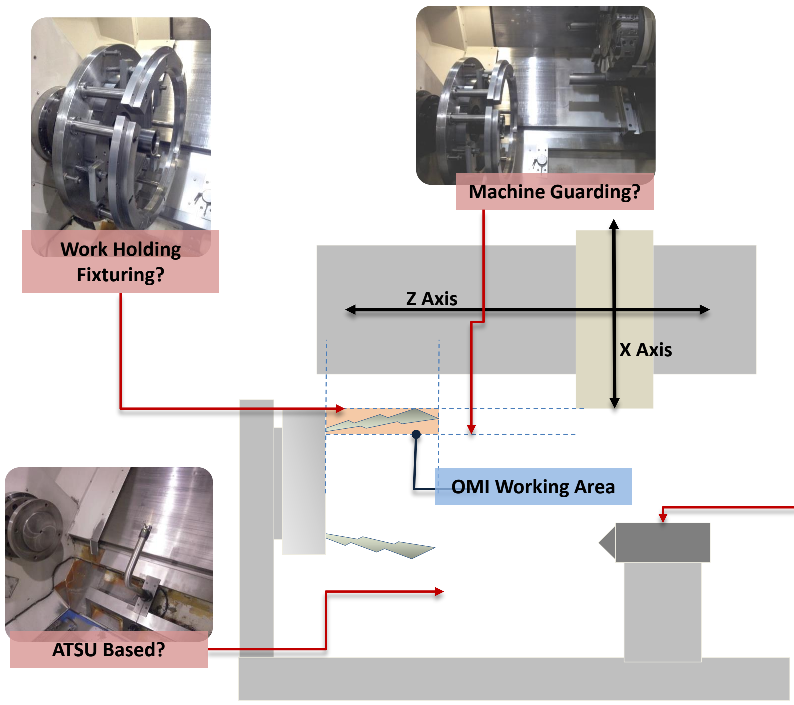


Figure 7-7: Potential machine mounting points for verification artefact

In addition to the fixing of the OMP verification artefact solutions were also proposed for its design; considerations were made for Z-axis verification as per Figure 7-8.

Z-axis Verification Artefact Design Options

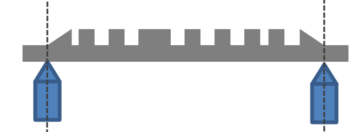
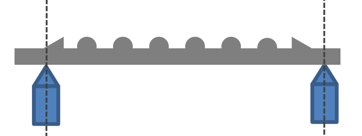
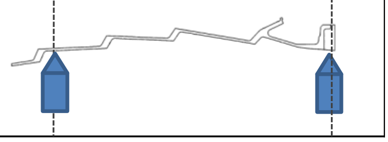
Option 1 – Bespoke machined artefact	Pros – Low cost of manufacture, R-R ownership Cons – Unproven	
Option 2 – Pre-made artefact	Pros – Off-the shelf, proven history Cons – Higher cost, cannot create bespoke features	
Option 3 – Alternative bespoke artefact (University of Huddersfield Optimised)	Pros – Optimised design, endorsed by specialists, support with data analysis diagnostics Cons – Higher cost, potential IP issued, time restrictions	
Option 4 – Cut-out section of production part	Pros – 'Gold' standard part, exactly representative Cons – Unknown if can withstand environment,	

Figure 7-8: Z-axis verification artefact options

7.11 Chosen verification solution

Despite the number of solutions available, a consensus decision was made to custom design and manufacture stepped artefacts, as this would be the most ideal solution. The University of Huddersfield – Centre for Precision Technologies (CPT) was engaged to design, manufacture and test artefacts. The work with the University of Huddersfield was split into two phases. The 1st phase involved the design and manufacture of 2 x 1 fixtures (2 in total) and set of 2 x 2 artefacts (4 in total) for a single Puma 2+1 axis slant-bed lathe. Phase 2 involves the optimisation and manufacture of additional artefacts, fixtures and temperature sensors (to be installed by Rolls-Royce personnel) on the remaining seven machine tools.

Figure 7-9 illustrates the fundamental design of the artefact:

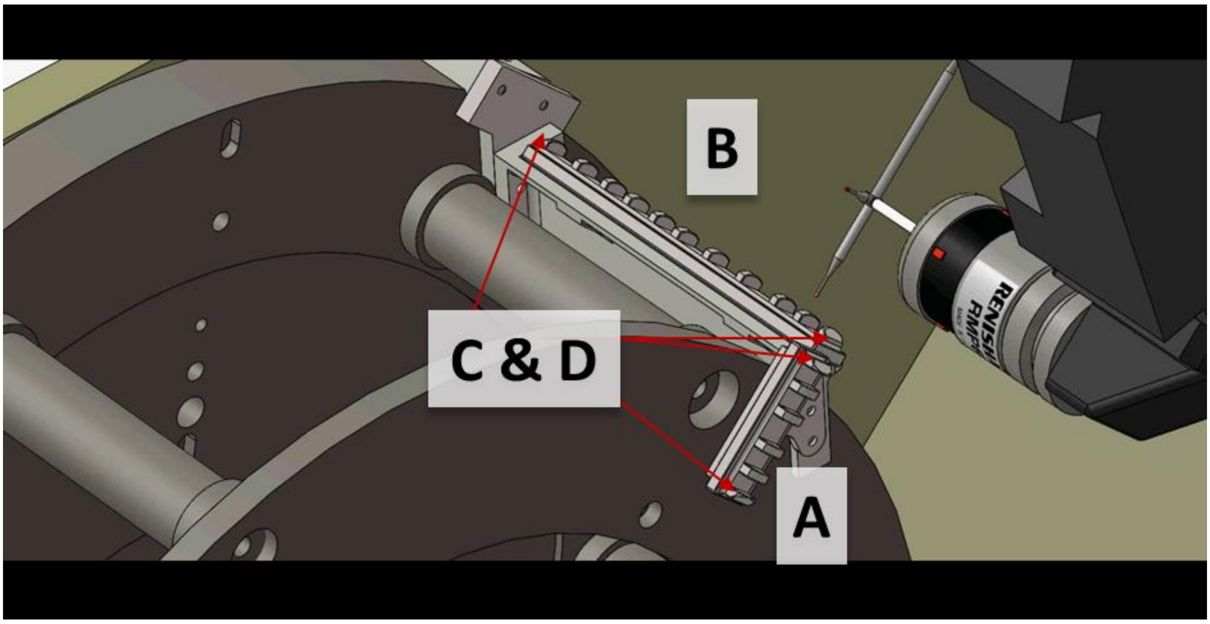


Figure 7-9: Final design of machine verification artefact

Key features of the artefact include 6 steps for the measurement of X axis positional bi-directional repeatability (A), 11 steps to measure Z axis bi-directional repeatability (B), two features (C and D) for the measurement of machine tool backlash and a kinematic location system for loading/unloading the artefact fixturing to the machine tool.

All artefacts unique for each machine, utilising variable step gap sizes, in order to avoid the contamination of artefacts being transferred onto the wrong machine tool.

Although the step sizes are not exactly in the same positions as on the products it was agreed that this was not critical; as the solution was only to be used as an indication of change of machine condition in-process; where it fits in to a larger more hierarchical machine tool measurement strategy i.e. Renishaw plc.'s Productive Process Pyramid™ (Figure 7-10).

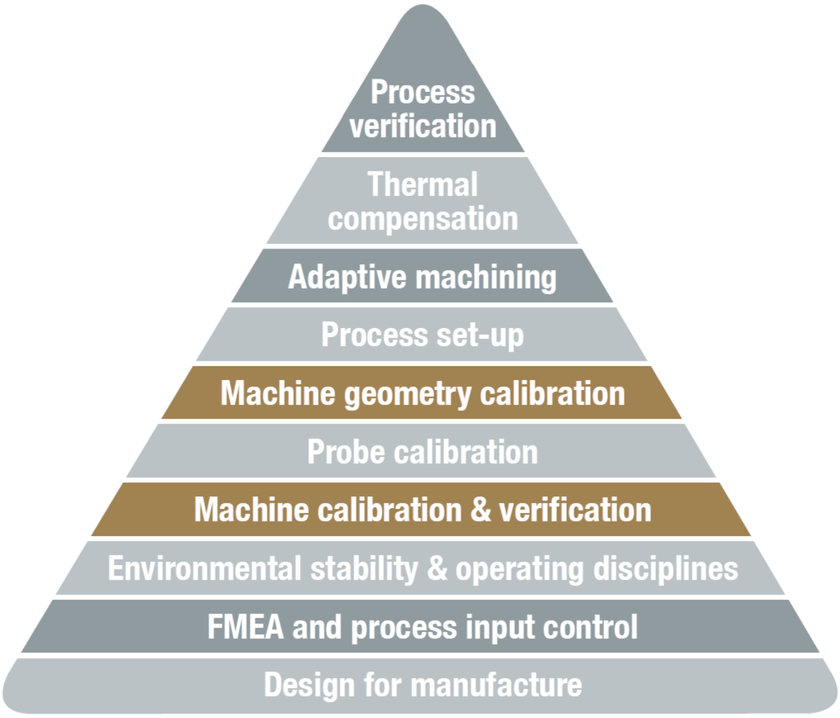


Figure 7-10: Renishaw Productive Process Pyramid™ [237][238]

7.12 Artefact validation

During the design phase of the artefact and fixturing system a series of Finite Element Analyses (FEA) were completed to understand if the artefact would deflect under contact from the on-machine probing (Figure 7-11). A series of iterations were performed to improve the fixturing design to mediate such effects.

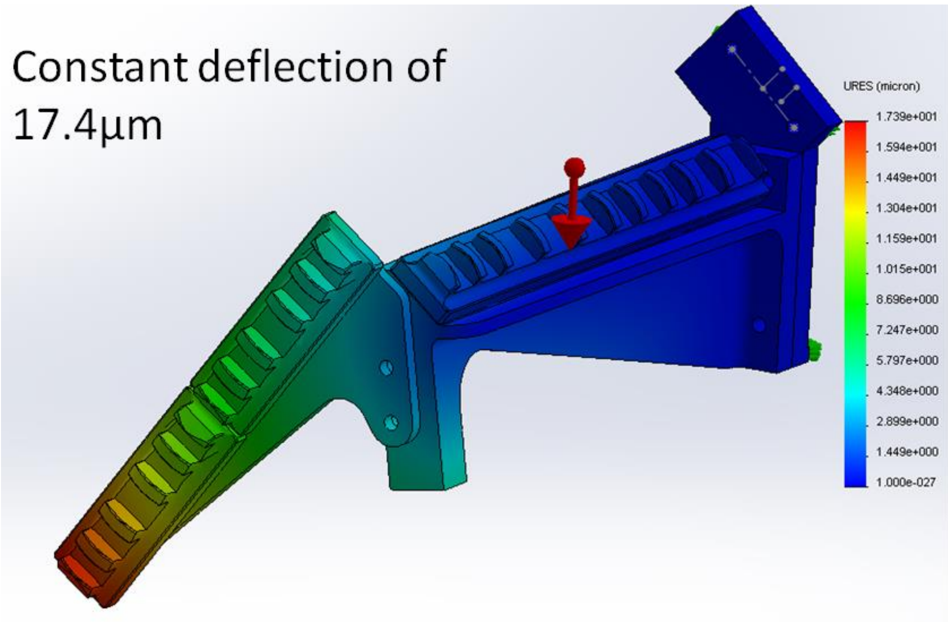


Figure 7-11: FEA analysis on verification artefact (effect of gravity)

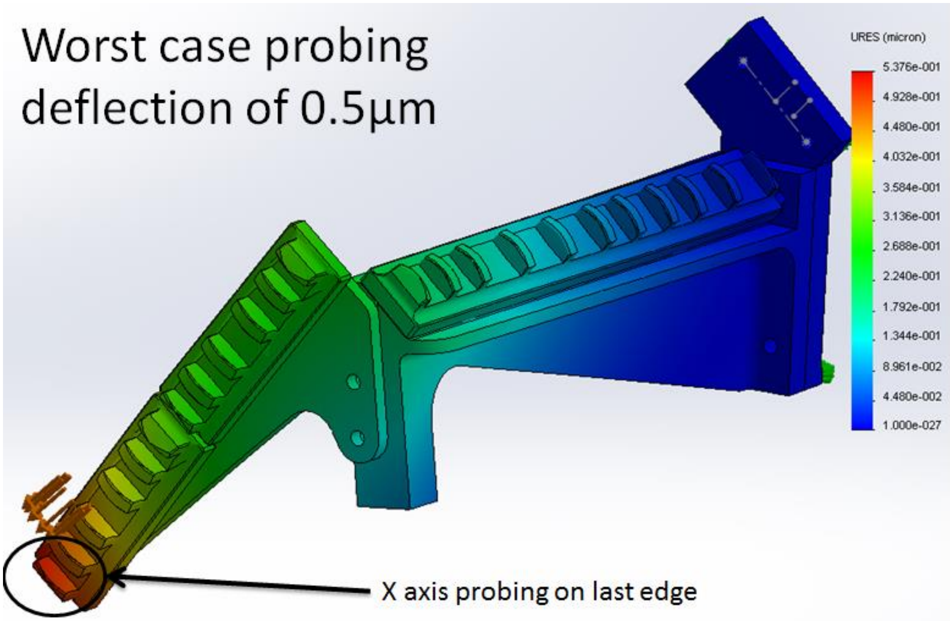


Figure 7-12: Worst case deflection (0.5µm) due to probing of artefact

The design of the artefact was also supported by preliminary Uncertainty Estimation simulations as performed with working with the University of Bath (LIMA) as per Paper V.

7.13 Solution buy-off

An internal Rolls-Royce Manufacturing Capability Readiness Level (MCRL- Gate 4) review was used to ensure that the introduction of on-machine measurement enabled by the use of machine tool verification artefacts was ready for implementation. The use of this process enables the manufacturing business to accept this new process via a sequence of gate reviews [223]. Fundamentally this process is used to manage complexity associated to capability acquisition. Typically, a panel of key stakeholders from various business functions will assess the solution proposed and cast judgement on whether or not it matches business needs and that it will be supported long term. The Rolls-Royce MCRL process is summarised in Figure 7-13.

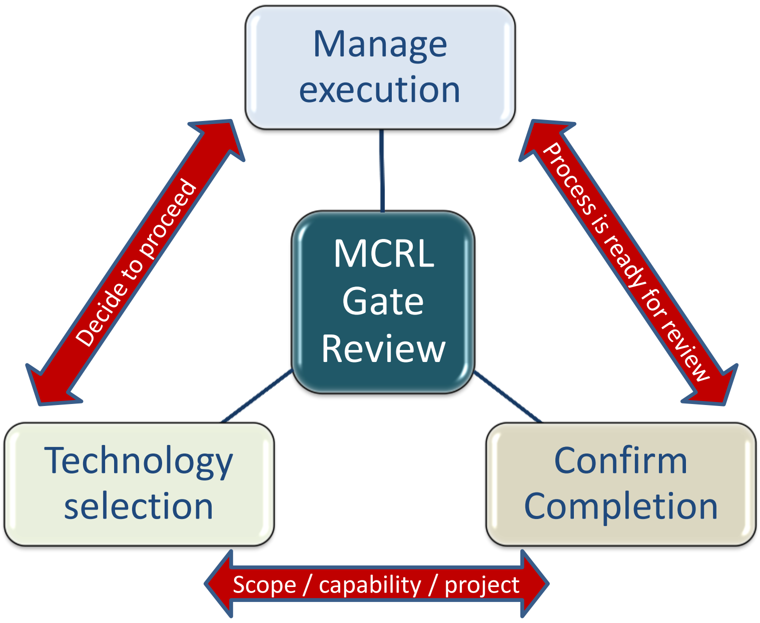


Figure 7-13: Rolls-Royce MCRL gate review criteria

7.14 Findings and reflections

The action-case considering the validation of the proposed framework is currently on-going. Despite this, the researcher will reflect upon and discuss the key aspects associated to implementation of the framework based on the findings of the case study. Although in this particular instance the technology and process 'passed' relevant gate reviews this may not have been the case if other key variables where not as favourable. Key learning was as follows:

7.14.1 Artefact design and installation

The action case used to test and validate the proposed framework was based on a manufacturing cell and process familiar to the researcher. In this case the product, the machining process, hardware and software constrains as well as metrological capability of the machine were already known and understood. Additionally, the number of freedoms of movement for the machine tool was relatively limited due to it only being a 2+1 axis machine. Should a machine, product, machining process which was unfamiliar to the researcher have been chosen, it is likely that the challenge of enabling an on-machine verification process would be different. Such challenges would involve the consideration of:

1. The limitation of size and weight of the verification artefact i.e. a larger product would require a larger verification artefact
2. Number of ‘representative’ features which it holds i.e. products which have zones of high tolerance or hard to reach features; this would have to be considered with the design of the artefact.
3. Limitations in terms of artefact location inside the machine volume i.e. for situations where there is no physical space inside the machining volume. Such an artefact would have to be transferred into or integrated within existing fixturing or the machine.
4. The artefact in this case only considers probing utilising linear axes only. If rotary axes need to be used, such as in mill-turn instances, then the complexity of creating representative artefacts and adequate probing strategies will increase.

7.14.2 Impact of change (Ownership and resource requirement changes)

Change management was a critical issue with the regards to the implementation of this new process. The researcher was in an advantageous position where many of the stakeholders involved were also involved in the installation of on-machine probing systems, as per Chapter 4, and therefore already bought into the step of taking this further. This may not have been possible in other manufacturing cells where if:

1. Ownerships of product quality are not clear or have to be redefined i.e. once the machine tool is reporting product quality data does ownership of that data shift from the CMM operator to the machine tool operator?

2. Challenges of adding in new manufacturing operations were resisted or difficult to introduce; such as a new requirement for caring for and calibrating all new verification artefacts regularly
3. Business case data was unclear or untraceable and therefore difficult for stakeholders to agree upon
4. Areas where IT and machine tool NC capabilities were still immature, such as the ability to create go, no-go machining probing cycles or the machine tools ability to process, store and distribute probing data.

7.14.3 Data management and automatic decision making

During this action case it became apparent that a robust IT infrastructure and product lifecycle management (PLM) system would be a key enabler for such a framework; as robust and efficient data management, NC programming, deployment and post-processing and analysis is crucial. Such a PLM system would need to have capabilities for handling:

1. Part geometry and tolerance information and its permitted variation
2. Product information, such as feature criticality and traceability across the manufacturing process as well as artefact feature criticality and traceability
3. Measurement resource availability and capability as well as machine tool availability and capability
4. Bespoke measurement rules for both CMM programming and on-machine programming
5. Deployment of standard programmes which are comparable with CMM systems

7.14.4 Tolerance specification

In this particular case study, a product and process were chosen where machining tolerances were large enough to avoid debate on whether or not measurement of artefact features would be representative enough in terms of precision and uncertainty. In cases where machining tolerances are tighter i.e. in the region of single to tens of microns rather than hundreds; then a greater amount of validation would be required in terms of the verification system. Although the framework does consider this via the prove process phase, what is potentially unknown is the time it would take to complete this phase; which is likely to be extensive where the process of artefact and product measurement is not mutually exclusive. Ideally to mitigate this prove out could be performed on an offline basis where the majority of the work is completed during the earlier phases of the framework.

7.15 Conclusions

This chapter started with the discussion that to enable traceable OMI within a shop floor environment was a socio-technical challenge, rather than a purely technical one. With this the researcher discussed the potential key decisions, both social and technical, which manufacturers will have to make to change their manufacturing paradigm from 100% final product (CMM) inspection to a sampled basis. Ultimately it was concluded that, where products are produced in low batch sizes, rather than shifting a manufacturing process to a reduced inspection based on historical capability data a safer and more robust option would be to shift some of the measurement burden to the machine tool. This would increase efficiency due to reducing the process steps required to set up a product for post-machining measurement, as well as provide live manufacturing data at time of manufacture rather than post manufacture therefore in theory increasing the reliability of data.

In consideration of this a novel framework was developed which was designed to cover aspects of moving to such a manufacturing paradigm as those indicated in Figure 7-14.

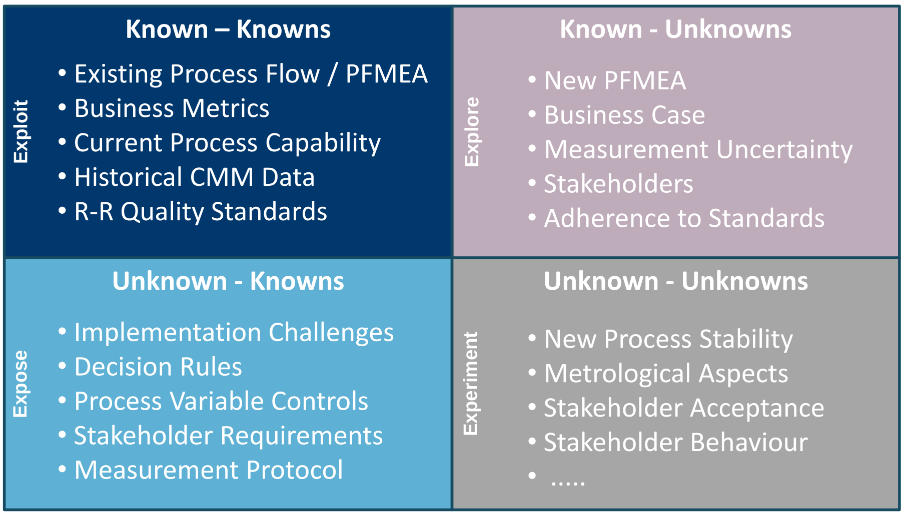


Figure 7-14: Known-Unknown matrix for OMI and on-machine verification implementation

In order to test and validate this framework an action-case study was performed, on the same manufacturing process and cell as the action-case made in Chapter 4. With this the first three stages of the framework were completed and bought off by the respective manufacturing business unit; where now the process is being proved out over a period of 6-8 months.

Key drivers and enablers for the implementation of the framework were: the availability of manufacturing data in order to create a business case; the support of on-site manufacturing engineers familiar with the manufacturing process and use of on-machine probing; the simplicity of the current manufacturing equipment; and most importantly the introduction of an in-process rapid verification system able to monitor the on-going equivalence of the machine tool.

In this case study the introduction of an independent verification of the artefact was the most challenging aspect for the framework. Although, this may or may not be the case for other manufacturing sites/cells, machines or operations. As a result of this challenge it was found that a specialist technical resource would always be required to design and implement the verification system. This resource would be used to integrate a verification process into the machine tool, with assurance that all required features were being considered; either directly or in-directly. Additionally, this resource would be trusted to follow fundamental metrological requirements including the metrology index for the machine tool itself.

The introduction of any new process into a manufacturing operation comes with new challenges, which arguably increases complexity rather than reduce it. Such challenges observed in this case mainly revolved around: introducing a verification artefact or system into the machine tool during or in-between machining operations; the challenges associated to any manufacturing change including the redefinition of staff roles; data management and processing challenges; and the management of tolerance specifications and traceability for the verification system itself. Other key parameters needing consideration included: the design of the artefact and fixturing with an eye on the product being manufactured; the location within the machining volume where it can sit and not interfere; and the measurement uncertainty associated to both the machine tool and the verification process. Finally, it was identified that the use of virtual simulation would be a valuable tool in the design and testing of artefact-machine tool capability without having to disrupt the manufacturing process. This would be firstly for the creation and testing of artefact designs in combination with the kinematics of the chosen machining platform; the subsequent FEA and uncertainty analyses; and the testing for collision detection. This was demonstrated in Paper V.

With this work; including the definition of metrology indices, rapid machine tool measurement systems and potentially the use of uncertainty estimation software (UES), the option for high precision manufacturers to move to 100% OMI is now a much more viable one.

Chapter 8

Estimating OMI measurement uncertainty with UES

As discussed in previous chapters, all measurements performed by the machine tool are subject to certain measuring uncertainty. Aspects of machine technology, part attributes, the geometry of measured features, the operating environment and the operator will all influence the magnitude of measurement uncertainty. The use of computer simulation of measurement uncertainties has become a viable option for CMM systems, as described by ISO 15530-4 [188]. In this chapter the researcher aims to repurpose such methods for use with machine tool inspection.

The objective of this chapter is to consider the validity of utilising off-the-shelf uncertainty estimation software (UES) for machine tool metrology purposes. In this chapter the researcher first introduces the concept and potential benefits of utilising software as a tool for optimised OMI uncertainty evaluation. Subsequently, the validity and suitability of utilising such software is tested via a real-world case. The work in this chapter references two published papers, one co-authored and the other sole author as well as it being related to another concurrent EngD being carried out on the topic of *'The study of the relationship between engineering design and measurement technology'* by Saunders. The work by Saunders covers the validation of commercial UES packages for co-ordinate measurement machines in much detail. This chapter focuses solely on the application of UES for machine tool metrology purposes. The work presented by Saunders focuses around the overall capability and development of UES especially for CMM inspection operations as a whole. All studies contained within this chapter are performed using a Zeiss CMM Check® artefact [251].

8.1 Theory

Monte Carlo methods are becoming ever more utilised for the estimation of measurement uncertainty and have been successfully used for determining machine tool and CMM error maps as well as tolerance analyses [108], [252]. More recently these methods have been used to build uncertainty models for CMM measurements [253]. Recently Virtual CMM (vCMM) software has gained popularity in both academic and industrial settings, where fully functional software packages have been developed and commercialised. Such software has been designed to automate, improve accuracy and improve uncertainty simulation time. However, the fundamental benefit of vCMM software is through the emulation of measurement strategies and physical behaviours in order to optimise measurement tasks; where in practice this would be impossible to do in an industrial environment due to production constraints. The primary drivers for utilising simulation software have been summarised in ISO 15530-1 [185]. Metrosage LCC have commented on the benefits and challenges associated to each option available [254]. This is summarised in Figure 8-1.

