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Investigation of the Impacts of Standardisation and Data Handling within the Machine tool Service Environment

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Abstract

The advance of modern machine tools has created the situation where the traditional approaches to machine tool measurement and reporting are beginning to fall short. Due to the large number of measurements required to fully qualify a complex machine tool, along with ever-tightening time constraints, it is extremely important to understand what the end goals are before any measurements are taken. Existing methods of determining what errors are present in a machine tool, i.e. through the manual assessment of the machine tool configuration, are both time-consuming and susceptible to human errors. The combination of this increased complex with the vastly increased quantity of data recorded by modern measurement and calibration equipment has led to large amounts of human resources being required to process and record it. Worse than this, it has led to captured data being underutilised and opportunities for improvement being missed.

A system that can automatically produce a comprehensive list of the errors that are present within a machine tool would save valuable time. Additional benefits would include the development of a common language for describing and storing machine tool configuration, along with a consistent database, both of which would dramatically increase the efficiency of the search and recall activities. The information to develop such a system was collected during the course of this research in a partnership with a leading industrial partner.

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1 Introduction

Manufacturing processes are continually evolving to meet the new demands created by the progression of science and engineering. Modern manufacturing and engineering has long since advanced beyond the point where human-controlled hand tools can provide the accuracy, speed, and, importantly, repeatability required by these new manufacturing demands.

The need to fulfil these requirements has resulted in complex Computer Numerical Control (CNC) machine tools that have come to the forefront of manufacturing over the last 60 years (1).

With the limitations of human operators removed, the abilities of these machine tools have increased steadily until the required accuracies challenge the abilities of the best measurement equipment and operators (2). New measurement techniques, such as high-precision electronic levels, laser interferometers, and high-accuracy optical scales, and technologies have been developed to match pace with these new levels of production.

As a consequence of these ever-tightening manufacturing tolerances, machine tools have ventured into territories where a multitude of new factors, such as temperature, external vibrations, non-rigid errors, or even the curvature of the earth, can influence their function and must also be considered when taking measurements (3). In order to account for these additional influences, their effects must be monitored and recorded throughout any measurements to allow them to be compensated for.

The consequence of this is that the amount of data necessary to ensure that the measurements of machine tool performance are as accurate, reliable, and repeatable as the machines they are taken from has increased significantly.

This additional data has meant that there are now more analysis options available to the metrology teams working on high-accuracy assets, for example volumetric analysis, allowing more trends and problems to be uncovered. This has also meant that the time and effort required to fully analyse the data has increased.

As smaller machine shops may not have the number of machines to warrant investment in a full-time metrology or predictive maintenance system and the larger blue chip organisations may require that the skills be more mobile than is feasible, a skills gap has arisen. The machine tool service industry has provided these facilities and has had to adapt to these changing demands and provide additional high-class measurement and diagnostic abilities within their more traditional