	Tractable	Comprehensive	Detects Measurement Bias	Detects Measurement Variability	Versatile	Predictive	Economical
Sensitivity Analysis	?	?	✓	✓	X	✓	X
Expert Judgment	✓	?	?	?	X	✓	?
Substitution	✓	✓	✓	✓	X	X	X
Computer Simulation	✓	?	✓	✓	✓	✓	?
Measurement History	✓	✓	X	?	X	X	X

Figure 8-1: Options available for measurement uncertainty estimation (Source: Metrosage LLC)

Figure 8-1 clearly illustrates that the use of computer simulation techniques offers a clear advantage over other available methods. The researcher agrees with this reasoning. The main advantage of computer simulation is that it can be easily applied to a wide range of situations. Additionally, it is considered a versatile and traceable solution. Finally, computer simulation methods can be used to capture both bias and variability of the measurement process [254]. Questionable aspects of using computer simulation techniques are that (1) it can be variable in comprehensiveness, where results generated are only as complete as the full model and (2) the economics of using such a technique in an industrial environment is unknown. The researcher believes that with continuous development of the software issues with comprehensiveness are being addressed. Additionally, with the use of rapid machine tool measurement methods i.e. those generated and tested in this thesis, the generation of parametric models for industrially based machine tools can contribute to this as well as improve economic efficiency.

Computer simulation methods for estimating measurement uncertainty for multi-axis machine tools have created and tested in an academic arena [255]–[257]. However, these methods are not commercially available or are known to have been tested in a live manufacturing environment. As such the researcher aims to identify and utilise commercially available uncertainty simulation software for use with machine tools and on-machine inspection tasks.

8.1.1 Virtual Machine Tool / vCMM

In order to model CMM or machine tool behaviour, all contributions to measurement uncertainty must be measured, controlled and estimated. Typically, probe errors are determined with a calibration sphere, geometric errors are measured using an artefact or parametrically, and remaining error contributors that are more difficult to control are used as inputs to the vCMM model. Such errors could include calibration uncertainty, drift, operator, fixture stability etc. Additionally, these other error contributors are often difficult to continuously measure and monitor e.g. temperature and environmental influences [185].

Previous chapters have developed rapid calibration techniques to determine geometric errors of machine tools and CMMs, the data generated by these systems can be used to feed virtual machine parametric models. Now with an ability to measure and verify all machine tool errors in considerably less time such existing virtual machine models will in turn be more robust (due to the limiting impact of thermal effects or temporal drift) as well as adaptive based on the data they are receiving from calibration systems.

8.1.2 PUNDIT CMM

PUNDIT CMM is commercially available software, developed by Metrosage LLC., designed for uncertainty estimation of CMM measurements. The software is based upon the simulation by constraint (SBC) approach developed by NIST [167]. The software has been designed to be independent of any particular CMM manufacturer platform. Users are able to import CAD file data and have a repository of common CMMs which users can choose from.

A significant amount of research has shown that PUNDIT is suitable for the evaluation of task-specific measurement uncertainty with respect to CMM equipment [167]. However, no work has been performed in terms of using this software with machine tools. Ramu *et al.* identified PUNDIT as a potential solution for five-axis machine tool task specific uncertainty estimation [257]. However, this solution was not pursued as it was not capable for five-axis machine modelling due to an inability to consider rotary axes. Though this is correct, the researcher purports that PUNDIT can still be applied with five-axis machine tools, should only linear axes be used to take measurements i.e. rotary axes are not moved during the measurement cycle.

As users have the ability of creating their own ‘virtual CMMs’, via parametric method; the researcher conceives that machine tool models can also be created within the software. With this feature available, the software can then be used as a very powerful tool for:

- Identifying which features can and cannot be measured using the machine tool; the predicted uncertainty of feature characteristics being measured
- Identifying which variables have the biggest impact on task specific measurements
- The specification of tolerances that are specific to in-process machine tool measurement
- Optimisation of probing routines
- Optimisation of product placement within the machine tool volume
- Live condition monitoring to establish whether a machine tool remains in ‘calibration control’
- The design and virtual testing of traceable machine tool artefacts

Despite this potential opportunity the challenge for validating PUNDIT for machine tools is very difficult; due to the large number of variables that need consideration.

8.2 Testing PUNDIT for use with OMP

In Paper IV, the researcher has performed a study that has been completed to investigate the potential application of UES software (in this case PUNDIT CMM) with respect to the performance of machine tool. This study was completed using a Zeiss CMM Check® artefact, typically used for performing regular CMM overchecks. The experiment was split into two phases. In phase one, PUNDIT UES was validated against CMM results using the Zeiss artefact. In phase two, the same Zeiss artefact was measured on a 3-axis machine tool. Here a design of experiments study was carried out with the aid of PUNDIT UES software (Six factor, two level, full factorial = 64 experiment). Key findings of the work were that the UES uncertainty predictions correlated well with the uncertainty calculated from measurements performed by the CMMs; UES predictions for the chosen machine tool under 'improved industrial conditions' [78] were around 50% higher. On analysis of the calibration data from the machine tool it appeared that poor geometry repeatability of the machine tool was a governing factor. In addition to this there was a question around the parametric model created for the machine tool and its relevance due to the number of days taken to complete the full measurement cycle.

In a preceding study the same artefact has been used to compare the measurement performance of several multi-axis machine tools and to understand the impact of measurement variables not applicable to CMMs i.e. machine warm up and tool change repeatability (Paper III). In this study it was demonstrated that some of the higher performing machine tools were not significantly impacted by warm-up or tool changing operations. The study also validated that the impact of machine tool geometry and repeatability was the likely cause of inaccurate UES predictions. Therefore, it is a logical step to use one of these machines as well as the rapid machine tool measurement solution to re-evaluate PUNDIT UES for machine tools.

8.3 Test case – PUNDIT UES with rapid machine tool calibration data

This study was performed on a new five-axis machine tool, similar to the one represented in Figure 8-2. Exact machine details cannot be disclosed for confidentiality reasons. The machine has a wCBXYZt structure, where the C and A axis operate as a trunion system. The machine is equipped with a Siemens Sinumeric 840D Powerline control system. This control system allows the recording and transferring of on-machine probing data.

Figure 8-2: ‘Trunion’ type 5-axis machine tool

Installed in early 2014 the machine is in a pre-production status located in a manufacturing cell based at Rolls-Royce Derby in an uncontrolled industrial environment. It has not yet been used for continuous production. The machine has a working volume of approximately 980x980x1100mm and has ballscrew driven linear axes with linear encoders. The machine is equipped with a Renishaw OMP 400 touch trigger strain gauge probe system.

8.3.1 Rapid measurement of 5-axis machine

True parametric data was collected for the machine by trained the University of Huddersfield staff utilising the recently commercialised Renishaw XM-60 (6 DOF) laser interferometer. Squareness measurements were captured both by a Renishaw QC20W Ballbar and granite artefact. Rotary axes were measured utilising a Renishaw XR20W wireless rotary encoder with Renishaw XL80 laser interferometer. Spindle measurements were captured utilising a IBS Precision SpindleCheck system. Material sensors were located on the x-axis guideways underneath machine covers as well as on the machine tool workholding spindle. In total the full measurement of the machine was completed in one-shift (less than 6 hours). All linear axes were calibrated in less than 2 hours. Appendix E presents the collected measurement data from the machine with regards to 18 of the 21 linear parametric errors for the machine. Collected measurement data was then provided to Metrosage LLC. to create a Virtual CMM within their PUNDIT CMM software. As the software was still only capable of modelling uni-directional measurements an average of the bi-directional laser measurements was used.

8.4 Zeiss artefact

Utilising a Renishaw OMP 400 machine probing system a calibrated Zeiss KMG CMM Check® device was set up and probed using the machine tool (Figure 8-3).

Figure 8-3: Zeiss KMG CMM Check Artefact (Source: Carl Zeiss)

This Zeiss artefact (Figure 8-3) comprises of a number of measurement features including:

- a 50mm diameter ring gauge
- a 50mm diameter cylinder,
- two length bars (50mm and 400mm)
- three ceramic spheres of 30mm diameters

The Renishaw touch trigger strain gauge probe utilised a 100mm long carbon fibre stylus with a 6mm diameter ruby tip. The probing system, newly acquired, was verified to the following repeatability and lobing:

- Linear repeatability <0.35µm
- 2D Lobing <0.25µm
- 3D Lobing <1.75µm

Renishaw Inspection Plus software was used to programme the probing device and assist with data capture. The probe was calibrated in the machine before loading of the Zeiss artefact. The Zeiss artefact was loaded as indicated in Figure 8-4.

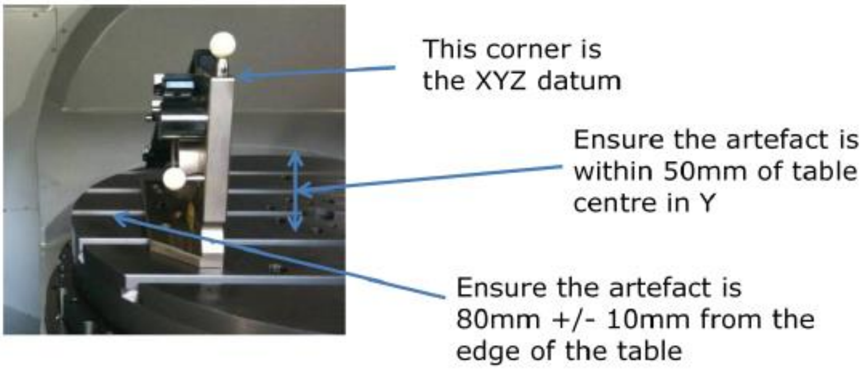


Figure 8-4: Zeiss Artefact ® Set-up within machine tool

The artefact was loaded to run across the table so that it is parallel with the Y axis and B axis centrelines. The artefact was then roughly aligned by rotating the B-axis and C-axis. A G57 (XYZ) work offset was set to the corner of the artefact as shown in Figure 8-4: Zeiss Artefact ® Set-up within machine tool. A null value was assigned to G57 (B & C) axes as they were not used during testing. Both G57 and G56 NC commands were used during testing, where G57 was set by the machine operator and G56 is automatically calculated via the NC based on G57 values. Probing points were captured using a two-touch probing strategy with ‘Fast’ feedrate of 3000mm/min, retract, ‘Slow’ feedrate of 30mm/min for data capture. The reason for this approach was:

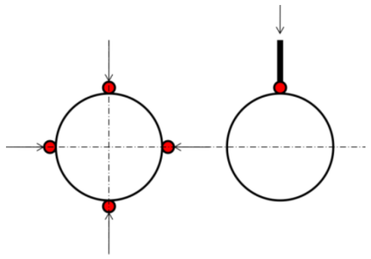
- Some machine tool controls have an input that is only monitored every 4ms (15mm/min = 0.001mm per input scan). The researcher was not sure if this machine did or not.
- Using high feed rates one-touch probing relies on the distance to the trigger point being greater than the machines acceleration distance for that feed rate.
- Using high feed rates one-touch probing relies on the distance from the trigger point to the target point being greater than the machine’s deceleration distance for that feed rate.

8.5 Capturing measurement data

A first set of 10 measurements was performed on the installed machine which had not been used at least 12 hours prior to testing. A second set of 10 measurements was then performed once the machine had completed a one hour warm up cycle. The warm up cycle is performed as per the manufacturer guidelines and did not include the machining spindle. The artefact was not removed at any time once it was fitted to the machining table. This enabled measurement results to be captured before and after warm up.

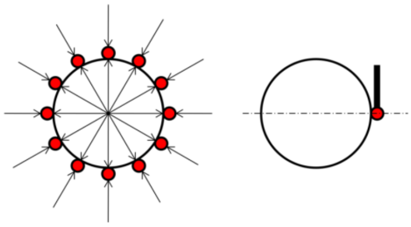
A set of measurements was completed as follows:

8.5.1 Sphere position



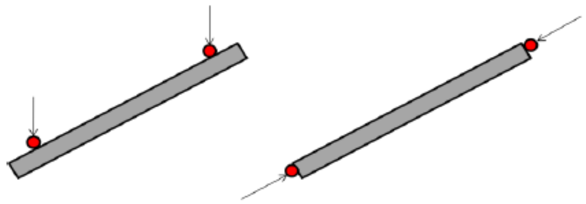
This is established by taking four points on or near to the equator of the sphere at the 3/6/9/12 o'clock positions and calculating the mid-point from these four points. This mid-point is then moved and a further point is taken on the top of the sphere. The position of the sphere centre is then calculated to be one sphere radius below this point.

8.5.2 Sphere size



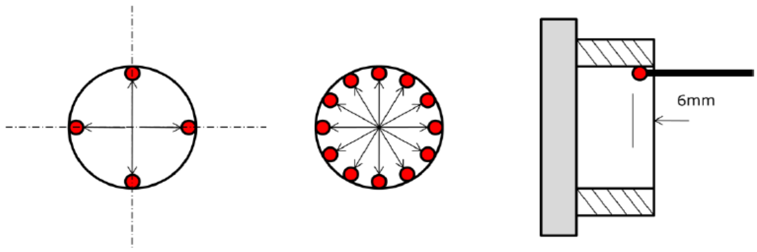
The exact sphere centre is moved to and twelve points are taken at 30˚ intervals by measuring normal to the surface (target point is sphere centre) at a point that puts the equator of the sphere and stylus at the same position. Opposite readings are used to establish a distance across the sphere, from these readings six distance measures are calculated at 0˚30˚ 60˚ 90˚120˚& 150˚

8.5.3 Length bar size



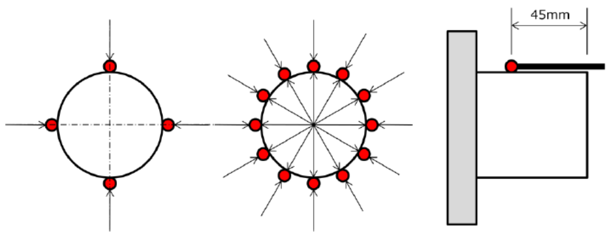
This is established firstly be finding the actual angle the length bar is located at to the machine axis by taking two readings and calculating the angle. A reading is taken on each end of the length bar by using the calculated angle to vector onto the ends of the length bar.

8.5.4 Ring gauge size



This is established by taking four points in the ring gauge at 3/6/9/12 o'clock positions at 6mm from the front of the ring gauge and calculating the mid-point from these four points. The exact ring gauge centre is moved to and twelve points are taken at 30˚ intervals by measuring normal to the surface. Opposite readings are used to establish a distance across the ring gauge, from these twelve readings six distance measures are calculated at 0˚, 30˚, 60˚, 90˚, 120˚and 150˚

8.5.5 Cylinder size



This is established by taking four points around the cylinder at 3/6/9/12 O'clock positions at 45mm from the front of the cylinder and calculating the mid-point from these four points. The exact cylinder centre is moved to and twelve points are taken at 30˚intervals by measuring normal to the surface (target point is cylinder centre). Opposite readings are used to establish a distance across the cylinder, from these twelve readings six distance measures are calculated at 0˚30˚ 60˚ 90˚120˚ & 150˚.

8.6 PUNDIT modelling and comparison to physical testing

The PUNDIT model was created using the following sets of data:

- The CAD model for the Zeiss Artefact
- Zeiss artefact feature form errors from PPM data
- Probe repeatability values as specified by the OEM
- Parametric data of the machine via the rapid calibration system (in XML format)
- Temperature measurements at time of testing
- Measurement plans

The machine tool was modelled with this 'Full Parametric Specification'. Table 8-1 compares standard deviation values predicted by PUNDIT to those of the real-world testing. Data indicates that although the results are a similar order of magnitude the PUNDIT model predicted higher standard deviations than was found during experimentation.

Table 8-1: Standard deviation comparison between PUNDIT and physical testing (1.75µm Probe Repeatability)

			Physical Experiment	PUNDIT Estimation	
Feature	Type	Nominal (mm)	Std Dev (σMc)	Std Dev (σPUN)	|Mean Error|
Sphere 1	Size	30.0011	0.0011	0.0026	0.0003
Sphere 3	Size	29.9999	0.0010	0.0027	0.0002
Length Bar (Long)	Size	400.0015	0.0040	0.0109	0.0010
Ring Gauge (ID)	Size	49.9983	0.0010	0.0031	0.0007
Cylinder (OD)	Size	50.0020	0.0010	0.0030	0.0008
S1-S2	Volumetric Distance	447.1832	0.0021	0.0122	0.0059

It was decided that perhaps a cause of the difference was that the researcher was too 'safe' in estimates for machine tool probing repeatability; where although the OEM stated probe repeatability as 0.25µm in fact 1.75µm was modelled. It was initially deemed that OEM specifications were unrealistic due to experience with running simulations with previous CMM models. Therefore, the model was updated to suit a higher precision probing system.

Table 8-2: Standard deviation comparison between PUNDIT and physical testing (0.25µm Probe Repeatability)

			Physical Experiment	PUNDIT Estimation	
Feature	Type	Nominal (mm)	Std Dev (σMc)	Std Dev (σPUN)	|Mean Error|
Sphere 1	Size	30.0011	0.0011	0.0010	0.0008
Sphere 3	Size	29.9999	0.0010	0.0011	0.0001
Length Bar (Long)	Size	400.0015	0.0040	0.0141	0.0058
Ring Gauge (ID)	Size	49.9983	0.0010	0.0017	0.0008
Cylinder (OD)	Size	50.0020	0.0010	0.0015	0.0009
S1-S2	Volumetric Distance	447.1832	0.0021	0.0164	0.0008

As indicated by Table 8-2 results of the PUNDIT model compare more closely with the real-world testing, except for two cases. These cases involved the measurement of features of a larger size/distance; namely the length bar and the distance between S1 and S2. It is also noted that in these cases estimates of standard deviation has also gone up rather than down. This indicates that perhaps there will be difficulties for UES estimation for larger components. Nevertheless, the researcher finds that despite PUNDIT not yet fully tailored for machine tool applications, results are still very promising.

8.7 Machine tool measurement capability estimation

Despite the experimental case being inconclusive, the researcher suggests that with further testing, tailoring and validation PUNDIT may well be fully capable for modelling machine tool measurement uncertainty. In anticipation of this the researcher hypothesises such a tool can be used to specify which component features and characteristics can be measured on the machine tool to an exact tolerance. Therefore, in advance of this, the researcher chooses to explore this by utilising current industrial decision criteria typically used by high precision manufacturers regarding process capability.

8.7.1 PUNDIT as gauge capability decision tool

In Chapter 7, the concept of using capability targets to make decisions on sampling and transferring measurement onto the machine tool was explored. With these decision rules in place PUNDIT can be used to simulate expected mean error and standard deviation for task specific measurements. Based on full parametric profiling of the machine tool, specific machine tool inspection tolerances can be generated offline for any given feature or characteristic.

8.8 Inverted gauge capability study

With results generated by PUNDIT in conjunction with the above decision criteria tolerances can be derived for the machine tool as a gauge using (1) and (2).

$$C_g = \frac{{}^{k}\!/_{100} \cdot Tolerance}{V} \tag{1}$$

$$C_{gK} = \frac{{}^{k}\!/_{200} \cdot Tolerance - |\overline{X}_g - X_m|}{V/2} \tag{2}$$

Where:

- Cg = Capability of the “Gauge” considering gauge variation only
- CgK = Capability of the “Gauge”, considering both gauge variation and bias
- V = Variation as per study
- V = $k_x * \sigma$
- k_x = Coverage factor (k = 2 for 95% confidence, k=3 for 99.7%)
- σ = standard deviation of all measurements
- *k* = Percentage of tolerance required (=20)

PUNDIT reports ‘Mean Error’, which is an equivalent to bias [167]. Therefore, Bias = $|\overline{X}_g - X_m|$.

Rearranging (1) and (2) to make Tolerance the subject expected tolerances based on 1.33 and 1.50 capability indices, as per (3) and (4), can be simulated.

$$Tolerance = \frac{C_g \cdot V}{{}^{k}\!/_{100}} \tag{3}$$

$$Tolerance = \frac{\frac{C_{gK} \cdot V}{2} + |\overline{X}_g - X_m|}{k/_{200}} \quad (4)$$

It must be noted that PUNDIT reports uncertainty as |Mean error| + V with k=2.

Hence for all features measured Table 8-3 presents potential tolerances that could be specified as derived from the PUNDIT machine tool simulation.

Table 8-3: Inverted gauge C_g and C_{gK} tolerance specifications derived from PUNDIT model

			Category A Features (Cg = CgK = 1.33)		Category B Features (Cg = CgK = 1.50)	
Feature	Type	Nominal (mm)	C_g Tolerance	C_{gK} Tolerance	C_g Tolerance	C_{gK} Tolerance
Sphere 1	Size	30.0011	0.035	0.021	0.039	0.024
Sphere 3	Size	29.9999	0.036	0.018	0.041	0.021
Length Bar (Long)	Size	400.0015	0.145	0.101	0.164	0.111
Ring Gauge (ID)	Size	49.9983	0.041	0.025	0.047	0.027
Cylinder (OD)	Size	50.0020	0.040	0.024	0.045	0.027
S1-S2	Volumetric Distance	447.1832	0.162	0.085	0.183	0.096

From Table 8-3 it can be seen that to achieve gauge capability of 1.33 for the 5-axis machine, tolerances of 35 micron upwards will have to be applied for Category A features and 39 micron upwards for Category B features. Results show that for larger features tolerances are generated in the range of 0.145 to 0.183mm, which would potentially be unrealistic for high precision products. These results also correlate well with findings from Paper III, whereby despite excellent machining precision being demonstrated by the machine tool, tolerances for machine measurement would be significantly wider than that is specified for machining. Despite these findings it was demonstrated that the use of UES software, like PUNDIT, can be a powerful tool for specifying and qualifying machine tool inspection guidelines.

8.9 Discussion

In order to achieve the goal of using PUNDIT UES software for the planning of industrial CMM or machine tool inspection activities, there are several key learning points that still need addressing. Identifying and commenting on all of these points is out of scope for this research, however key functionality improvements with respect to OMI are noted as:

8.9.1 User generated parametric/kinematic profiles

At the moment there is no straightforward process for converting machine tool measurement data into a compatible format which PUNDIT UES can seamlessly accept. Where the industry is moving forward to standardise using XML as a common language platform this would provide a suitable platform. At time of writing Metrosage LLC are actively working with the National Composites Centre (UK) and the Manufacturing Technology Centre (UK) [192] to achieve this.

In addition to this the ability to model more than just cartesian framed machines would also be of significant benefit. Where multi-axis machining is now the norm, multi-axis probing is sure to follow.

8.9.1 Improvement in quality of parametric data and its acceptance

Another key challenge worthy of future investigation and intervention is with respect to the parametric data being inserted into the modelling software. At this moment only uni-directional measurement data can be inserted where bi-directional data as per ISO 230-2 is more appropriate. Additionally, the consideration of uncertainty of the parametric data itself due to the inherent in the measurement of the machine tool is currently not considered in the UES.

8.9.2 Form error consideration

In this investigation form errors were very low as a high precision artefact was being utilised. For the measurement of products this would have to be considered very carefully. Solutions to this could be to create a central database for which PUNDIT can access to gain and share this information. Alternatively, with the use of scanning probe technology this could be captured and imported directly into the software.

8.9.3 Larger scale components

It has been shown that PUNDIT appears to significantly overestimate uncertainty for larger features (~300-400mm), this will of course only increase for larger scale components. In order to proceed with the use of PUNDIT for such features this irregularity will need to be fully understood and mitigated. This may include the modification and/or re-validation of the UES algorithms that the software utilises.

8.9.4 Dynamic/point cloud data acceptance

Perhaps an ambitious step, but with the advent of scanning probe technology becoming available for machine tools, there may be an opportunity to create virtual models that can simulate and estimate their capability. How these models will be created and validated is a potential major avenue for further study.

8.10 Conclusions

The questions that are most often asked when utilising machine tools as measurement systems are associated to uncertainty. To be able to confidently quantify the uncertainty of task-specific measurements that have been made by a CMM or machine tool, without ambiguity, is of immense value to manufacturers.

Today CMM measurement relies upon a number of methods for uncertainty reduction and evaluation. This includes use of multiple measurement strategies, the use of calibrated workpieces, parametric modelling and expert judgement. The most ideal method has still not been defined for the production environment. Currently virtual modelling and simulation appears the least intrusive and most cost-effective method for uncertainty estimation. This is perhaps reflected by the emergence of commercially available UES software packages such as PUNDIT CMM. By combining such software packages with machine tool metrology indices and rapid measurement systems, this can potentially be a significant enabler for industrial scale on-machine inspection.

In this chapter the researcher has explored the utilisation of PUNDIT CMM as a potential tool for specifying tolerances for on-machine inspection via on-machine probing systems. Although a similar exercise was performed in a previous investigation, the chosen machine tool was not accurate enough to allow for reasonable correlation. In this case a new state-of-the-art 5-axis machining centre was utilised. This machine had recently been installed and calibrated on site using rapid measurement methods developed within this thesis. With this, tests were performed to illustrate the validity of an off-the-shelf UES package when using real-world parametric data. Testing involved the comparison between standard deviations between PUNDIT and the machine tool; for the measurement of size and distance for various features on a Zeiss CMM-check artefact.

Results showed that in initial investigation the PUNDIT UES model overestimated standard deviations for small features when compared to real-world experimentation. Where it significantly overestimated standard deviations for larger >100mm features. Initially a hypothesis was made that this overestimation was derived from the use of a probe repeatability error of 1.75µm. When this was adjusted to a repeatability value not typical for on-machine probing devices, 0.25µm, the UES model became better aligned; however again not for the larger features measured.

Based on evidence shown in conclusions made in previous studies, the researcher still believes that hand-in-hand with rapid machine tool calibration and verification there is potential for real-time UES simulation. Therefore, the use of PUNDIT as a tool for specifying on-machine inspection gauge tolerances can be hypothesised. It was found that even for an exceptionally high precision machine tool, operated under exceptional conditions, tolerances to be applied would have to be reasonably wide to enable confident on-machine inspection. This was still with minimal form error, the lack of tool change considerations, as well as not using any of the machine's rotary axes.

Seamless implementation will however only be enabled with a robust high-precision manufacturing orientated product life-cycle management (PLM) system in operation. Here, live, task-specific measurement uncertainty estimation capable to emulate the dynamic nature of the manufacturing shop-floor and machine tool environment is theoretically possible.

Chapter 9

General conclusions and contributions to knowledge

This thesis has focused on addressing several fundamental questions associated to the goal of enabling industrially based high precision machine tools as traceable measurement systems. This chapter presents the conclusions of the main contributions of the research conducted. It concludes with suggestions for further research opportunities.

9.1 Main contributions

This section summarises the most important contributions of the research.

9.1.1 Demonstration of the impact of on-machine inspection

As described in Paper II (Appendix A) there is considerable debate within manufacturing circles whether more measurement should be brought on-to the machine tool. Chapter 2 (The literature and state-of-the-art review) highlighted that despite a number of researchers and equipment manufacturers purporting the potential benefits of on-machine inspection, few case studies had in-fact been reported. In Chapter 4 an action case study was performed on a live manufacturing cell, dedicated to producing aero-engine combustion casings.

Findings from this investigation re-enforced that the conversion of machine tools from being solely machining systems to both measurement and machining systems was a socio-technical challenge. Satisfying internal and external stakeholder needs was foundational. The research also highlighted key practical implications, these are identified as: 1) A need and process for a probe qualification; 2) The need and process for machining strategy change; 3) The requirement of bespoke programmes designed to automatically calculate offsets; 4) The need for greater control of the machining system, exceeding requirements for machining.

With this a significant improvement in product right-first-time post intervention was demonstrated, from circa 18-60% pre-intervention to 92-96% post introduction of the on-machine measurement system. Until this case study this form of evidence in terms of the value of introducing on-machine measurement systems onto a cell of industrially based production machine tools has not existed in the academic arena.

9.1.2 Creation of ‘Machine tool metrology index’ concept

It is well known that a machine tool will vary in capability throughout its lifecycle. This will not only affect its machining performance, but it will also impact upon its ability to perform measurements; and subsequently reduce trust in the measurement results it will provide. Paper I and chapter 2 identify that, yes, there are a series of measurements that potentially can be made. However, there was no systematic approach to generating machine tool and process specific indices.

The investigation performed in Chapter 5 generated and developed the concept of the ‘Machine Tool Metrology Index’. The purpose of such an index is for the specification, communication and approval of a full list of error parameters which require measurement in order to qualify a machine tool system for measurement purposes.

In chapter 2, a number of ‘standard’ practice methods for generating such metrology indices were tested. These approaches where then applied to a sample of machine tools typically utilised to produce gas turbine components. In parallel to this, metrology indices were compiled based on consensus view, where participants including skilled and experienced machine tool service engineers, University staff, and manufacturing maintenance engineers.

This analysis has shown the need for the creation of machine tool ‘metrology indices’ before an assessment of machine tool precision capability can be made. Where the current best approach for their creation is a systematic approach, via consensus agreement.

9.1.3 Rapid machine tool measurement concept

Chapters 1 to 3 discussed in detail the need for faster more efficient machine tool measurement processes, particularly with regards to calibration and verification. Chapter 2 of this thesis was devoted to the research and development of rapid machine tool measurement methods. As an extended literature study this chapter reviewed and critiqued the suitability of current off the shelf machine tool methods for both capability and speed of measurement. Following this, six new measurement tools were developed and tested via industrially based research exercise in Chapter 6. Additionally, Paper V was also written and published which presented a novel artefact-based methodology for rapid machine tool verification.

The research has therefore demonstrated that it is now possible to fully measure a multi-axis (5-axis) machine tool, according to its full metrology index, in a space of 2 hours as opposed to 4-5 days. Similarly, the research work has demonstrated that machine tool verification, fundamental for on-machine inspection, requires complex systems integration to operate effectively. This improvement in efficiency is significant for high precision machinists, as knowledge of machine metrological performance can now be gathered with minimal spindle downtime and disruption to business. The impact on academic research is also significant as the reduced lead time in performing repeat measurements. This enables full error mapping and monitoring on both live and non-production machines. This means that full geometric mapping and compensation can be performed on a more regular basis thus accelerating learning and knowledge generation.

9.1.4 OMI implementation framework

As indicated by chapters 1 and 2, although perhaps prevalent in some manufacturing areas, there is little existing evidence or documented studies examining the use of machine tools as measurement systems. In Chapter 4 a cell of machine tools was augmented with the introduction of on-machine probing systems. This presented the benefits of introducing measurement systems on machine tools, irrespective of age or configuration. Following on from this study the same cell of machine tools was again augmented to not only include in-process offset updates but to act as traceable measurement systems able to reduce burden on post-process CMM inspection systems. This example case demonstrated that although some machine tools may be able to perform inspection activities the introduction of on-machine inspection via on-machine probing was a complex socio-technical challenge. This thesis subsequently generated new knowledge which resulted in the creation of a novel on-machine inspection implementation framework (Chapter 7). This framework was proven to be a powerful tool for a manufacturing organisation which could only speculate about introducing on-machine inspection, in order to move to a sampled inspection basis. The framework provided a structure for engineers; to make a decision to proceed to OMI; scope capability and intervention; select the most appropriate technology; manage execution; and confirm correct completion.

In a parallel study Paper III demonstrated that even newly built ‘state-of-the-art’ machine tools, although entirely capable for producing components to specification, did not show consistent performance when treated as measurement systems. In the study, most of the machine tools demonstrated high levels of variance, which was attributed to tool-change, pallet-change and warm-up cycles. This original work provided powerful evidence to both academia and industrialists that the measurement performance of machine tools cannot be assumed solely on machining capability. This knowledge is useful not only to machine tool users but also machine tool builders.

9.1.5 Application of UES on machine tools

The measurement accuracy of a machine tool will vary over its full working volume and lifecycle. This is mainly due to geometric and kinematic errors of individual axes in combination with Abbe-offsets with machine encoders and/or scales. In order to understand the impact of these errors the researcher aims to create ‘virtual machine’ models in order to predict performance.

In Paper IV and Chapter 8 a proven off-the-shelf uncertainty estimation software (UES) package was employed to model machine tool metrological performance. This study highlighted several opportunities and deficiencies with both the machine tools and the design of the commercial UES software being employed. As current UES software is tailored for CMM devices rather than machine tool systems. This research has subsequently resulted in a commercial uncertainty estimation software provider (Metrosage LLC) adapting its software to directly accept and generate a full parametric model of any three-axis machine tool. Here parametric data can be directly imported from the rapid measurement solution as tested in Chapter 6. This contrasts with utilising error maps based on ISO 10360 methods, which are less relevant for machine tools.

With further development this potentially opens up an avenue for an entirely new research field. This could include the development of new standards, with regards to the creation of machine tool kinematic models. This is likely to be driven by industry as it adopts such commercial software for its CMM equipment. With these investigations, society is closer to a reality where OMI uncertainty statements can be specified by machine tool builders; these can then be validated on a continuous basis.

9.2 Suggestions for future research

This thesis has been written in conjunction with a post-graduate Engineering Doctorate (EngD) study. This EngD, a PhD study aimed to generate new knowledge and subsequently apply it in an industrial context, has by its nature covered a broad spectrum of potential research areas. This is indicated in the diversity of content contained within each of the chapters presented. As such this EngD has generated new manufacturing process knowledge, new technical knowledge and it has had industrial impact and generated customer value. This learning can be transferred internally within the sponsoring organisations and externally, to other similar manufacturers and interested academic institutions. All these chapters can therefore be developed within and further beyond the current scope, as indicated by Figure 9-1.

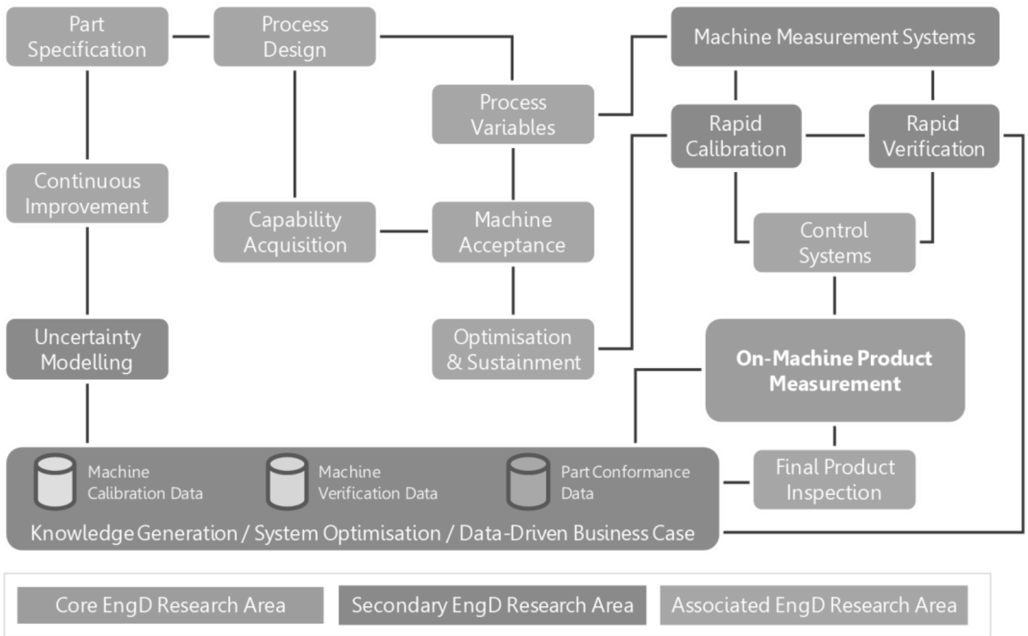


Figure 9-1: Scope of EngD Thesis as presented in Chapter 3

In reference to the original core question being *"How can traceable on-machine inspection be enabled and sustained in an industrial environment?"* the researcher is closer to addressing this question, but there are new avenues of research which can be pursued, including:

- Investigation of thermal influences via on-machine verification

It is well known and widely documented that thermal influences have a significant effect on both machine and measurement system precision. With the ability to both calibrate and verify a machine tool in a shorter cycle time, one can potentially validate virtual models with more certainty due to the reduced delay time between experimental data and interventions. This subsequently could be used to make UES models more accurate.

- Machine probing system validation and improvement

Machine probing systems, for both CMMs and machine tools, are typically modelled via a random error parameter. This error parameter is typically provided by probe manufacturers and is often not validated. This can perhaps be improved by research focusing on systematic errors present with such systems. With this research both the capability of probing technology can potentially be improved as well as modelling tools which utilise such information.

- UES improvement specifically for machine tool application

One of the key findings identified in Chapter 8 was that current UES software is tailored for CMM applications. One major deficiency identified was with regards to the handling of, or lack of, reversal and bi-directional errors. Additionally, such software can be further improved to consider dynamics and effects of thermal gradients within the machining volume. Through this implementation such software could not only be used as a tool for estimating uncertainty of in-process measurements but as a tool for generating design tolerances. This work is also likely to lead to the generation of new standards.

- Multi-degree of freedom compensation

The creation of new multi-degree of freedom technology, able to measure multiple linear axis error parameters in a single pass, enables a broad opportunity for future research. Such research can confidently involve associating relationships between pitch, roll, yaw and straightness measurements as well as developing multi-degree of freedom compensation algorithms.

- Dynamic performance modelling, compensation and validation

Currently a major assumption, forced by practical reasons, with current machine tool measurement is that the machine is compensated in an unloaded quasi-static state.

This therefore needs to be investigated and potentially addressed. Although there are measurements standards that do cover dynamic errors, with the advent of scanning probe technology, these systems are unsuitable due to inherent limitations. It would therefore be useful to be able to 'calibrate' dynamic effects of machine motion for both machining and measurement applications.

- Spindle performance monitoring

The creation of a rapid in-process spindle verification system developed and commercialised in support of this research, enables both industrial and academic learning with respect to the performance and degradation of high speed, high torque spindles during machining. Much research can be performed focusing on spindle geometry during the machining process.

- Manufacturing IT systems integration

OMI as well as the system and technology to efficiently and effectively enable it requires data connectivity between several manufacturing databases, as part of a 'digitisation' strategy. This can include integration between manufacturing execution and information systems dedicated to machine tool maintenance, inspection results, calibration control, tooling, CAD/CAM and process/product planning systems etc. Although the researcher gained exposure to this challenge via implementation of OMI, there is a clear need to unify and link such systems. Additionally, as a start, a machine tool accuracy database could be created which could act as a central repository for both academics and industrialists to compare the performance of different machine tools.

- Machine tool adaptive compensation

With the introduction of faster machine tool calibration and verification in conjunction with the data stream from OMI there is an opportunity for a novel statistical analysis system. Such a system could be utilised for the adaptive control and optimisation of the machine tool and its systems.

- Robotics, special machines and additive systems

There is prime opportunity to develop the methods and technology generated via this research for the application of in-process inspection on robotic equipment, special purpose machines and perhaps even additive manufacturing systems. The researcher has found relatively little work performed in these areas in comparison to what is found for conventional multi-axis machines.

- Non-contact OMI

This thesis has focused on the use of on-machine probing for the inspection of products whilst in process. As of yet the availability of non-contact machine tool in-process measurement devices is limited (in terms of technology on the market). Many of the principles and much of the learning in this thesis can also be applied here. Therefore, a significant avenue for future research is via the investigation of auto-visual inspection methods, or equivalents, being introduced and utilised on production machines.

- Large volume solutions

The scope of this thesis has been limited to only consider small to medium sized machine tools utilised to produce high-speed turbo machinery components. Enabling on-machine inspection for large-volume machines is very different, arguably more challenging, but provides a greater opportunity. This is since large components may remain on a machine tool from weeks to months, rather than hours or days. In this case relocating such a component to an equally sized CMM is not ideal.

- Live error compensations, tolerance decision making and/or UES updates

Chapter 8 explored the concept of applying uncertainty estimation software (UES) for machine tool applications. Typically, current UES systems have not been designed for this application. Therefore, the researcher believes this is an area which provides extensive fertile ground for investigation, experimentation, development and knowledge generation. Future research can be carried out from both a technical and systems perspective i.e. understanding and correlating UES uncertainty estimations to machine tool performance assessment or linking UES software to PLM systems for purposes of live product routing.

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Appendix A

This piece of work set out to uncover whether machine tool metrology - the measurement of machine tools, is perceived as value-adding within a high-value high-precision manufacturing organisation. The research work, carried out in conjunction with The University of Bristol – Systems Centre, uncovered that there was the general opinion that a more holistic approach was necessary to realise the full value of metrology with manufacturing. This can be very significant if some key implementation issues are to be managed.

The Value Of Industrial Machine Tool Metrology: A Systems Thinking Approach

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Abstract: High precision manufacturers continuously strive for greater process capability and consistency in an effort to gain competitive advantage. The importance of metrology and measurement towards this objective can seldom be overvalued.

Within manufacturing organisations the impact of measurement intervention can be observed throughout the organisational hierarchy, where depending on viewpoint perceptions of value can vary dramatically. This piece of work set out to uncover whether machine tool metrology - the theoretical and practical aspects of the measurement of machine tools, is perceived as value-adding within a high-precision manufacturing organisation.

The research methodology consisted of performing facilitated focus group exercises followed by semi-structured interviews with stakeholders from multiple business functions. Both sets of data were used to understand the opportunities and problems encountered by manufacturing engineers when choosing to implement machine tool metrology systems into their production process.

The aim of this paper is to present an argument that better 'Systems Thinking' can enhance the benefit, and subsequently value, of machine tool metrology – the application of measurement to machine tools.

Keywords— Metrology, High Precision Manufacturing, Machine Tool Calibration, Cost, Socio-Technical Systems, Systems Thinking

I. Introduction

Improvements in machine tool precision have significantly increased the value of manufactured parts. In today's manufacturing environment the requirement for high precision is also in parallel with high production rates, reducing cost and limiting environmental impact. Machine tool metrology presents itself as vital and cost-effective tool for achieving these ambitions.

In this paper we use a Systems Thinking approach [1][2] to explore various stakeholder views in order to uncover perceptions of the value of machine tool metrology. We start this paper by examining the concepts, background and case for improved machine tool metrology within a global aerospace manufacturer. We then explain the methodology we have used to answer the question "Is machine tool metrology perceived as value-adding?" We then present and discuss key findings based on responses from participants of our research activity.

A. Background

The economic impact of metrology within manufacturing can be difficult to quantify due to its complex interactions with the manufacturing system. Some work has been done previously to evaluate the benefits of implementing metrology systems within manufacturing cells [3][4][5] . However these models often purely look at the operating inputs such as design, manufacturing and inspection costs and relate them to manufacturing outputs such as rework, lost production and final product quality costs. Although economic cases are difficult to form it is widely accepted that reliable and capable metrology plays a key role in achieving consistent manufacturing excellence [4]. Manufacturing metrology is the core requirement for process control and quality management and therefore of vital importance for profitable manufacture of high quality products.

Often literature is, as expected, favourable towards the use of industrial metrology where benefits are well defined and communicated, where the 'non-benefits' are often unspoken of [5][6]. An interesting paradox highlighted by Kunzman [3] is that although Metrology is widely accepted as important it is not necessarily perceived as a value adding. This is made on the argument that Metrology does not in-fact generate new knowledge due to its focus on the application of measurement rather than its utilisation. Kunzman therefore introduced the term 'Productive Metrology' to enforce this argument and describes mechanisms in which such pro-active metrology can generate business benefit via intervention (Figure 1).

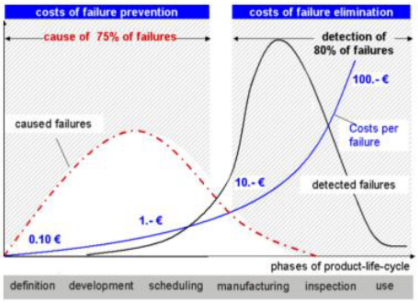

Figure 1 - Origin, elimination and cost of faults [3]

Modern manufacturers typically concentrate the majority if not-all their metrology budgets on final product inspection activities as a means of preventing in-service product failure and incurring costly penalties [4]. This manufacturing model emphasises the importance of defect detection over prevention i.e. customer protection rather than customer cost-reduction. A reason for this behaviour may be attributed by a difficulty to quantify benefits of metrology within and prior to the manufacturing process [3]. As a result it is often up to decisions by managers to make choices with limited information, where high ratios of fixed costs to marginal costs and externalities exist.

It is believed by applying productive metrology more holistically and better integrating management and engineering systems this paradigm can be changed; in order to add greater value through; more efficient control of processes i.e. manufacturing processes; and testing of conformance to specification

B. *Systems Approach*

Sydenham (2003) highlighted that many manufacturers invest a lot of time and money into the science and art of measurement without 'Systems Thinking' [1][7] involved to ask the fundamental questions of "Why are we making the measurements?" and "Where will this lead to in the future?". It was observed that often many metrologists often conduct their critical thinking in relative isolation of the holistic world in which their contributions sit which reduces its impact of the activities of the business and can potentially cause more problems than solve.

Swann [4] consequently picked up these questions and presented a compelling argument about the need for metrology within manufacturing. The report however stopped short of a critique on what implementation challenges are likely to exist should an organisation adopt the practice. The report also emphasised the role that measurement plays in not only the verification of products but with the testing and verification of production equipment to assess and improve its capability.

C. *Business Case for Machine Tool Metrology*

Multi-axis machine tools are key utilities in the manufacture of complex high precision parts. These assets are required to produce components accurately, repeatability and reliably throughout their life-cycle.

In terms of the current machine tool market, the UK spends on average £600M per year on new machine tools alone [8]. Research has also found that a high precision manufacturer is likely to invest 5-15% of its annual turnover in new machinery. Therefore with an average life of 6-10 years per machine [9] this indicates that a valid business case must exist for focusing effort on optimising and sustaining the capability of these assets.

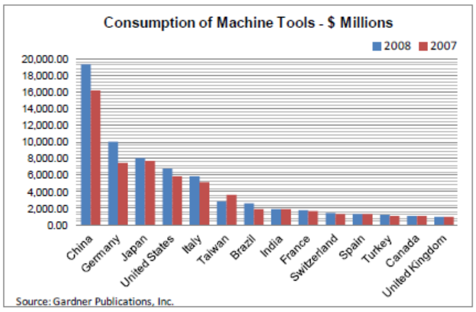

Figure 2 - Machine tool consumption (Source Gardner Publications)

Increases in product performance are constantly driven by designers, who specify tighter manufacturing tolerances, constrained design specifications, increased complexity of product geometries, higher performance materials, which effectively results in parts that are difficult to machine. From a manufacturing process perspective engineers are continuously trying to improve machine tool capability in terms of availability, performance and quality. This is with the aim of reducing the frequency and severity of process breakdowns as well as increasing machine uptime, material removal rates and automation. Therefore a paradoxical situation has arisen where more severe conditions are being imposed on the machine tool where higher performance is expected but with lower levels of process interruption.

In order to produce conforming product at a high level of process capability it is fundamental that a machine tool is demonstrably accurate. To bring machines into such a condition they themselves must be measured via 'direct' or 'in-direct' measurement systems (Figure 3). Other than just validating fundamental accuracy other benefits of this measurement activity include the ability to pin-point sources of variation, prevent manufacturing non-conformance and increase process know-how. In fact, the clear value-adding strands associated to productive metrology can also be applied here, being the:

- Reduction of inefficient manufacturing due to value-adding activities on defective parts
- Reduction of warranty cost due to product failures on the market, including logistics
- Increase of know-how e.g. greater understanding of product functionality
- Reduced liability issues after product failures

Figure 3 - Examples of State of the Art Machine Tool Metrology Equipment

D. *Current State*

Machine tool metrology processes are typically time consuming. Currently it can take multiple days to measure some advanced CNC machine tools correctly [10][11]. As a consequence manufacturing output can be significantly disrupted if all machines are subject to such interruption on a regular basis. Equipment operators, maintainers and manufacturers will argue that the process interruption, irrespective of duration, is vital, as it improves manufacturing system performance and productivity through Total Productive Maintenance (TPM). However is has been shown that with such a competitive environment and complexity of the manufacturing system, commitment to release machines for such TPM is difficult to achieve [2].

II. Methodology

A. *Research Questions*

This study has employed multiple methods in order to gather data, substantiate responses and gain consent amongst key stakeholders. The central data collection methodology was via use of a Visual Image Reflection (VIR™) technique [12] developed by The Creative Problem Solving Group. This technique was utilised to focus the thoughts of users onto the subject of machine tool metrology and to reveal individual value(s) and concern(s). Following the VIR™ exercise participants were asked to provide two opposing statements on the subject, preceding with:

- **Machine tool metrology can be value adding because...**
- **Machine tool metrology may not add value because...**

This research strategy was generated at the University of Bristol - Systems Centre using a focus group involving multi-disciplined Systems Thinkers. The participants of the group did not have prior knowledge of machine tool metrology or have any direct involvement with the researcher and were therefore ideal for impartiality on question choice.

The consensus made by the group was not to concentrate on generating quantitative data but aim to understand stakeholders perception of current academic definitions and interpret their 'values'. The choice of two opposing statements was also agreed as it allowed the generation of a balanced viewpoint from participants of the study, rather than leaving the opportunity for extreme views.

B. *Research Environment*

Rolls-Royce plc., is a world-leading provider of power systems and services for use on land, at sea and in the air. Over the next 20 years, Rolls-Royce forecasts demand for 141,000 engines, worth over £500 billion. The demand comes from fast-growing markets in Asia, the Middle East and Latin America, but also from replacing many thousands of older aircraft in the more mature markets of Europe and North America [13]. Additionally, the aftermarket and services opportunity created by these deliveries equates to £370 billion over their service lives [14]. This of course will bring huge new challenges and opportunities to the business especially in the areas of manufacture and assembly.

The strategy for identifying stakeholders involved studying organisational charts, key suppliers and potential interested parties. Criteria for selection was based on two categories being:

- is the user involved with or affected by changes in manufacturing capability and/or
- is the user interested in or influenced by changes in manufacturing capability

Due to the sensitive nature of the information we are unable to disclose details of location, facility and user names however we have strived to ensure all views have been captured from the relavent functions as seen in Figure 4.

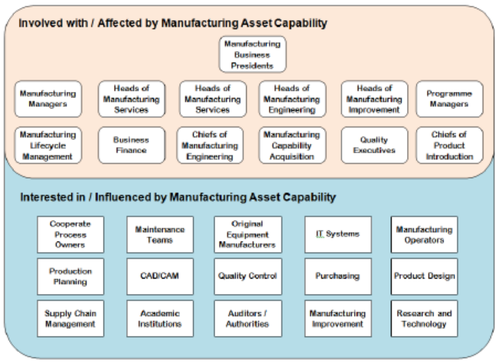

Figure 4 - Machine Tool Metrology Stakeholders

In total this study included forty participants via group meetings and semi-formal interviews. Participants included relevant academics, external suppliers, and key manufacturing operations staff. Information gathered during these exercises was recorded in single line statements which were organised using mind-mapping software. Supplementing this collected data follow-up informal interviews were held with key stakeholders and extensive reviews of company documents was completed. The collection of data, its consolidation, the follow-up interviews and analysis was performed over a period of 5 months.

C. *Current organisational literature*

Central to this study was the extensive review of company literature relating to the organisations manufacturing ambitions, strategy and plans. It was found that Rolls-Royce plc. is not unlike many of the manufacturing organisations operating throughout the world, where its manufacturing and assembly operation is its largest, the most complex and arguably the most difficult to-manage area of the business. Due to tight profit margins and the safety critical nature of the products that the company produces its manufacturing operations cannot afford to operate in isolation; as they affect and are affected by an array of external and internal organisational systems. Clear in the businesses top-level strategy is the requirement to simultaneously focus on safety, quality, delivery, people and cost; where each manufacturing SCU is strongly encouraged to build and maintain synergy with finance, engineering, R&D, HR, purchasing and logistics business functions.

D. *Application of Production Metrology*

Rolls-Royce's products are exceptionally safety critical, the firm focuses heavily on product quality assurance activities in an effort to "protect the customer" and maintain the organisation's mission statement of "trusted to deliver excellence". The importance of capable metrology systems for achieving these objectives cannot be overstated. Tangential to this, is the drive for continuously improving manufacturing right-first-time (RFT) and reducing cost of non-quality (CoNQ). Here focus is brought onto the manufacturing assets of the organisation to provide capability, repeatability and reliability.

During the study we found that although most new machines are validated when they are first installed, the number of machines re-assessed correctly at regular intervals post-installation is seen to be much less. Also, in spite of what a machine tool manufacturer's brochure may say, the true performance of a machine may be proven to be significantly poorer than expected, where it degrades further throughout its lifecycle. As a result of the situation, key manufacturing stakeholders see the focus of metrology on the machine tool as an excellent opportunity for increasing process knowledge and improving capability. This in turn is expected to have a variety of further benefits in terms of productivity, quality, safety and cost.

E. *Stakeholder engagement*

The next phase of work involved obtaining the input of the functional users as identified in Figure 4 above. This was achieved through various facilitated focus groups, semi-formal interviews as well as telephone and email communication. Each respondent was informed that their comments would be kept anonymous to encourage free thought. Responses were recorded via hand simply using slips of paper purposely proportioned to limit responses. All data was then transposed and grouped via mind-mapping software. Following this exercise further semi-formal interviews were held in order to further substantiate conclusions.

III. Findings and Discussion

Among numerous remarks made during the employment of this research strategy, the following may have significant implications for researchers and industry professionals. Firstly, the study has lent validity to comments made by Swann [4], Sydenham [15] , Savio [5] and Kunzman [3] in terms of their emphasis on the need for metrology to create new business knowledge.

To expose central thoughts, all data was inserted into a 'Word Cloud' [16] tool to visually represent the most prominent terms used by all involved in the survey Figure 5.

Figure 5 - Word Cloud Output from Survey Responses

Looking at terms within the cloud, there are several points which are exposed, which although may / may not be universal, raise significant points of discussion about the validity and applicability of shop-floor metrology systems. The next section of this paper further explores these findings which are directly interpreted from the collected data.

A. *Definition of Machine Tool Metrology*

Of the responses received it soon became apparent that not everyone was clear about the definition of machine tool metrology. It was observed that many used the term metrology interchangeably with the terms measurement, calibration and verification. The anticipation was that participants of the survey would comment on the use of metrology for a productive role of measuring and optimising machinery. However many perceived the term machine tool metrology as the use of machine tools as measurement devices or just the calibration of the linear accuracy of machine tool axes.

Where the terminology was understood some had also commented on the importance on clarity of definition. Emphasis was made that to achieve value from the activity the activity of machine tool metrology "repeatability, reproducibility and the bias of the measurement systems used must be fully understood and communicated" and that "the guarantee of traceability would be crucial". It was also communicated by business metrologists that without uncertainties combined with Gauge Repeatability and Reproducibility [17] being confidently known then the non-conformance of machining equipment is just as likely to come from the measurement systems used as the asset under investigation i.e. *"It can be very value adding only if it removes more uncertainty in the manufacturing process than it adds to it".*

B. *Metrology Good Practice*

A common theme that also emerged from responses was via questions of traceability. Where confidence in the numbers reported was strongly emphasised by many respondents. To reduce variability in measurement and improve traceability recommendations were made to reduce the number of measurement devices for machine measurement to a minimum and perform thorough Measurement System Analysis (MSA) [18] on all equipment used. This would allow for reduced complexity of the process through reducing and better understanding of the measurement uncertainty of tools used. Due to the relatively hostile shop-floor environments in which machinery operates, reducing the time of measurement and eliminating all other potential sources of variation would be vital.

C. *Tolerance Specifications*

Another sticking point to whether or not machine tool metrology could be value adding was through the specification of tolerances. Multiple comments were made about the sensitivity of tolerances used for interpretation of measurement data collected. Over inflating capability requirements would likely to lead to overconfidence in machining systems, wasting production time, reducing confidence in the process and induce potentially incorrect repair/optimisation activities. Conversely tight tolerances would likely to incorrectly classify machinery assets as incapable and potentially could induce additional costs to the business in terms of lost time, unnecessary repair/optimisation activities and organisational disruption leading to late product delivery. This scenario would also deem the interpretation of any data collected as meaningless therefore eliminating its value to the organisation.

From further discussions it was also highlighted that tolerances provided by international machine tool standards and original equipment manufacturers were often not appropriate for the production of high tolerance aerospace parts as they were specified more for machine tool builders rather than users. This therefore raises further questions about linkage between metrology and true machine tool condition.

D. *Defining Limitations*

Comments about the usefulness and limitations of machine tool metrology is also appears heavily. Due to the complexity of machining systems and the number of potential sources of variation (Figure 6) the scope of any measurement activity used to define capability must be clearly defined and communicated. For example, many observers state that since all key performance variables of the machining process will not be verified then the process of measurement is of no value.

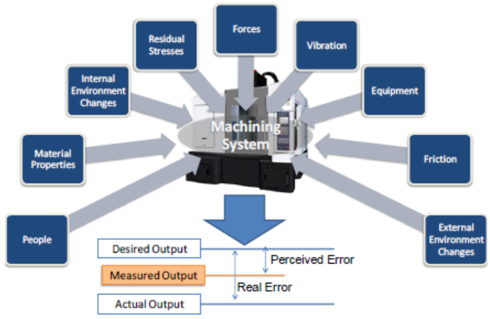

Figure 6 - Sources of machine tool variation

Conflicting opinions exist on the validity of machine tool metrology where individuals will claim that thermal errors, fixture or tool push-off are the prime contributors of machining variation.
These views support arguments of others being that unless machine tool metrology is used as part of a holistic process its only value is by validating machinery to specification and the creation of capability 'benchmarks' which are only relevant at the time of measurement.

E. *Value of machine tool metrology and its link to process improvement*

Defect and cost reduction are priorities for many in the manufacturing organisation, engineers are continuously searching and implementing manufacturing interventions for improving scrap rates, right-first-time and unplanned process interruption. In conjunction to these improvement activities organisations are also looking for soft systems improvements via the various manufacturing operations such as design, engineering, production and quality. Such improvements are likely to add value to the business as focus moves from reacting to quality issues to process optimisation. Due to the complex interactions of hard and soft systems the introduction of machine tool metrology systems without clear understanding of what will be changed and what is causing variation is seen to be a waste of time. Many agree that machine tool metrology has the potential for significant process improvement but without robust statistical process control, overall equipment effectiveness and understanding of environmental conditions means there is limited data to indicate what has changed and when.

There is a belief that only when machine tool metrology is introduced with appropriate statistical process control (SPC) systems then it is likely to be adopted. However, this requires additional time and resource from the company which may not be available. This perception leads many to believe that should the systems be implemented using limited resources it is not likely to be done with the required rigor making a further waste of time and resource. On further investigation of these comments, managerial staff intimated that past experience has shown that money has been wasted on inadequate metrology systems where benefits have not equaled or surpassed costs.

F. *Improper Implementation*

Many have argued that short-cuts taken with the implementation of metrology systems either via lack of knowledge, time constraints and/or budget constraints lead to lack of faith. This comes from bad experience where previously people have considered that adequate investment in metrology has been implemented but improvement in productivity or quality has not been seen.

It has also been communicated that the requirement for instant process feedback is also imperative not just by the measurement process itself but the rate at which data is fed back into the business. Due to the variability of the manufacturing process and the number of operations a part may go through before it reaches an inspection gate it is imperative that the business realises the true capability of a machine at the time of measurement rather than days or weeks later when it potentially has changed condition again.

G. *Human factors*

Much of the feedback from stakeholders has focused on soft systems aspects of machine metrology implementation.

Concerns were raised about the heavy reliance on tacit knowledge of individuals to take measurements, diagnose and carry out corrective action. There was a belief that current technology existed which could rapidly measure, calibrate or verify machine accuracy but a skills gap existed where the data could not be confidently interpreted and utilised. Examples were giving about operators making changes to machining equipment which either was not communicated to the rest of the business or corrective action was incorrectly diagnosed and implemented, creating quality issues and adding to production disruption. In these cases greater automation of the process was strongly recommended.

To overcome this issue, recommendations were made to adopt support from established machine tool metrology specialists and simultaneously develop in-house competency through training, involvement with academia, working with key technology suppliers and research and technology investment.

As mentioned previously, bad experience and limited business metrics are also likely make it difficult to adopt process-interrupting metrology systems. Others conclude even if such case studies did exist there may still be resistance to change manufacturing process due to a lack of understanding of non-experts and production pressures. A theory was also presented that *"Since we always work at the edge of technology will only further encourage tighter tolerances, technology cannot solve this"* which is a compelling philosophical argument.

Emergence was also touched upon; where members explained that political influences may be a factor of implementing new technology. *"Issues may come in the form of management realising that recently procured capital equipment is in-capable"*; or *"there may be an inflammation of tension between maintenance and production engineers based on new data and knowledge"*.

H. *Potential*

Often was the case that for every statement that machine tool metrology may not be value adding several were made of how it could be. Individuals perceived the strongest benefits as:

- Bringing confidence in the accuracy of machining assets
- Optimising and sustaining capability
- Improving right-first-time
- Allowing for greater 'intelligence' when specifying and procuring machine tools
- Adding traceability to equipment procurement
- Knowledge-based systems engineering
- Being an enabler of Lean TPM
- Enabling all machines to become 'calibration-controlled' metrology systems

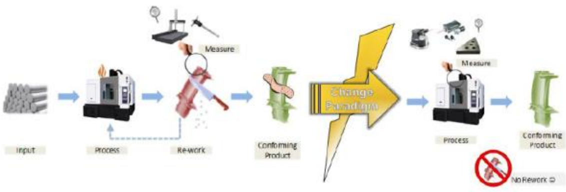

Figure 7 - Change in Manufacturing Paradigm

Ultimately the concept fitted well with the ambitions of senior manufacturing staff of focusing metrology on the measurement and control of manufacturing key variables as opposed to just output (Figure 7).

This change in paradigm is seen as a step further from lean manufacturing which principally focuses on streamlining flow. This philosophy focuses on tackling variation at source in order to bring predictability, repeatability and reliability to the manufacturing process.

IV. CONCLUSIONS

All manufacturing organisations venture on initiatives to improve quality, reduce cost and increase efficiency. Where 'lean' manufacturing methods have worked to help achieve these objectives they often ignore the unpredictability of the machining process itself. Manufacturing organisations are realising this and see that productive metrology is the new weapon of choice for achieving manufacturing excellence.

In this paper we have presented the case for machine tool metrology as a potential solution for understanding, improving and controlling sources of variation within the machining process. When presenting this idea to various stakeholders whom are involved with; affected by or interested in this topic; they have offered a spectrum of views. In terms of whether machine tool metrology could be value adding; we did not find much resistance about its potential; to reduce scrap, rework and concessions; inspection costs; operational costs; and generate greater knowledge of manufacturing processes. Where its implementation is likely to ensure predicable and capable manufacturing; without careful consideration about its implementation into the bigger system it is just as likely to add to the complexity of the machining process and reduce organisational performance. Key stakeholders argued that through total management of the technology via clarifying; definitions; business expectations; and investing in the appropriate training and equipment the metrology could be game changing. However short-cuts if taken could just as likely be treacherous.

To conclude, a final view is that machine tool metrology can only be value adding if either; it is only used to bring equipment to the specification expected by the organisation; or if it is implemented within a system where all other known manufacturing key performance variables were in already in control.

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Appendix B.1

The metrology index for a Makino 5AX 5-axis machine tool, as produced by consensus view:

G = Geometric Test (using precision artefacts)

L= Laser Interferometer Test

LX = Rotary Axis Test (using Laser interferometer and indexer)

TEST / ERROR	TYPE
Test 1 - Straightness of motion of the X axis in the Y Plane (X in Y)	G
Test 2 - Straightness of motion of the X axis in the Z Plane (X in Z)	G
Test 3 - Straightness of motion of the Y axis in the X Plane (Y in X)	G
Test 4 - Straightness of motion of the Y axis in the Z Plane (Y in Z)	G
Test 5 - Straightness of motion of the Z axis in the X Plane (Z in X)	G
Test 6 - Straightness of motion of the Z axis in the Y Plane (Z in Y)	G
Test 7 - X axis about X axis (X about X)	G
Test 8 - X axis about Y axis (X about Y)	G / L
Test 9 - X axis about Z axis (X about Z)	G / L
Test 10 - Y axis about X axis (Y about X)	G / L
Test 11 - Y axis about Y axis (Y about Y)	G / L
Test 12 - Y axis about Z axis (Y about Z)	G / L
Test 13 - Z axis about X axis (Z about X)	G / L
Test 14 - Z axis about Y axis (Z about Y)	G / L
Test 15 - Z axis about Z axis (Z about Z)	G / L
Test 16 - X axis positional accuracy (X Positional)	L
Test 17 - X axis accuracy and repeatability (X Acc Rep)	L
Test 18 - Y axis positional accuracy (Y Positional)	L
Test 19 - Y axis accuracy and repeatability (Y Acc Rep)	L
Test 20 - Z axis positional accuracy (Z Positional)	L
Test 21 - Z axis accuracy and repeatability (Z Acc Rep)	L
Test 22 - Squareness of Y axis to X axis	G
Test 23 - Squareness of Y axis to Z axis	G
Test 24 - Squareness of X axis to Z axis	G
Test 25 - Milling spindle axial runout	G
Test 26 - Milling spindle radial runout	G
Test 27 - Milling spindle internal taper runout	G

Test 28 - Parallelism of milling spindle centreline to Z axis in X plane	G
Test 29 - Parallelism of milling spindle centreline to Z axis in Y plane	G
Test 30 - Spindle trammel to X axis	G
Test 31 - Spindle trammel to Y axis	G
Test 32 - B axis axial runout (At centre hole and maximum diameter)	G
Test 33 - B axis radial runout (At centre hole and external diameter)	G
Test 34 - Parallelism of B axis centreline to Y axis travel in X plane	G
Test 35 - Parallelism of B axis centreline to Y axis travel in Z plane	G
Test 36 - B axis positional accuracy (B Positional)	LX
Test 37 - B axis accuracy and repeatability (B Acc Rep)	LX
Test 38 - Perpendicularity of the A axis to the YZ plane	G
Test 39 - A axis pivot length	G
Test 40 - A axis to B axis centreline offset	G
Test 41 - A axis positional accuracy (A Positional)	LX
Test 42 - A axis accuracy and repeatability (A Acc Rep)	LX
Test 43 - X axis reference position	G
Test 44 - Y axis reference position	G
Test 45 - Z axis reference position	G
Test 46 - A axis reference position (Zero setting)	G
Test 47 - B axis reference position (Zero setting)	G
Test 48 - Parallelism of table surface to X axis (At 4 rotary positions all pallets)	G
Test 49 - Parallelism of table surface to Z axis (At 4 rotary positions all pallets)	G
Test 50 - Repeatability of interchangeable pallets	G

Appendix B.2

The metrology index for a Mazak Integrex 35 horizontal mill-turn machine, as produced by consensus view:

G = Geometric Test (using precision artefacts)

L= Laser Interferometer Test

LX = Rotary Axis Test (using Laser interferometer and indexer)

TEST / ERROR	TYPE
Test 1 - Straightness of motion of the Z axis in the Y plane (Z in Y)	G
Test 2 - Straightness of motion of the Z axis in the X plane (Z in X)	G
Test 3 - Straightness of motion of the X axis in the Y plane (X in Y)	G
Test 4 - Straightness of motion of the X axis in the Z plane (X in Z)	G
Test 5 - Straightness of motion of the Y axis in the X plane (Y in X)	G
Test 6 - Straightness of motion of the Y axis in the Z plane (Y in Z)	G
Test 7 - Z axis about X axis (Z about X)	G / L
Test 8 - Z axis about Y axis (Z about Y)	G / L
Test 9 - Z axis about Z axis(Z about Z)	G
Test 10 - X axis about X axis (X about X)	G
Test 11 - X axis about Y axis (X about Y)	G / L
Test 12 - X axis about Z axis (X about Z)	G / L
Test 13 - Y axis about X axis (Y about X)	G / L
Test 14 - Y axis about Y axis (Y about Y)	G
Test 15 - Y axis about Z axis (Y about Z)	G / L
Test 16 - Z axis positional accuracy (Z Positional)	L
Test 17 - Z axis accuracy and repeatability (Z Acc Rep)	L
Test 18 - X axis positional accuracy (X Positional)	L
Test 19 - X axis accuracy and repeatability (X Acc Rep)	L
Test 20 - Y axis positional accuracy (Y Positional)	L
Test 21 - Y axis accuracy and repeatability (Y Acc Rep)	L
Test 22 - Squareness of X axis to Z axis	G
Test 23 - Squareness of Y axis to Z axis	G
Test 24 - Squareness of Y axis to X axis	G
Test 25 - Headstock spindle axial runout (At centrebore at maximum diameter)	G
Test 26 - Headstock spindle radial runout (At centrebore and external diameter)	G
Test 27 - Headstock spindle internal taper runout	G
Test 28 - Parallelism of Headstock centreline to Z axis travel in the X plane	G
Test 29 - Parallelism of Headstock centreline to Z axis travel in the Y plane	G

Test 30 - Tailstock parallelism to Z axis in the X plane	G
Test 31 - Tailstock parallelism to Z axis in the Y plane	G
Test 32 - Difference in height between headstock and tailstock centrelines	G
Test 33 - Milling spindle axial runout	G
Test 34 - Milling spindle radial runout	G
Test 35 - Milling spindle internal taper runout	G
Test 36 - Milling spindle parallelism to Z axis in the X plane (Spindle Horizontal)	G
Test 37 - Milling spindle parallelism to Z axis in the Y plane (Spindle Horizontal)	G
Test 38 - Milling spindle parallelism to X axis in the Y plane (Spindle Vertical)	G
Test 39 - Milling spindle parallelism to X axis in the Z plane (Spindle Vertical)	G
Test 40 - Concentricity of the headstock centreline and the horizontal milling spindle centreline	G
Test 41 - C axis positional accuracy (C Positional)	G
Test 42 - C axis accuracy and repeatability (C Acc Rep)	LX
Test 43 - X Reference Position	LX
Test 44 - Y Reference Position	G
Test 45 - Z Reference Position	G
Test 46 - C Reference Position	G

Appendix B.3

The metrology index for a Okuma V55R vertical lathe machine, as produced by consensus view:

G = Geometric Test (using precision artefacts)

L= Laser Interferometer Test

LX = Rotary Axis Test (using Laser interferometer and indexer)

TEST / ERROR	TYPE
Test 1 - Table level measurement in X and Y plane	G
Test 2 - Table level planarity	G
Test 3 - Workholding spindle axial runout (At centre bore and maximum diameter)	G
Test 4 - Workholding spindle radial runout (At centre bore and external diameter)	G
Test 5 - Parallelism of vertical motion of the Cross-Rail to the workholding spindle centreline in X plane	G
Test 6 - Parallelism of vertical motion of the Cross-Rail to the workholding spindle centreline in Y plane	G
Test 7 - Squareness between the X axis motion and the workholding spindle axis of rotation (X axis Parallelism to Table Bearing Rotation)	G
Test 8 - Parallelism of vertical motion of the Z axis ram to the workholding spindle centreline in X plane	G
Test 9 - Parallelism of vertical motion of the Z axis ram to the workholding spindle centreline in Y plane	G
Test 10 - Parallelism of X axis motion to table surface in vertical plane	G
Test 11 - Straightness of motion of the X axis in the Y Plane (X in Y)	G
Test 12 - Straightness of motion of the X axis in the Z Plane (X in Z)	G
Test 13 - Straightness of motion of the Z axis in the X Plane (Z in X)	G
Test 14 - Straightness of motion of the Z axis in the Y Plane (Z in Y)	G
Test 15 - X axis about X axis (X about X)	G
Test 16 - X axis about Y axis (X about Y)	G / L
Test 17 - X axis about Z axis (X about Z)	G / L
Test 18 - Z axis about X axis (Z about X)	G
Test 19 - Z axis about Y axis (Z about Y)	G / L
Test 20 - Z axis about Z axis (Z about Z)	G
Test 21 - Crossrail axis about Y axis (CR about Y) at all CR positions	G / L
Test 22 - X axis positional accuracy (X Positional)	L
Test 23 - X axis accuracy and repeatability (X Accuracy and Repeatability)	L
Test 24 - Z axis positional accuracy (Z Positional)	L
Test 25 - Z axis accuracy and repeatability (Z Accuracy and Repeatability)	L

Appendix B.4

The metrology index for a Geiss 5-axis machine, as produced by consensus view, with measurement timing information. Estimated and actual timings for calibration have also been included.

G = Geometric Test (using precision artefacts)

L= Laser Interferometer Test

LX = Rotary Axis Test (using Laser interferometer and indexer

Test	Estimated time (minutes) Regular service	Actual time (minutes)
Test 1 - Straightness of motion of the X axis in the horizontal plane/Y Plane (X in Y)	20	16
Test 2 - Straightness of motion of the X axis in the vertical plane/Z Plane (X in Z)	20	16
Test 3 - Straightness of motion of the Y axis in the horizontal plane/X Plane (Y in X)	20	16
Test 4 - Straightness of motion of the Y axis in the vertical plane/Z Plane (Y in Z)	20	16
Test 5 - Straightness of motion of the Z axis in the X Plane (Z in X)	5	6
Test 6 - Straightness of motion of the Z axis in the Y Plane (Z in Y)	5	6
Test 7 - X axis level in the transverse plane (X about X)	15	11
Test 8 - X axis level in the longitudinal plane (X about Y)	15	11
Test 9 - X axis about Z axis (X about Z)	20	21
Test 10 - Y axis level in the longitudinal plane (Y about X)	20	6
Test 11 - Y axis level in the transverse plane (Y about Y)	15	11
Test 12 - Y axis about Z axis (Y about Z)	15	6
Test 13 - Z axis about X axis (Z about X)	15	6
Test 14 - Z axis about Y axis (Z about Y)	20	6
Test 15 - Z axis about Z axis (Z about Z)	60	No result
Test 16 - X axis positional accuracy (X Positional)	10	6
Test 17 - X axis accuracy and repeatability (X Accuracy and Repeatability)	20	21
Test 18 - Y axis positional accuracy (Y Positional)	10	6
Test 19 - Y axis accuracy and repeatability (Y Accuracy and Repeatability)	20	21
Test 20 - Z axis positional accuracy (Z Positional)	10	6
Test 21 - Z axis accuracy and repeatability (Z Accuracy and Repeatability)	20	16
Test 22 - Squareness of X axis to Y axis	7	11
Test 23 - Squareness of Z axis to X axis	7	16
Test 24 - Squareness of Z axis to Y axis	20	16
Test 25 - Table surface parallelism to X axis	10	6
Test 26 - Table surface parallelism to Y axis	10	6
Test 27 - Spindle axial runout	10	5

Test 28 - Milling spindle radial runout	10	5
Test 29 - Milling spindle internal taper runout	5	6
Test 30 - C axis parallelism to X and Y plane	10	6
Test 31 - C axis zero setting	10	61
Test 32 - A axis zero setting	10	16
Test 33 - A axis parallelism to the Y and Z plane	10	6
Test 34 - Coincidence of the C axis centreline to A axis centre of rotation	10	11
Test 35 - Coincidence of the spindle centreline to C axis centreline	10	11
Test 36 - Pivot length calculation	10	11
Test 37 - A axis positional accuracy (A Positional)	70	No result
Test 38 - A axis accuracy and repeatability (A Accuracy and Repeatability)	40	No result
Test 39 - C axis positional accuracy (C Positional)	70	No result
Test 40 - C axis accuracy and repeatability (C Accuracy and Repeatability)	20	No result
Total	724	683[7]

Appendix C

The full list of machine tool measurement equipment considered in Chapter 7.

Type	Company	Device
Linear Axis Calibration Systems	Renishaw	XL-80 Laser Interferometer
	Renishaw	6DOF System
	Etalon	LaserTRACER
	Etalon	LaserTRACER-MT
	API	API VEC
	API	API XD Laser
	Optodyne	LDDM
	Hamar Laser	Machine Tool Alignment System
	IBS Precision	MT Check
	TBC	Photogrammetric System
	Microstrain	Miniature Displacement Sensors
	Ludeca Inc	Wireless Inclinometers (Various)
	Tesa	Wireless Inclinometers (Various)
	Wyler AG	Wireless Inclinometers (Various)
	Level Developments	Wireless Inclinometers (Various)
	Metronom	Tetranom Artefact with Machine Probe
	GOM	Pontos
	Faro	Laser Tracker ION
	Leica	Leica AT401
	Leica	Leica AT901
	Agilent Technologies	Agilent Laser Interferometer
	Heidenhain	KGM Grid Encoders
	Precision Balls	2D Ball Plate
	Precision Balls	3D Ball Plate

Rotary Axis Calibration	**Renishaw**	RX10
	Renishaw	RX20w
	Renishaw	Sprint Probe + AxiSet
	API	Swivel Check
	IBS	R-Test
Ballbar Systems	**Renishaw**	QC10 Ballbar
	Renishaw	QC20w Ballbar
	API	Ballbar System
	Bal-tec	Precision Balls
Spindle Geometry Measurement	**Multiple Manufacturers**	Wireless DTIs
	API	Spindle Analyser
	Lion Precision	Spindle Analyser
	MicroEpsilon	Spindle Analyser
	Multiple Manufacturers	On Machine Probe and artefact
	Renishaw	Ballbar System
	Microstrain	Miniature Displacement Sensors

Appendix D

This appendix outlines the substantiation to move to Reduced Inspection on the BR710 Inner and Outer walls (Chapter 7).

Process capability data was generated from Rolls-Royce Hucknall CMM measurement equipment. The data from the most recent 26 combustor inner walls was analysed. Raw data can be provided on request to the researcher, subject to Rolls-Royce plc. approval.

The following approach was taken:

1) Collate the CMM Data from the last 25 Inner walls
2) Sub-group the measurements into family of features which are created on the same tool path.
3) Collect the measured difference from nominal for each of the features for the 26 parts
4) Analyse the capability of those features across the 26 parts removing any special causes
5) Use the distribution to calculate the action limits based on 99% confidence of what fits under the distribution curve. If the reduced features fall outside the control limits on measurement, then all the intermediary points are to be measured.
6) Recommend which feature measurements to remove from the program and/or transfer to the machine tool.
7) Recommend changes the product inspection plan and the CMM Program

Families of features

1) Diameters

2) Thickness

3) Depth

4) Length

The measurements were sub-grouped into family of features which are created on the same tool path and which have the same specification limits.

Figure D-1 shows the features inspected at OP15 for both the Inner and Outer Wall, sub grouped by family.

Outer Wall – NQF002905		Inner Wall – NQF002904	
Family	**Feature Numbers**	**Family**	**Feature numbers**
Angles	61, 66, 70, 73	Angles	104, 107, 109, 111
Thickness 1	60, 65, 71, 72	Thickness 1	103, 106, 108, 110
Thickness 2	58, 511, 512, 513, 514	Thickness 2	105, 562, 563, 565
Diameters 1	62, 63, 64, 67, 68, 69, 74, 76, 78, 79	Diameters 1	113, 115, 117, 118, 120, 125
Diameters 2	75, 77	Diameters 2	114, 116, 119, 121, 126
Lengths	47, 48, 49, 50	Lengths	97, 98

Figure D-1: Sub-groups of features – Outer wall and Inner wall

Stability Process Charts and Capability Analysis

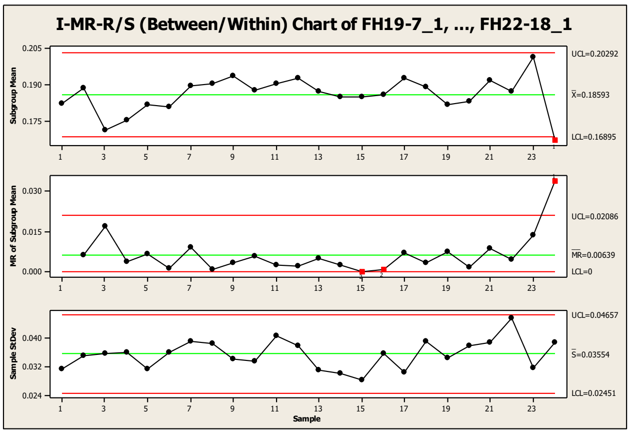
Data was analysed to assess the stability and capability of the turning process. Proof of stability and capability needs to be shown for this process. The parts were put in time sequence order to show how the machine varies over time.

Then the stability and the capability of the process were analysed for each feature and for each family of features among the 25 parts for the Inner wall and Outer wall.

Family by Family Analysis

Below it is shown the stability and capability study for each family of features for the Inner wall:

Inner wall – Angles (Bay AU – AT –AS –AR) showed a capable and centred process that was also within the control limits, except the last part that shows an out of control point located slightly under the lower control limit. The data fits within the normal distribution and has a Cpk of 3.11 and a Ppk of 3.12. Also, all the features within this family are noted as Control Plan features on the DCM. That means that the output value is well controlled for this family and in fact the process shows 0 PPM of non-conformance. So the process can be moved to Reduced Inspection.



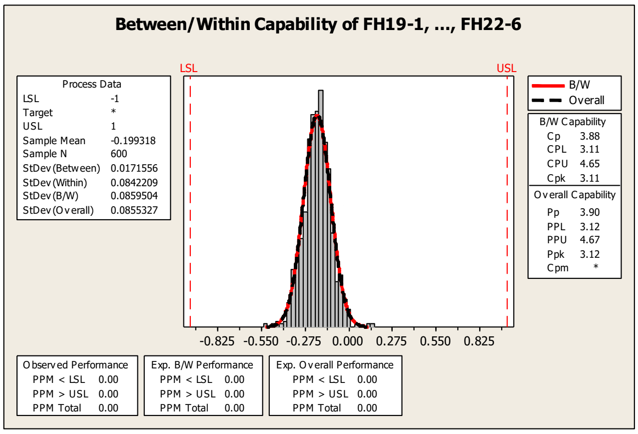


Figure D-2: Family “Angles” – Inner wall

Inner wall – Thickness 1 (Bay AU – AT –AS –AR) showed a stable process with a Cpk of 1.70 and a Ppk of 1.68 and PPM of 0.23. The process is centred but the spread is wide and so further investigation was conducted (see “Further Analysis”).

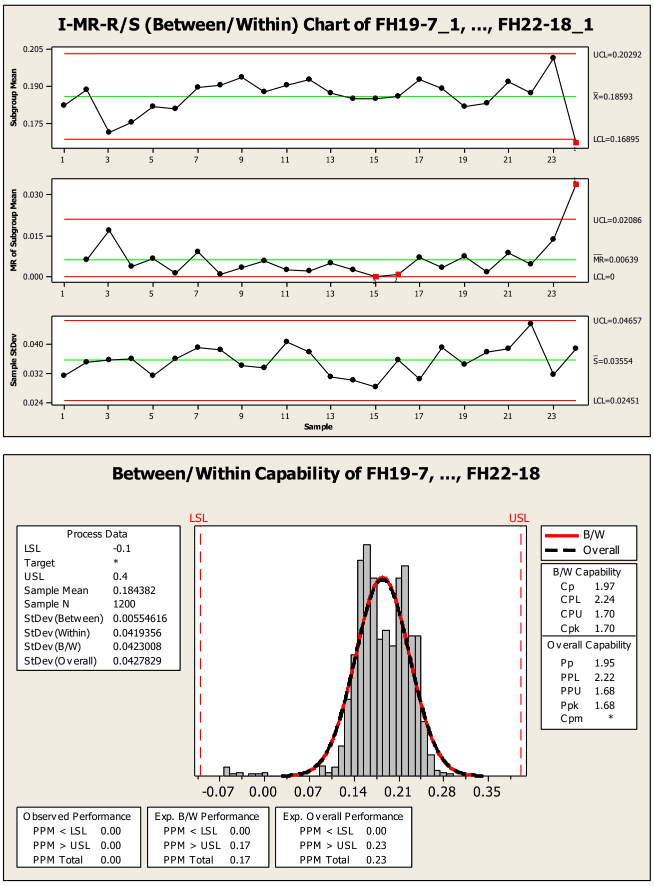
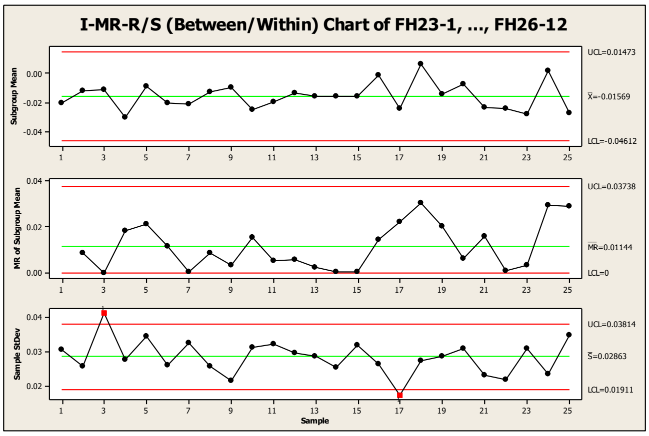


Figure D-3: Family “Thickness 1” – Inner wall

Inner wall – Thickness 2 (Bay AU – AT –AS –AR) shows a stable process but with a Cp of 1.66 and Ppk of 1.5. It is centred but the spread is wide and so further investigation was conducted (see “Further Analysis”).



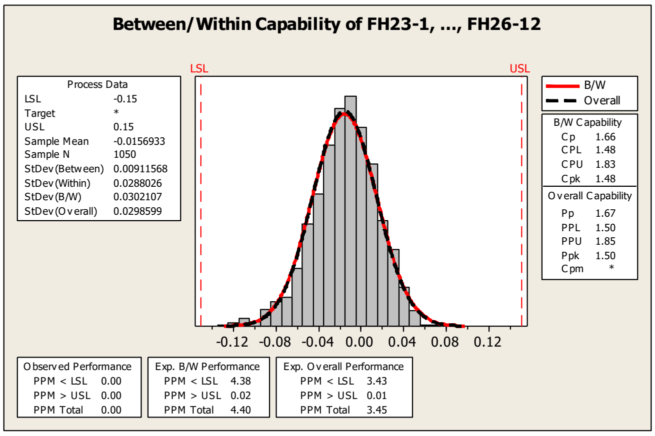


Figure D-4: Family “Thickness 2” – Inner wall

Inner wall – Diameters 1 family showed a stable and capable process with a Cpk of 2.33 and a Ppk of 2.38. So the process can be moved to the machine tool.

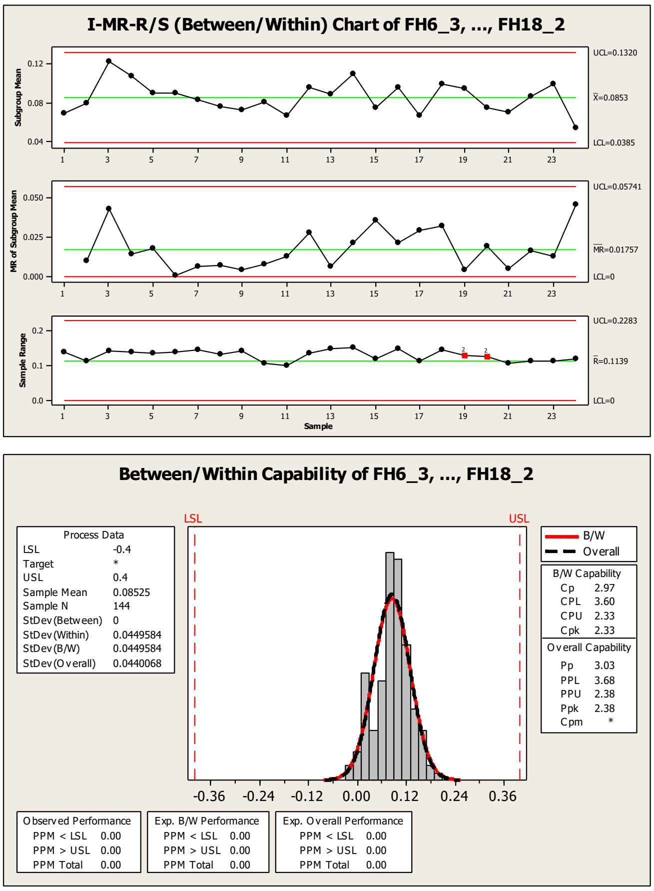
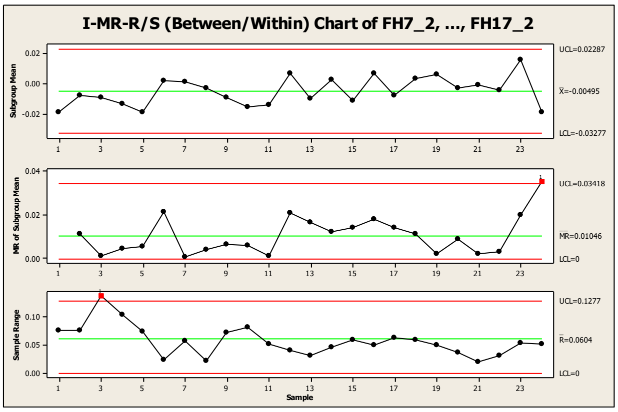


Figure D-5: Family “Diameters 1” – Inner wall

Inner wall – Diameters 2 family showed a stable and capable process with a Cpk of 5.07 and a Ppk of 5.26. So the process can be moved to the machine tool.



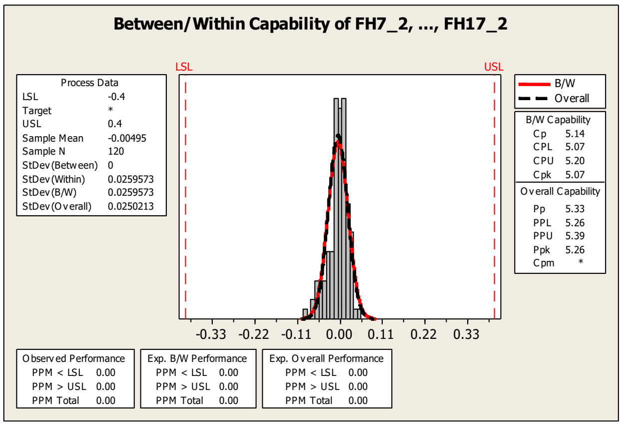


Figure D-6: Family "Diameters 2" – Inner wall

Inner wall – Lengths showed that the process has 2 out of control points and the spread of the process if wide. A further investigation was conducted for this family as well.

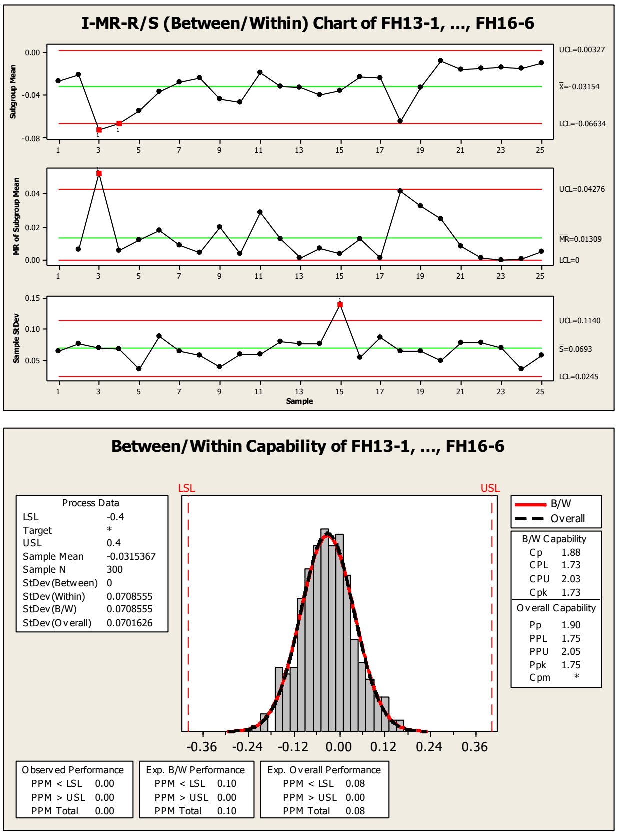


Figure D-7: Family "Lengths" – Inner wall

Analysis – Outer wall

Between/Within Capability for each family of features for the Outer wall was assessed. This study shows that the process is stable and capable.

Family by family Analysis

Below it is shown the stability and capability study for each family of features for the Outer wall:

Outer wall – Angles (Bay AU – AT –AS –AR) showed a capable process that was also within the control limits. The data fits within the normal distribution and has a Cp of 2.98 and a Ppk of 2.07. Also, all the angles are on the control plan, so the output values are well controlled and the process showed 0 PPM of non-conformance. So the process can be moved to the machine tool.

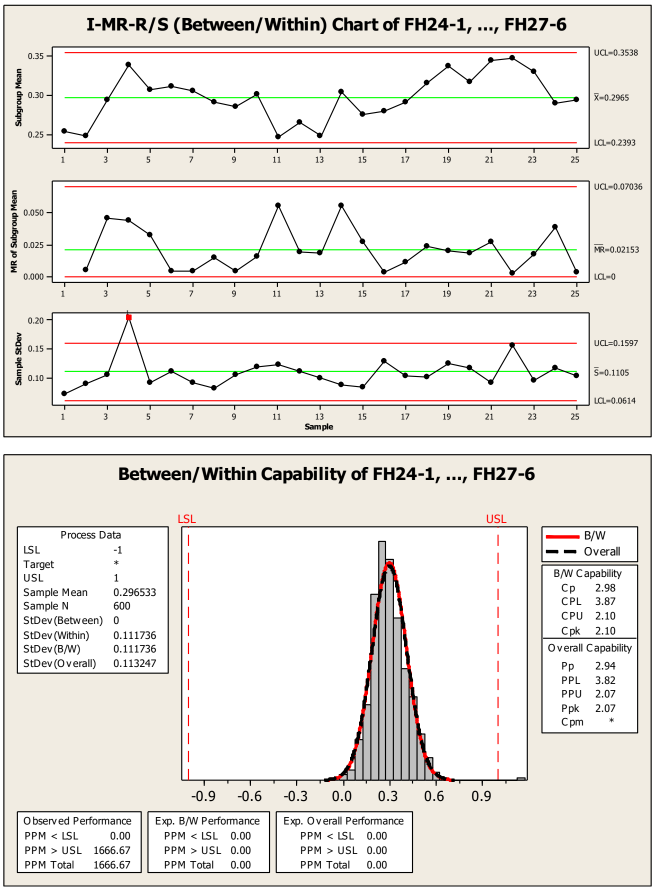


Figure D-8: Family “Angles” – Outer wall

Outer wall – Thickness 1 (Bay AU – AT –AS –AR) showed a stable process with a Cp of 2.33 and a Ppk of 1.58 and PPM of 1.05. The process is not perfectly centred so further investigation was conducted (see “Further Analysis”).

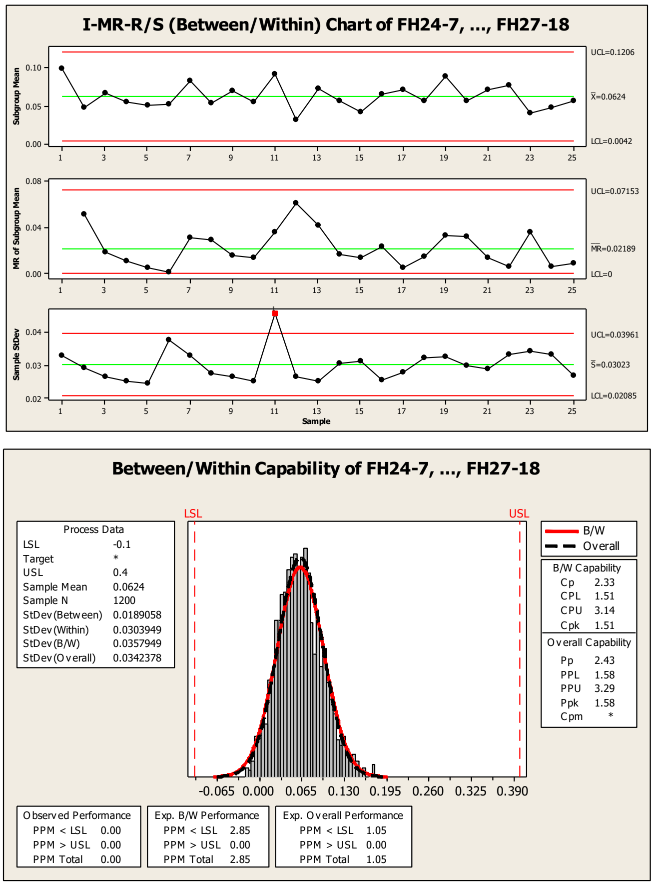


Figure D-9: Family “Thickness 1” – Outer wall

Outer wall – Thickness 2 (Bay AU – AT –AS –AR) shows a stable process but with a Cp of 1.29 and Ppk of 1.13. It is centred but the spread of the process is quite wide and so further investigation was conducted (see "Further Analysis").

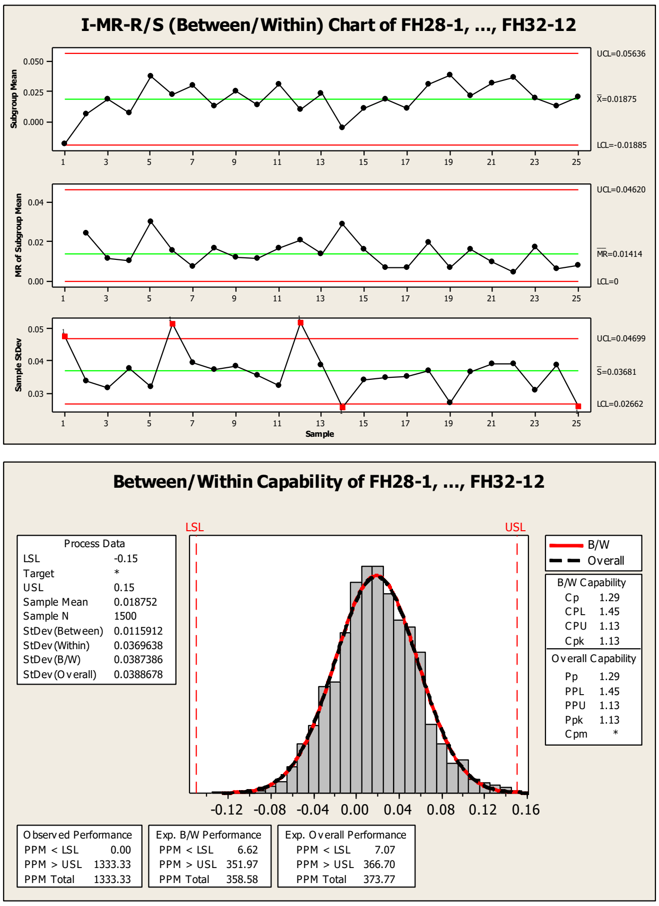


Figure D-10: Family "Thickness 2" – Outer wall

Outer wall – Diameters 1 family showed a stable and very capable process that fits very well within the normal distribution. This family has a Cp of 4.68 and a Ppk of 3.92, the spread is very low and the process is centred. Also, all the features within this family are on the control plan, so the output value is well controlled. In fact, the process showed 0 PPM of non-conformance. So the process can be moved to the machine tool.

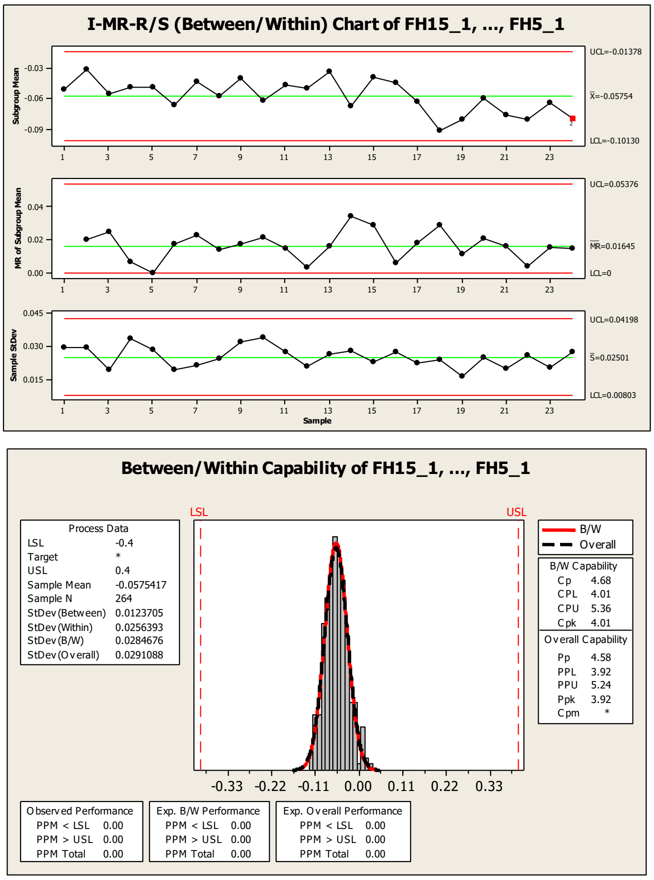


Figure D-11: Family “Diameters 1” – Outer wall

Outer wall – Diameters 2 showed that the process is stable and capable, with a Cp value of 3.43 and a Ppk value of 3.06. Also the spread is very low and the process is centred. Also, these features are on the control plan and the family study showed 0 PPM of non-conformance. So this process can be moved to the machine tool.

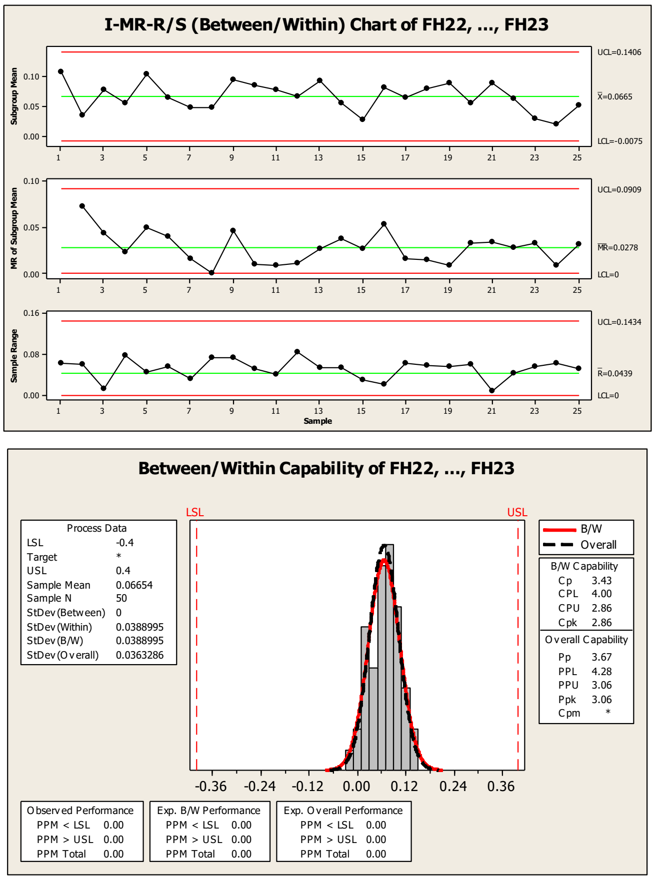


Figure D-12: Family “Diameters 2” – Outer wall

Outer wall – Lengths showed a stable process. The capability study showed a Cp of 2.14 and a Ppk of 2.09, with the process that fits within the normal distribution. The process is centred, but the spread is quite wide, so a further feature by feature analysis within the family was conducted.

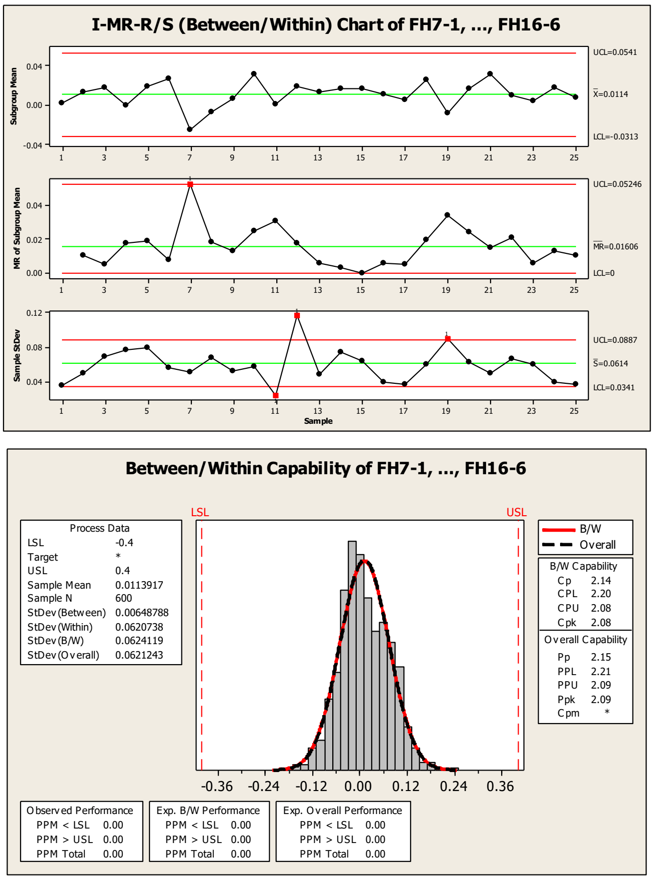


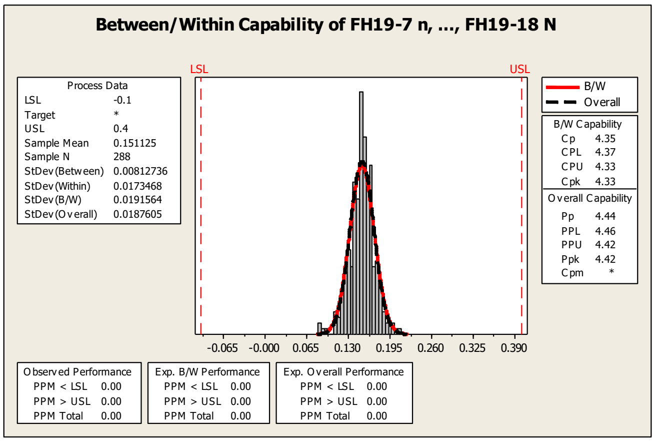
Figure D-13: Family “Lengths” – Outer wall

Further Analysis

Further analysis was conducted for families of features where the Capability Indices were not directly suitable for on-machine inspection.

Inner wall – Thickness 1

Even if the capability study shows a wide spread for the family “Thickness 1”, analysing each feature of the family among the 25 parts the process results very stable and capable, with a Cp > 4 and a Ppk > 2.8. Therefore, the process can be moved to the machine tool. Below there is the capability study for each feature (FH19 – wall thickness AZ, FH20 – wall thickness AY, FH21 – wall thickness AX, FH22 – wall thickness AW).



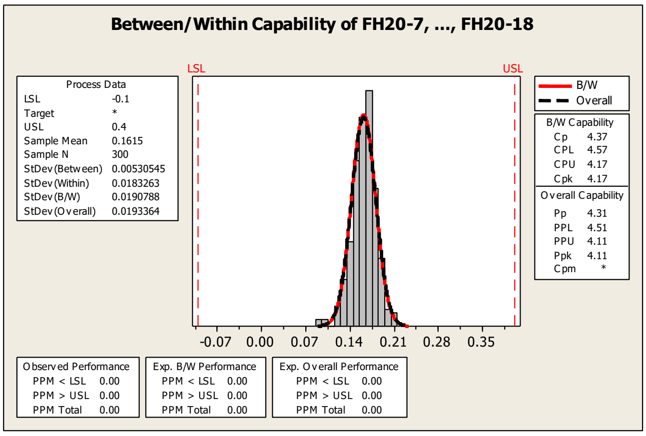
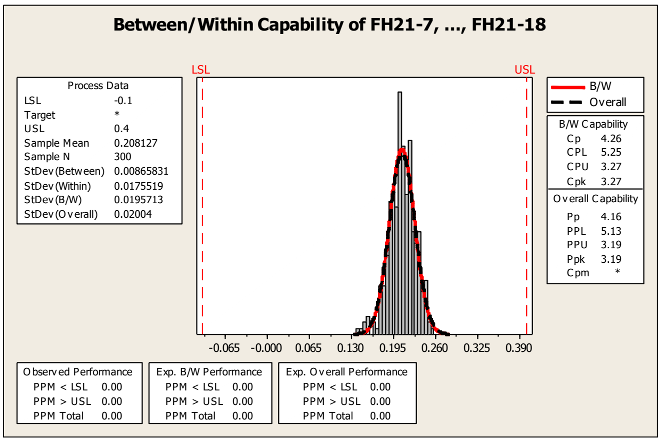


Figure D-14: Family “Thickness 1” – Inner wall



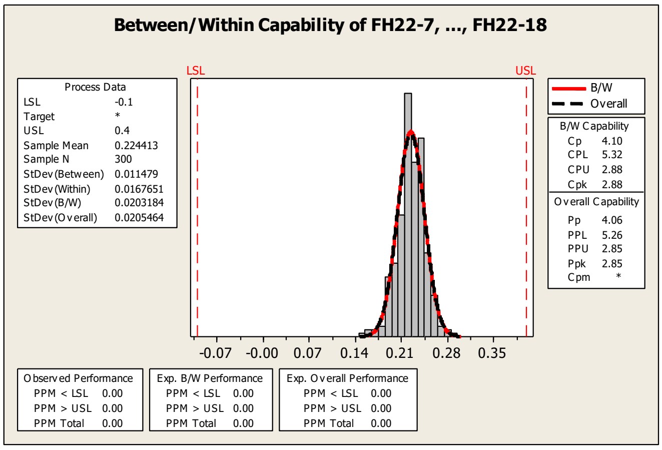


Figure D-15: Feature by feature capability analysis – Thickness 1 – Inner wall

Inner wall – Thickness 2

An analysis for each single feature of the family was conducted to assess the capability of the process. This showed a low value of Cp and a wide spread, especially for the feature 563 (FH25) that has a Ppk of 1.13 and the process is not properly centred.

For this family of features the individual values were checked against a computed set of warning limits (located 4 standard deviations within the specification limits). As a significant proportion of the data may fall outside the warning limits a full inspection of the feature group is recommended. Therefore, for the family “Thickness 2” the process cannot be moved to the machine tool. Below there are the distribution plots of the features 562 (FH24 – Thickness AZ-AY), 563 (FH25 – Thickness AY-AX) and 565 (FH26 – Thickness AX-AW) that show the percentage that falls outside the warning limits.

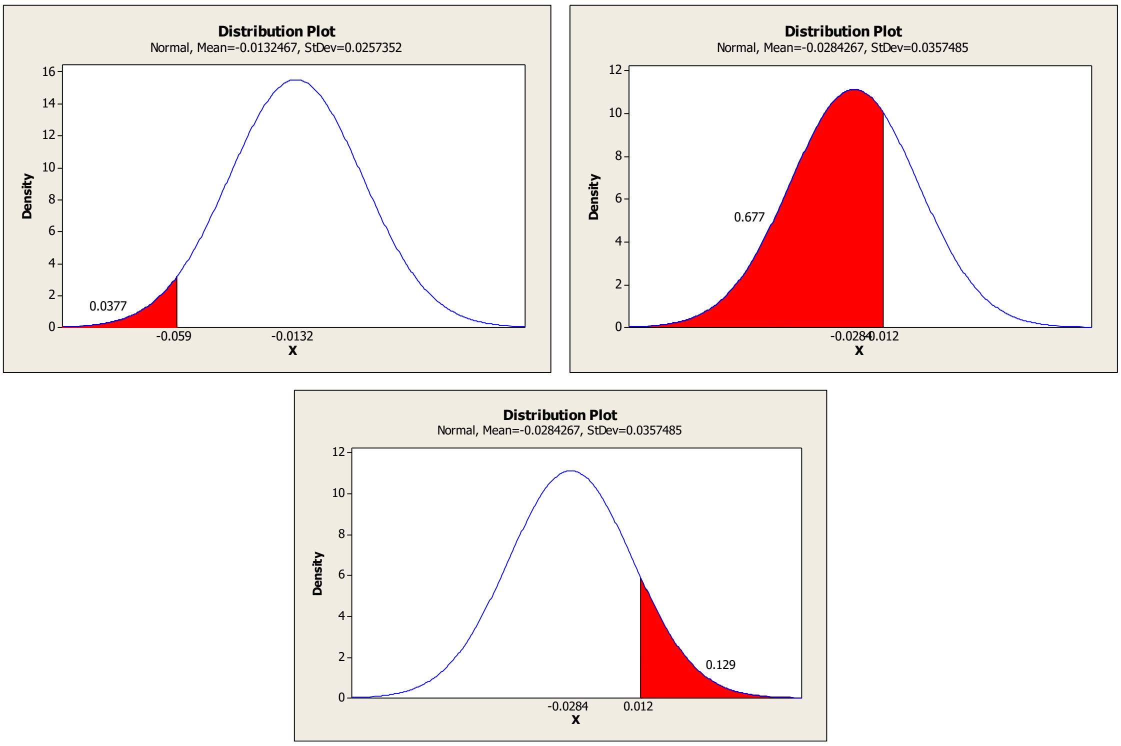


Figure D-16: Distribution plot of Feature 562 LWL and Feature 563 LWL and UWL

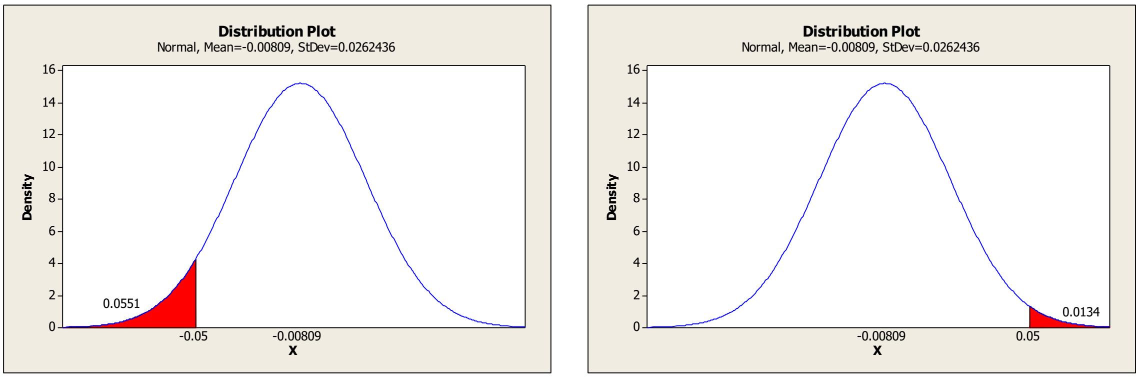


Figure D-17: Feature 565 – Distribution plot – LWL and UWL

Inner wall – Thickness 2

An analysis for each single feature of the family was conducted to assess the capability of the process. This showed a low value of Cp and a wide spread, especially for the feature 563 (FH25) that has a Ppk of 1.13 and the process is not properly centred. For this family of features the individual values were checked against a computed set of warning limits (located 4 standard deviations within the specification limits). As a significant proportion of the data may fall outside the warning limits a full inspection of the feature group is recommended. Therefore, for the family "Thickness 2" the process cannot be moved to the machine tool. Below there are the distribution plots of the features 562 (FH24 – Thickness AZ-AY), 563 (FH25 – Thickness AY-AX) and 565 (FH26 – Thickness AX-AW) that show the percentage that falls outside the warning limits.

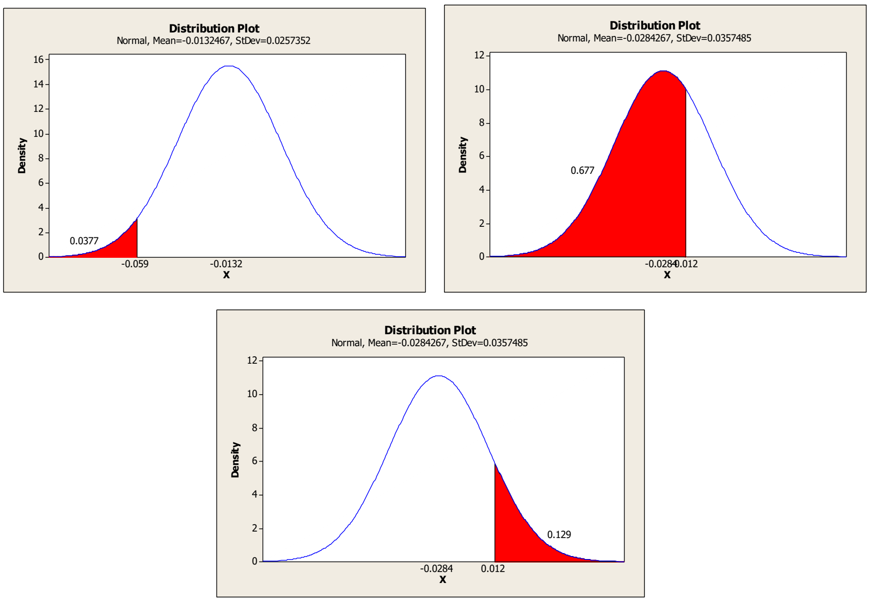


Figure D-18: Distribution plot of Feature 562 LWL and Feature 563 LWL and UWL

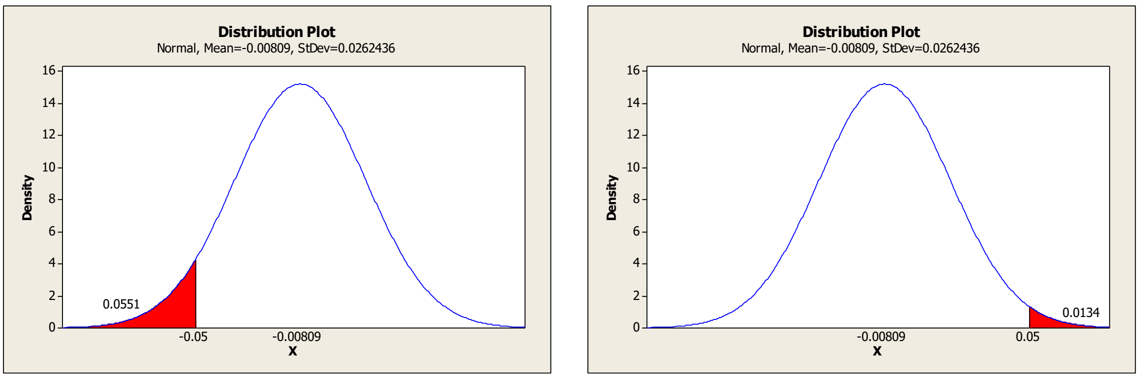


Figure D-19: Feature 565 – Distribution plot – LWL and UWL

Inner wall – Lengths

An analysis feature by feature within the family showed that the process is not very stable reasonably centred but the spread is wide. Therefore, the distribution plots were used and the warning limits (located 4 standard deviations within the specification limits) were calculated. Since the features fail these warning limits, then the process cannot be moved to the machine tool and a full inspection of the feature group is required.

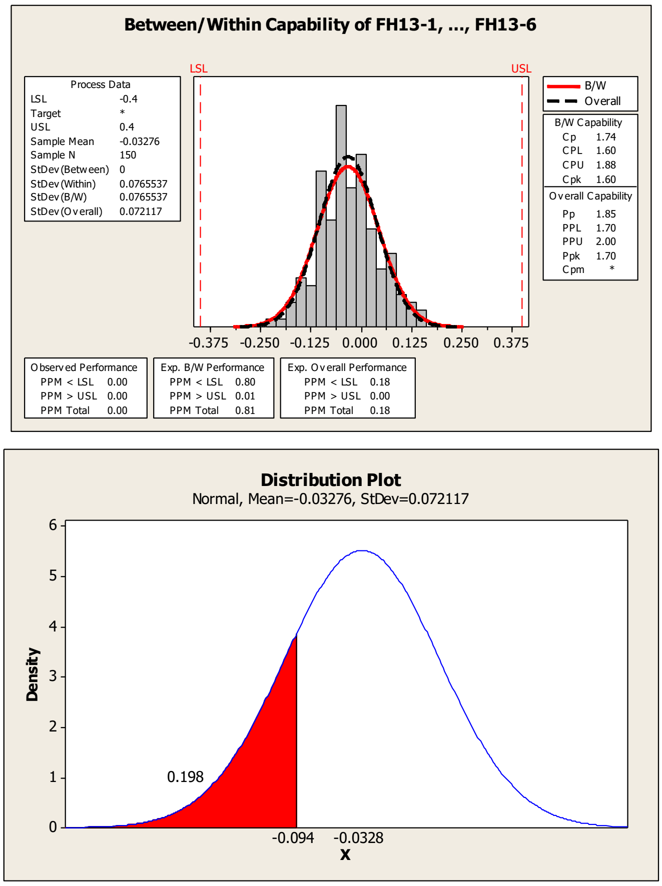
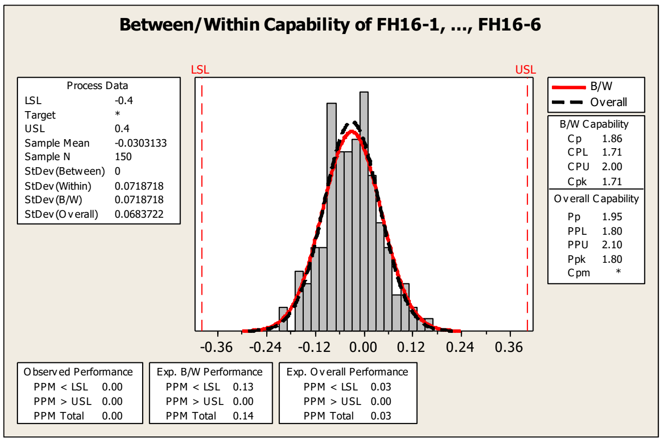


Figure D-20: Length – Capability analysis and Distribution plot – LWL



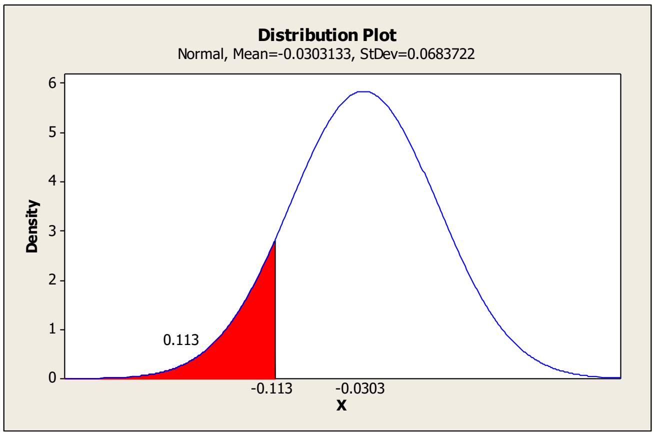
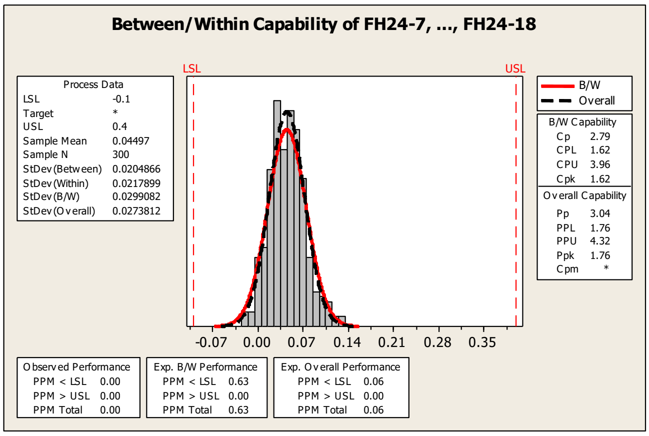


Figure D-21: Length – Capability analysis and Distribution plot – LWL

Outer wall – Thickness 1

Even if the process is not perfectly centred for the family "Thickness 1", analysing each feature of the family among the 25 parts the process results very stable and capable, with a Cp > 2.7 and a Ppk > 1.7. Therefore, the process can be moved to the machine tool. Below the capability study for each feature is shown (FH24 – Thickness AU, FH25 – Thickness AT, FH26 – Thickness AS, FH27 – Thickness AR).



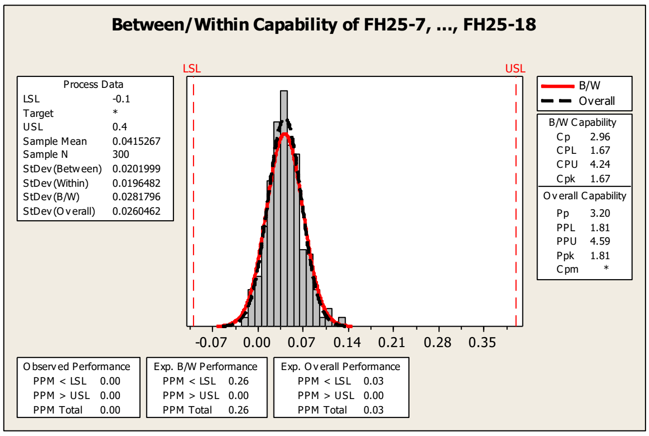
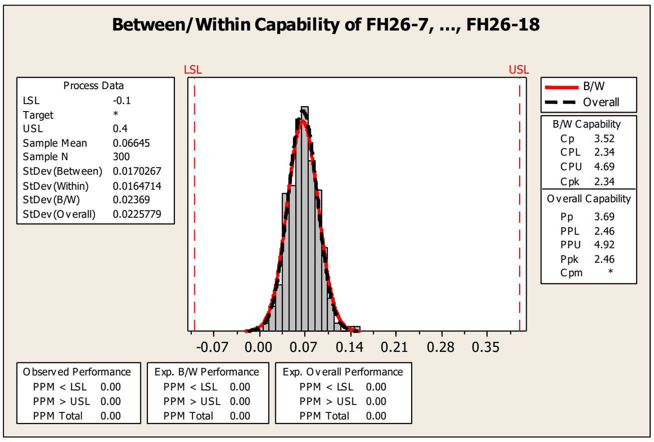


Figure D-22: Features 72 (FH24) and 71 (FH25) – Thickness 1 – Capability analysis



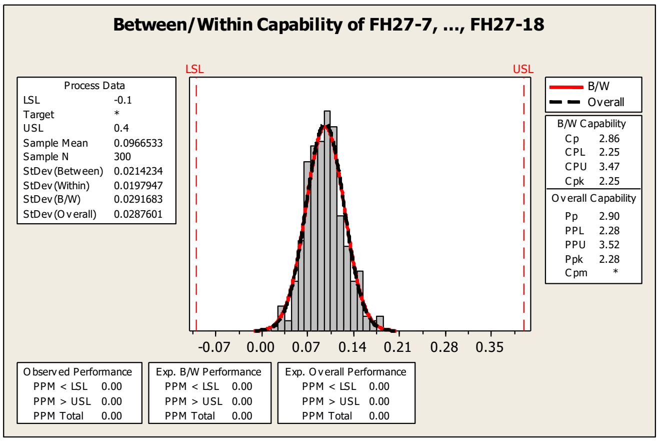


Figure D-23: Features 65 (FH26) and 60 (FH27) – Thickness 1 – Capability analysis

Outer wall – Thickness 2

An analysis for each single feature of the family was conducted to assess the capability of the process. This showed a low value of Cp and a wide spread, especially for the feature 514 (FH28 – wall thickness above AU) that has a Ppk of 0.88 and the process is not properly centred.

For this family of features the individual values were checked against a computed set of warning limits (located 4 standard deviations within the specification limits). As a significant proportion of the data may fall outside the warning limits a full inspection of the feature group is recommended. Below there are the distribution plots for the features 58 (FH32 – Thickness below AR), 511 (FH31 – Thickness AS-AR), 513 (FH29 – Thickness AU-AT) and 514 (FH28 – Thickness above AU) that show the percentage that falls outside the warning limits.

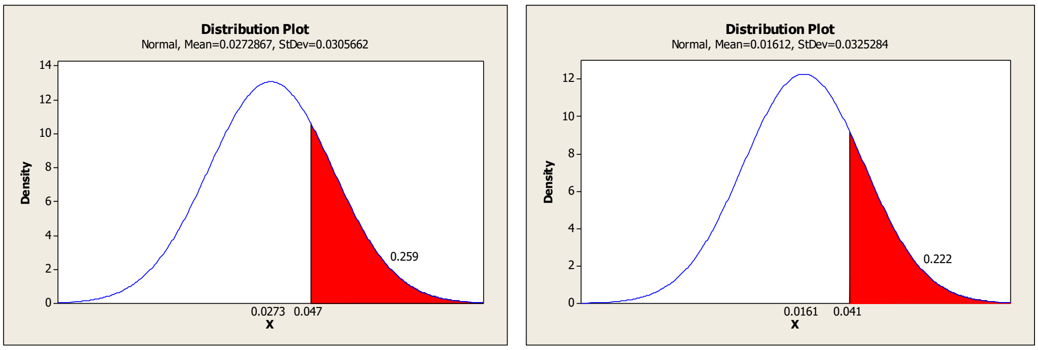


Figure D-24: Features 58 (FH32) and 511 (FH31) – Distribution plot - UWL

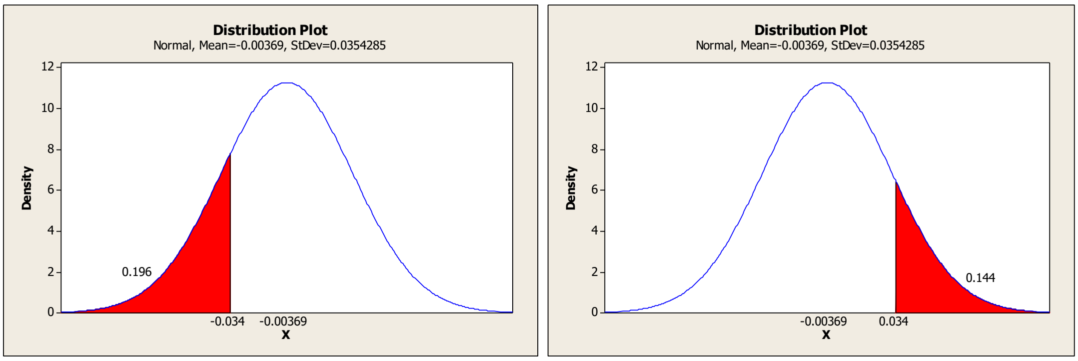


Figure D-25: Features 513 (FH29) – Distribution plot – LWL and UWL

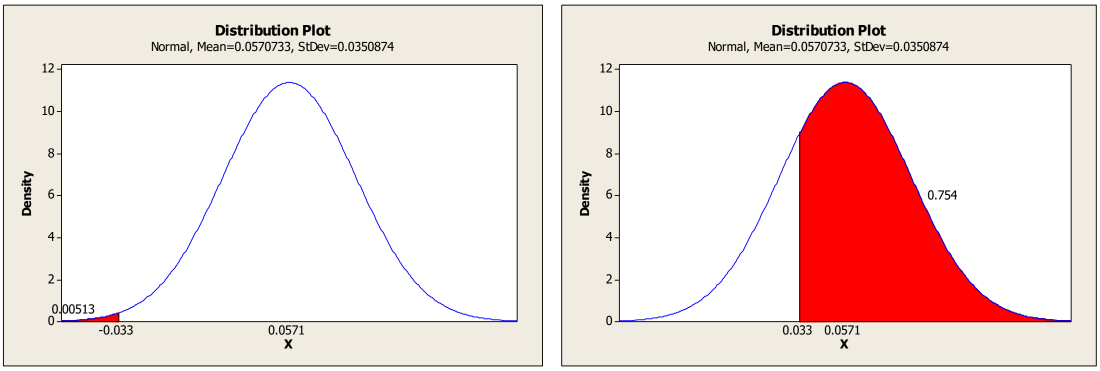


Figure D-26: Features 514 (FH28) – Distribution plot – LWL and UWL

Outer wall - Lengths

An analysis feature by feature within the family “Lengths” among the 25 parts showed that the process is stable with a Cp > 1.6 and a Ppk > 2. Since all these features are on the control plan, the output value is well controlled and the process results very capable (the family shows 0 PPM of non-conformance). Therefore the process can be moved to the machine tool.

Appendix E

The data presented here provides a summary of the results obtained from geometric error measurement tests completed on the 5-axis machine located in the Rotatives facility at Rolls-Royce Derby, during March 2014. The measurements were completed by Rolls-Royce maintenance personnel under the guidance of the University of Huddersfield staff.

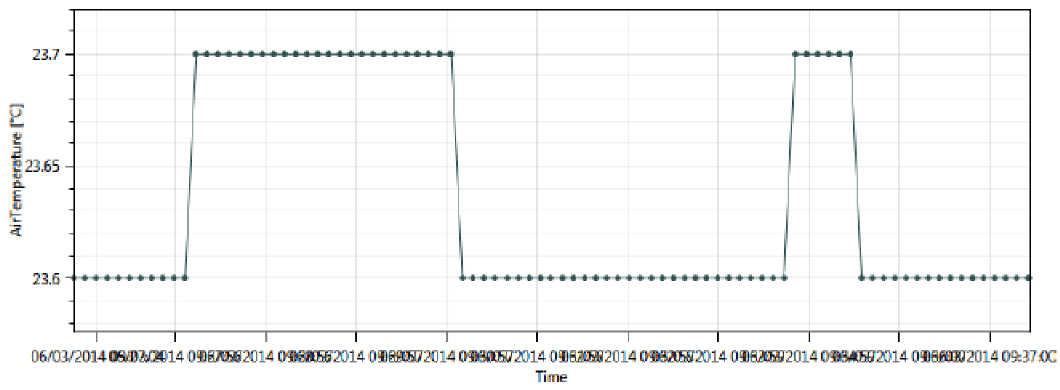
In this report, the roll results are provided by way of digital inclinometer measurement as the roll measurement capability on the prototype XM-60 laser is currently disabled.

The air temperature sensor was mounted above the table near to the laser source. The material temperature sensor was mounted onto the surface of the table.

The rotary axis measurements, using the IBS R-Test system, the tool centre point mode named TRAORI on the Siemens 840d controller, was active. The results at the tool centre point (TCP) are recorded. These results have not been presented as they were not used as part of the modelling or experimentation.

This data was subsequently utilised within the PUNDIT modelling in Chapter 9.

2.1 X axis		Traverse (mm)	+490	To:	-490
Feedrate (mm/min) :	3000	Step size (mm)	98	Dwell (s)	3
Notes:	Y at -184mm, Z at 285mm				
Air temperature:		Start:	23.6	End:	23.6



Material temperature:	Start:	23.4	End:	23.4

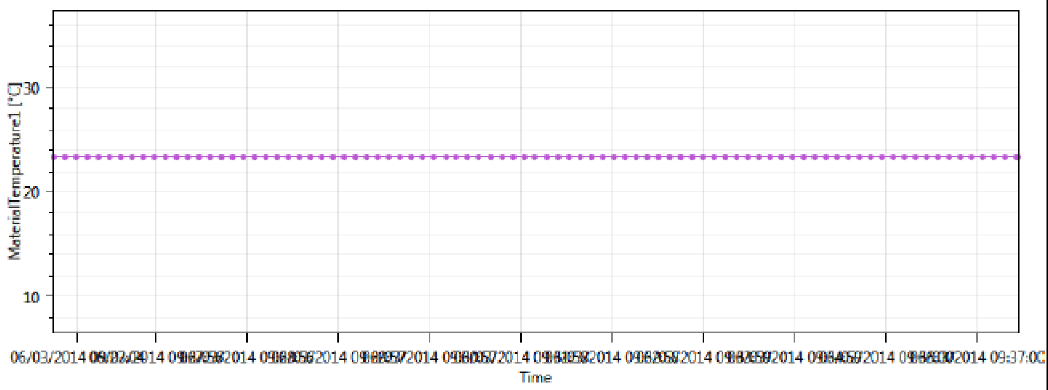
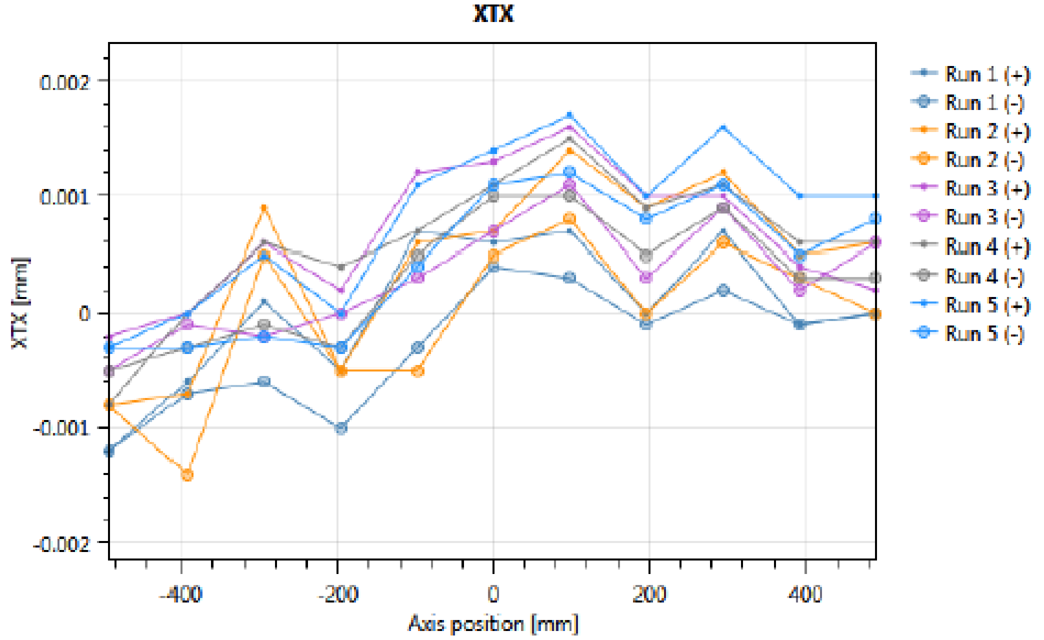


Figure E-1: X axis and environmental temperature readings during testing

Axis:	X	Error:	Linear positioning	XTX, EXX
Renishaw statistics (mm):	Accuracy (A)	0.0031	Notes:	
	Rep (+)	0.0011		
	Rep (-)	0.0013		
	Bidirectional repeatability	0.0017		



Axis:	X	Error:	Straightness in Y	XTY, EYX
Renishaw statistics (mm):	Accuracy (A)	0.0064	Notes: Analysis performed with highlighted spurious point removed	
	Rep (+)	0.0030		
	Rep (-)	0.0029		
	Bidirectional repeatability	0.0033		

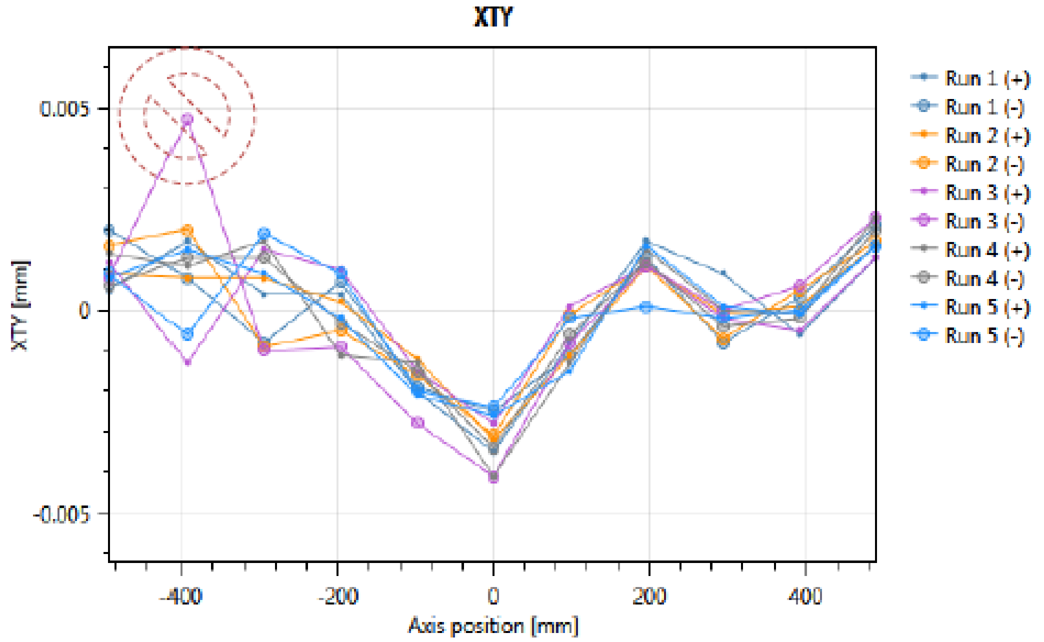
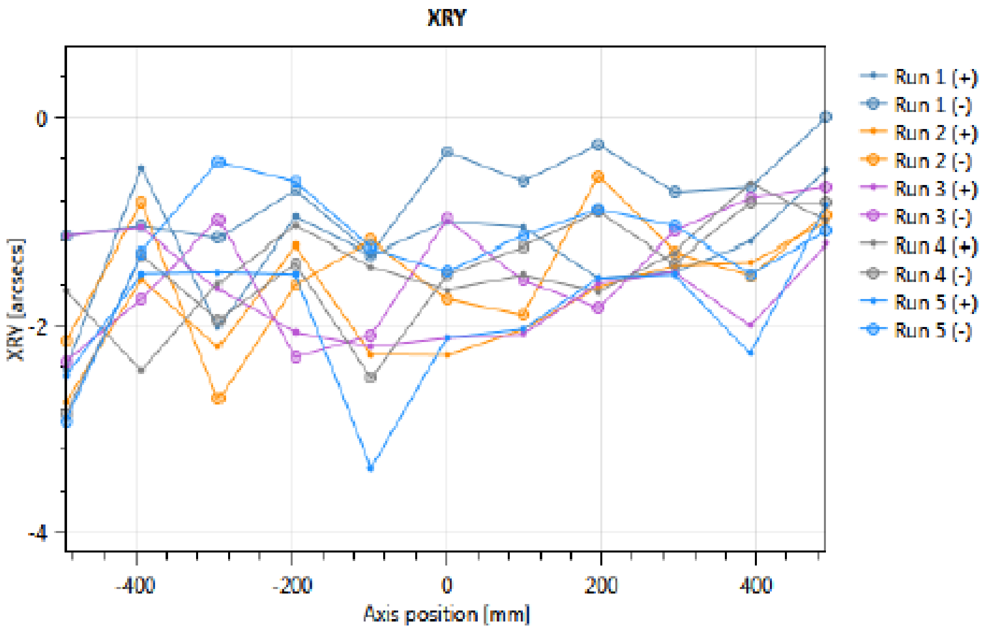


Figure E-2: X axis linear positioning and straightness measurement

Axis:	X	Error:	Rotation about Y	XRY, EBX
Renishaw statistics (arc-seconds):	Accuracy (A)	3.4	Notes:	
	Rep (+)	2.1		
	Rep (-)	2.3		
	Bidirectional repeatability	2.3		



Axis:	X	Error:	Rotation about Z	XRZ, ECX
Renishaw statistics (arc-seconds):	Accuracy (A)	3.8	Notes:	
	Rep (+)	2.9		
	Rep (-)	2.8		
	Bidirectional repeatability	3.1		

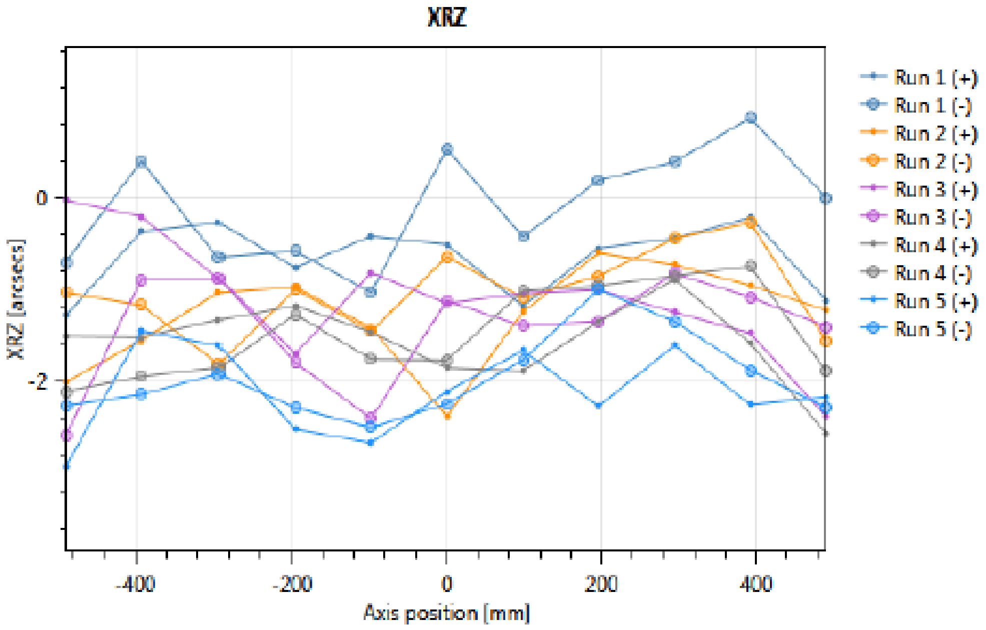
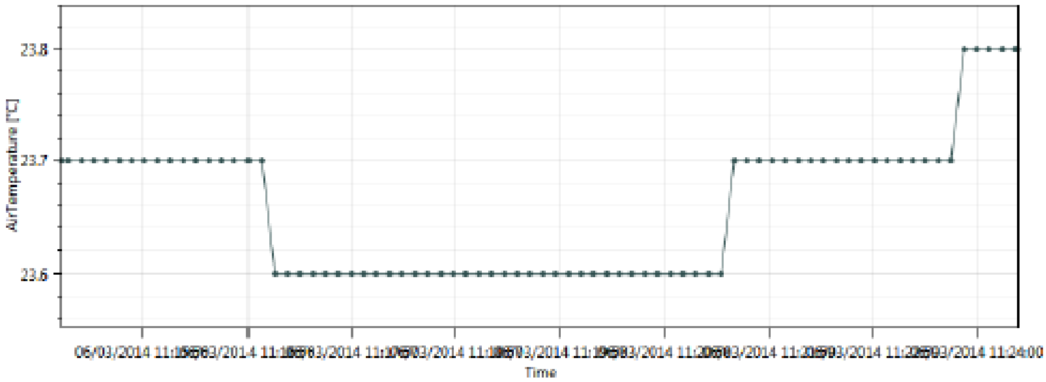


Figure E-3: X axis angular (X about Y, X about Z) measurement

2.2 Z axis		Traverse (mm)	+200	To:	+900
Feedrate (mm/min) :	3000	Step size (mm)	70	Dwell (s)	3
Notes:	X at -92mm Y at -54mm				
Air temperature:		Start:	23.7	End:	23.8



Material temperature:		Start:	23.6	End:	23.6

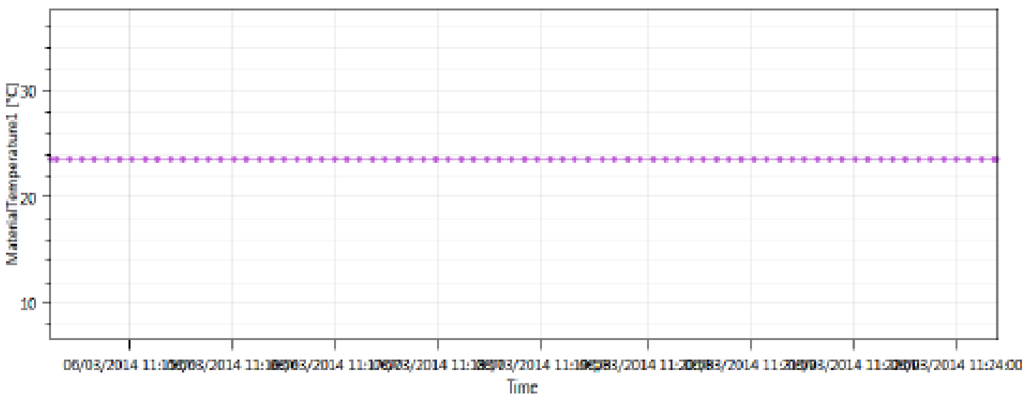
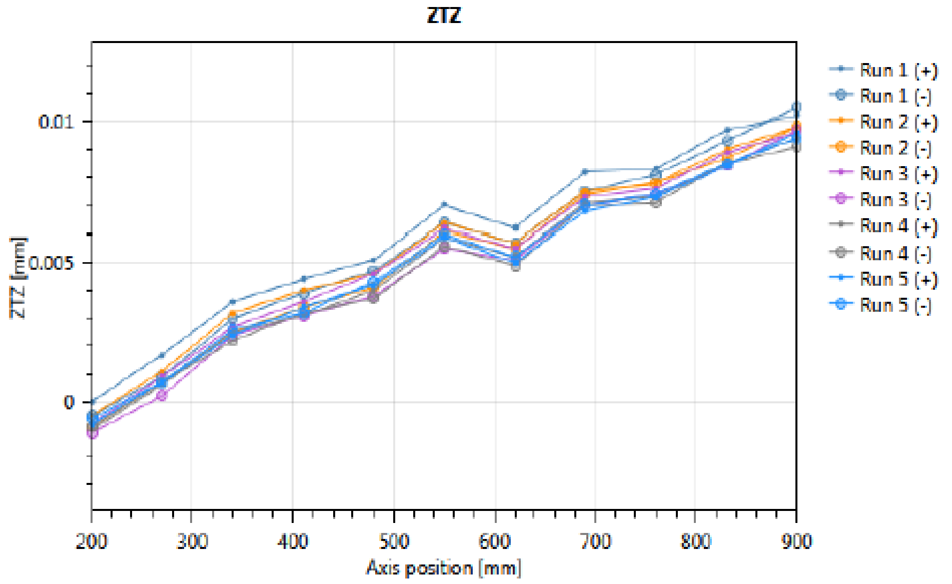


Figure E-4: Z axis and environmental temperature readings during testing

Axis:	Z	Error:	Linear positioning	ZTZ, EZZ
Renishaw statistics (mm):	Accuracy (A)	0.0116	Notes:	
	Rep (+)	0.0013		
	Rep (-)	0.0013		
	Bidirectional repeatability	0.0015		



Axis:	Z	Error:	Straightness in X	ZTX, EXZ
Renishaw statistics (mm):	Accuracy (A)	0.0087	Notes:	
	Rep (+)	0.0037		
	Rep (-)	0.0042		
	Bidirectional repeatability	0.0053		

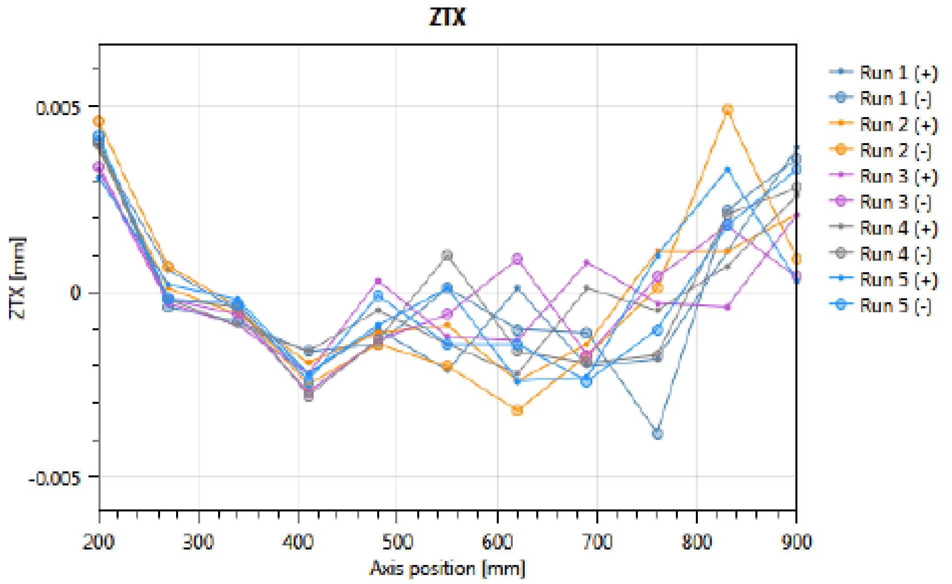
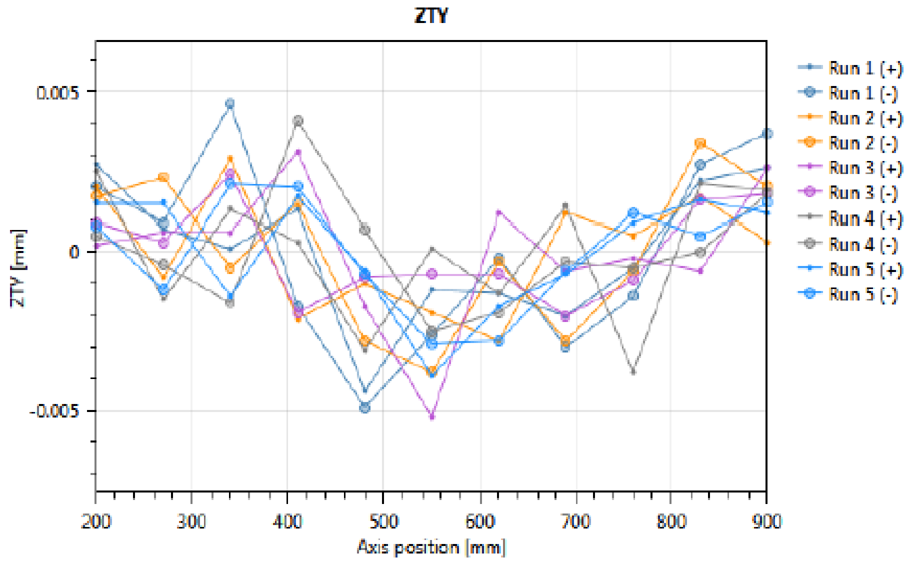


Figure E-5: Z axis linear positioning and straightness measurement

Axis:	Z	Error:	straightness in Y		ZTY, EYZ
Renishaw statistics (mm):	Accuracy (A)		0.0098	Notes:	
	Rep (+)		0.0053		
	Rep (-)		0.0062		
	Bidirectional repeatability		0.0063		



Axis:	Z	Error:	Rotation about X		ZRX, EAX
Renishaw statistics (arc-seconds):	Accuracy (A)		4.1	Notes:	
	Rep (+)		2.6		
	Rep (-)		1.7		
	Bidirectional repeatability		2.6		

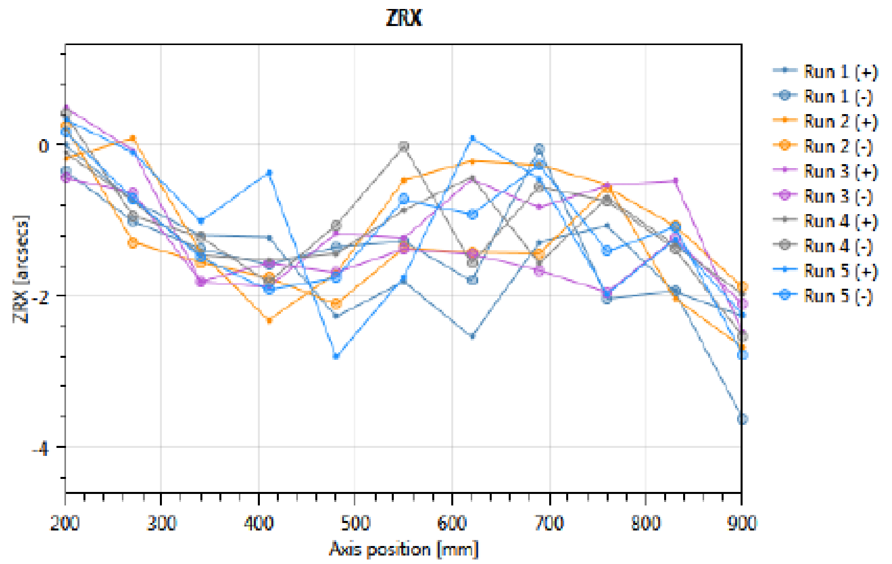
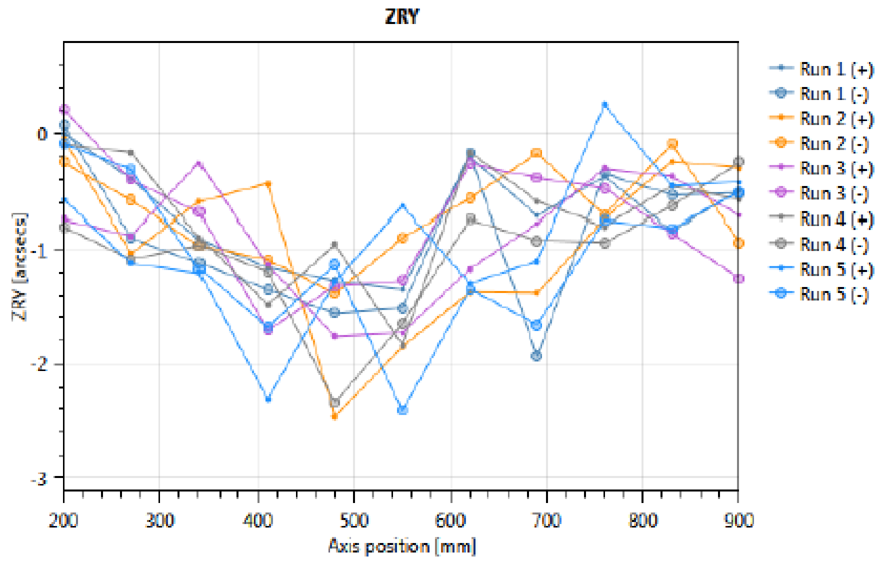


Figure E-6: Z axis straightness and angular error measurement

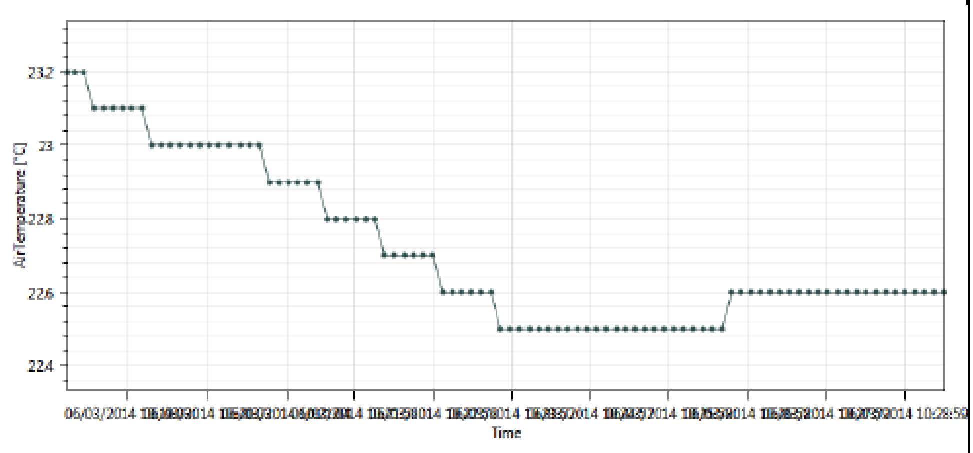
Axis:	Z	Error:	Rotation about Y	ZRY, EBZ
Renishaw statistics (arc-seconds):	Accuracy (A)	2.7	Notes:	
	Rep (+)	1.9		
	Rep (-)	1.8		
	Bidirectional repeatability	1.9		



Axis:	Z	Error:	Rotation about Z	ZRZ, ECZ
Renishaw statistics (arc-seconds):	Accuracy (A)		Notes:	
	Rep (+)			
	Rep (-)			
	Bidirectional repeatability			

Figure E-7: Z axis angular error measurement (Vertical roll not measured)

2.3 Y axis		Traverse (mm)	-590	To:	+490
Feedrate (mm/min) :	3000	Step size (mm)	108	Dwell (s)	3
Notes:	X at -25mm, Z at 371mm				
Air temperature:		Start:	23.2	End:	22.6



Material temperature:	Start:	23.3	End:	23.2

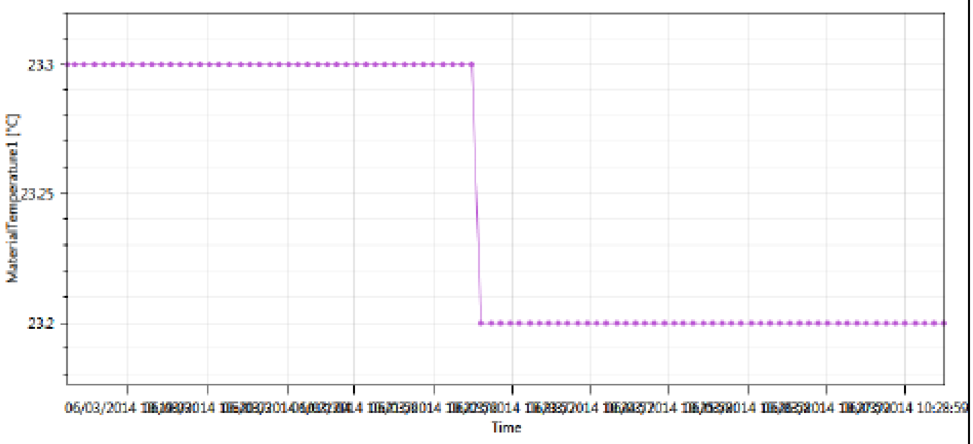
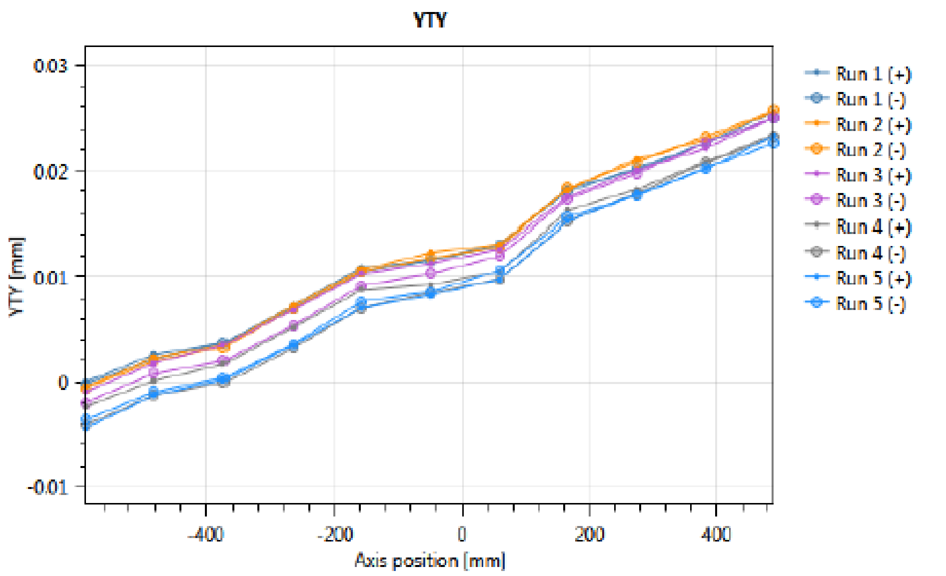


Figure E-8: Y axis and environmental temperature readings during testing

Axis:	Y	Error:	Linear positioning	YTY, EYY
Renishaw statistics (mm):	Accuracy (A)	0.0301	Notes: Result indicative of a thermal effect. Factory air conditioning system close to machine. Laser temperature may be different to Y scale temperature.	
	Rep (+)	0.0044		
	Rep (-)	0.0039		
	Bidirectional repeatability	0.0044		



Axis:	Y	Error:	Straightness in X	YTX, EXY
Renishaw statistics (mm):	Accuracy (A)	0.0104	Notes: Analysis performed with highlighted spurious point removed.	
	Rep (+)	0.0083		
	Rep (-)	0.0053		
	Bidirectional repeatability	0.0104		

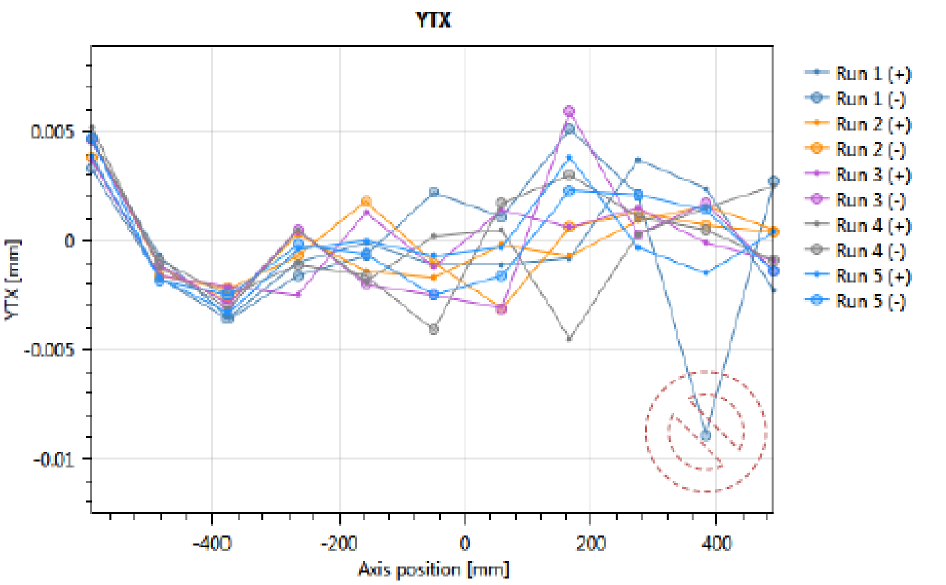
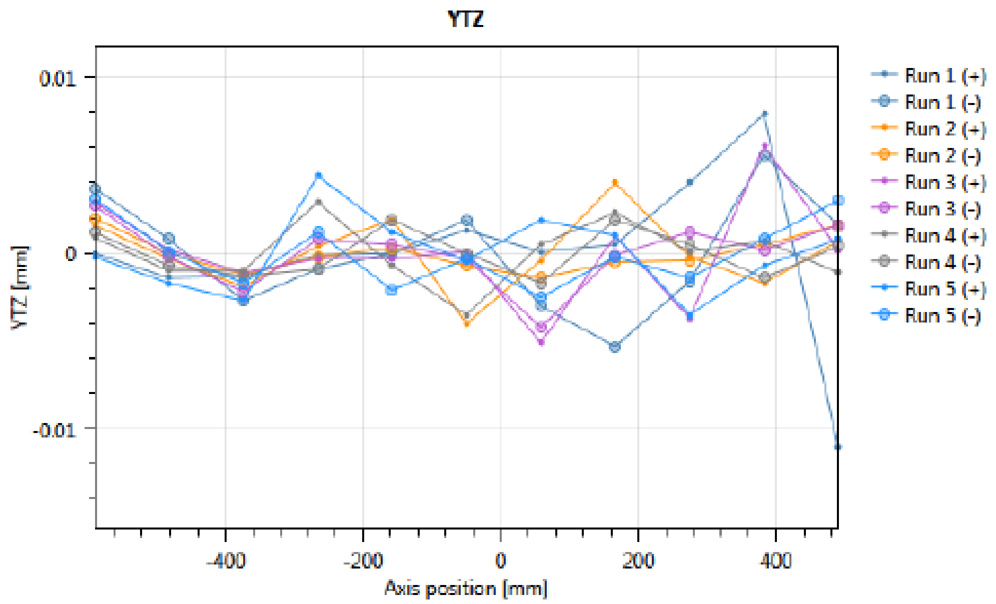


Figure E-9: Y axis linear positioning and straightness measurement

Axis:	Y	Error:	straightness in Z	YTZ, EZY
Renishaw statistics (mm):	Accuracy (A)	0.0115	Notes:	
	Rep (+)	0.0079		
	Rep (-)	0.0072		
	Bidirectional repeatability	0.0093		



Axis:	Y	Error:	Rotation about X	YRX, EAY
Renishaw statistics (arc-seconds):	Accuracy (A)	7.2	Notes:	
	Rep (+)	4.3		
	Rep (-)	5.3		
	Bidirectional repeatability	5.3		

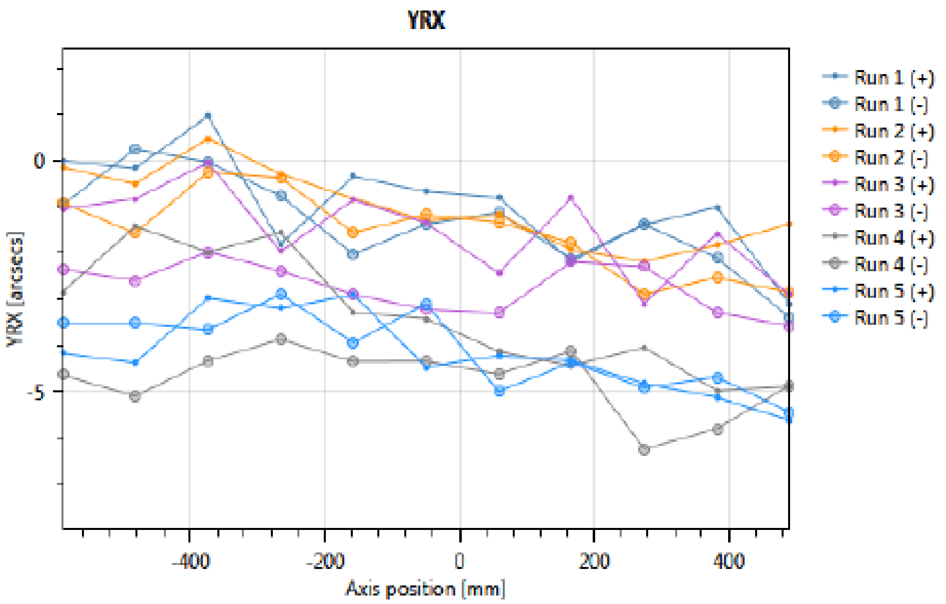
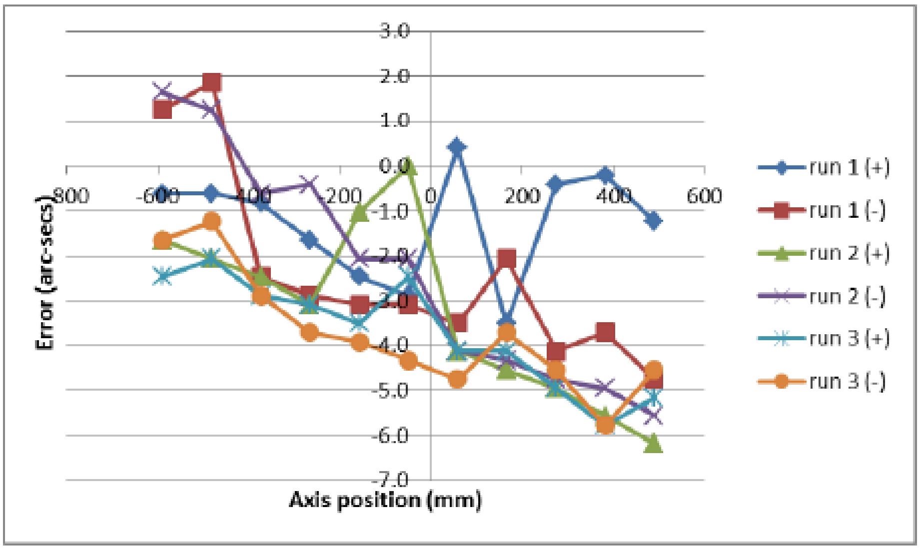


Figure E-10: Y axis straightness and angular error measurement

Axis:	Y	Error:	Rotation about Y	YRY, EBY
Renishaw statistics (arc-seconds):	Accuracy (A)	6.0	Notes: Roll measured manually using Wyler levels. It was noted that readings jumped randomly by 2 arc-seconds while the axis was nominally static.	
	Rep (+)			
	Rep (-)			
	Bidirectional repeatability			



Axis:	Y	Error:	Rotation about Z	YRZ, ECY
Renishaw statistics (arc-seconds):	Accuracy (A)	2.4	Notes:	
	Rep (+)	2.0		
	Rep (-)	2.1		
	Bidirectional repeatability	2.1		

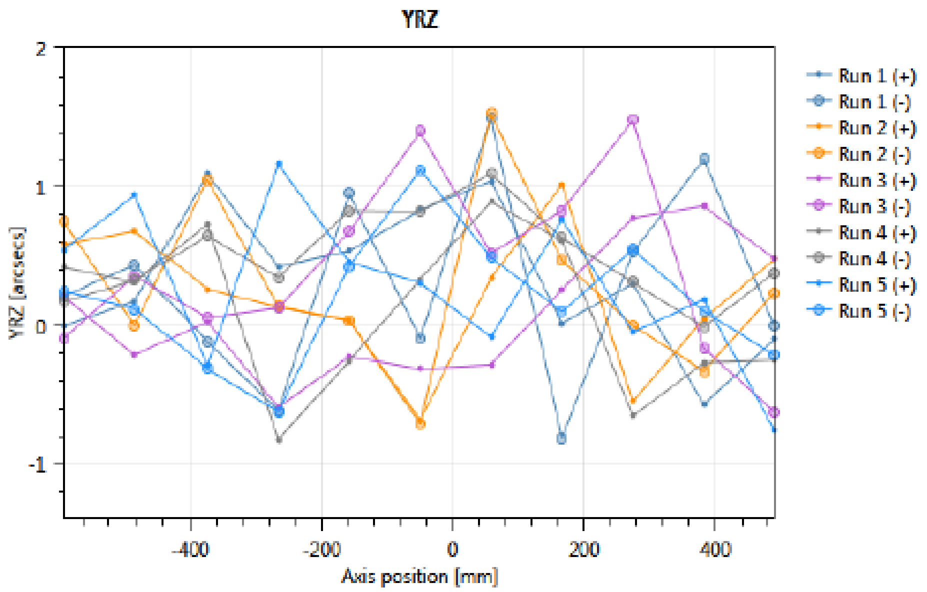
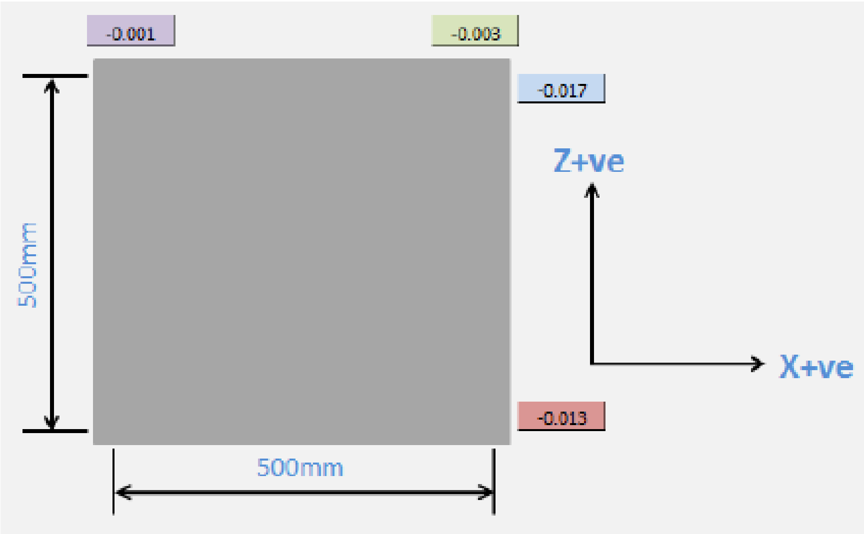


Figure E-11: Y axis angular error measurement (Y about Y measured with inclinometer)

2.4 Cartesian squareness

Axes:	XZ	Error:	XZ squareness		EB0ZX
Readings (arc-seconds):	Accuracy (A)		2.4	Notes: The Granite Square was sat directly on the table for all checks	
Reading positions (mm)	X start	-98	X end	460	
	Z start	200	Z end	727	



Axes:	XY	Error:	XY squareness		EC0YX
Readings (arc-seconds):	Accuracy (A)		0.2	Notes: The Granite Square was sat directly on the table for all checks	
Reading positions (mm)	X start	-248	X end	321	
	Y start	-187	Y end	354	

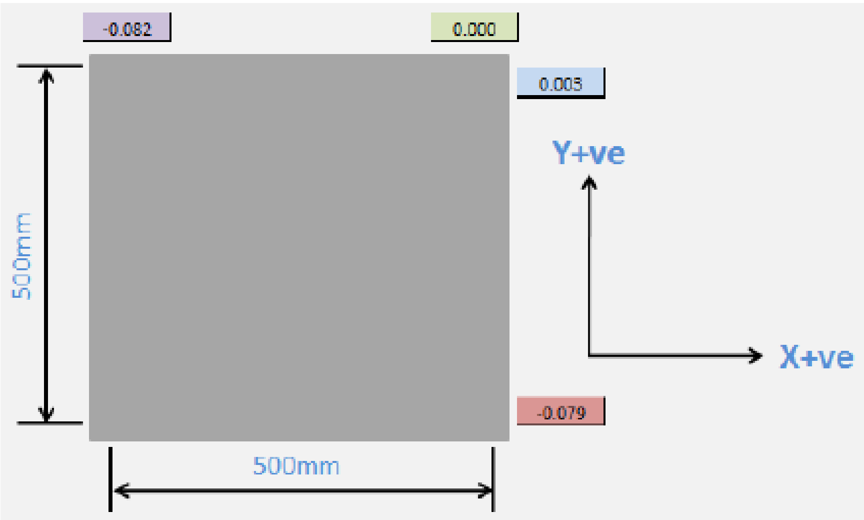


Figure E-12: Linear axis squareness measurement

Axes:	ZY	Error:	ZY squareness		EA0YZ
Readings (arc-seconds):	Accuracy (A)			3.7	Notes: The Granite Square was sat directly on the table for all checks
Reading positions (mm)	Y start	--260	Y end	287	
	Z start	200	Z end	727	

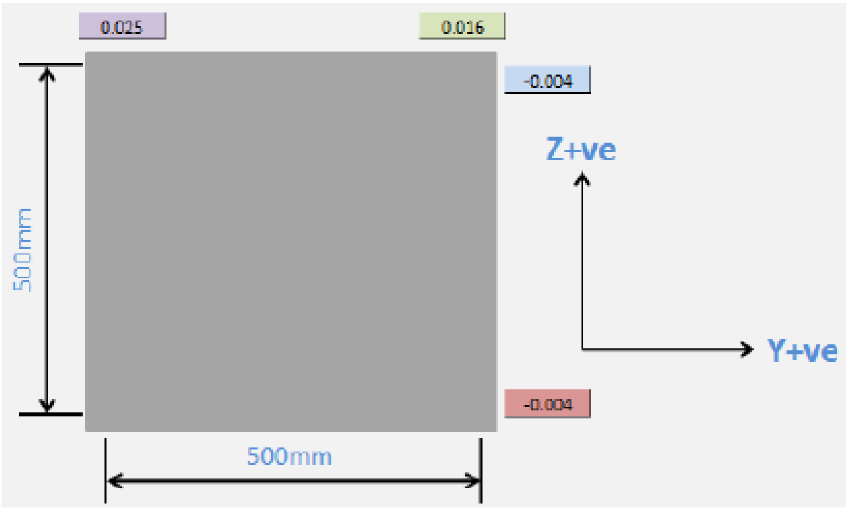


Figure E-13: Linear axis squareness measurement

Appendix F

This manufacturing vision was created from the various stakeholders associated to this research work (Chapter 3).

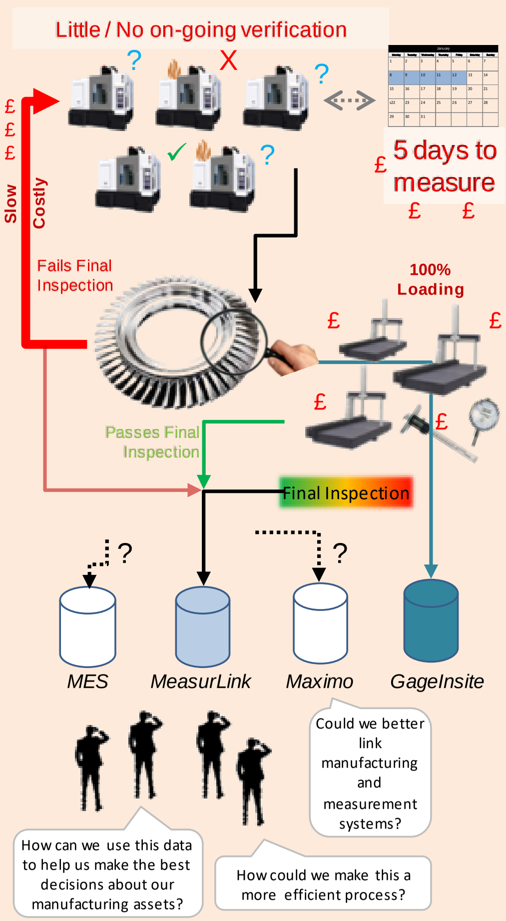
Capable Machine Tool Metrology - Vision

TODAY

Critical Metrics

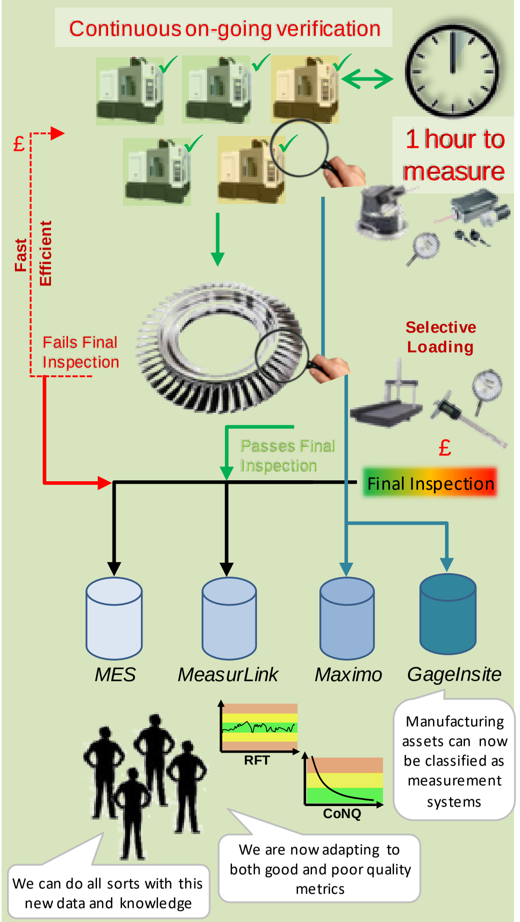
- ✘ 5 days to calibrate a 5-axis machine
- ✘ Machine verification is a manual intervention
- ✘ Total number of machines in calibration control = Low
- ✘ Number of machines with on-machine probing = Low
- ✘ Number of machines under regular verification = Low
- ✘ Number of machining operations with in-cycle verification built-in = Low
- ✘ RFT = Variable
- ✘ Cost of Non-quality = High
- ✘ 100% final inspection on CMM equipment
- ✘ Few engineers with knowledge of machine calibration
- ✘ Minimal external support
- ✘ Poor or low linkage between manufacturing IT systems

Current Situation



FUTURE

Future Situation



Critical Metrics

- ✓ Full 5-axis machine geometric and laser calibration in 1 hour ●
- ✓ Rapid automatic on-machine (process) verification on all key machines ●
- ✓ All key machines in calibration control ❖
- ✓ Number of machines with on-machine probing = High ❖
- ✓ Number of machining operations with in-cycle verification built-in = High ❖
- ✓ RFT = High
- ✓ Cost of Non-quality = Low
- ✓ Reduced dependency on final inspection ❖
- ✓ In-house competency in machine measurement ❖
- ✓ Strong academic support ❖
- ✓ Strong clear linkage between manufacturing IT systems

● Technology delivery via SAMULET 6.3.1
❖ Enabled by SAMULET 6.3.1

~ END ~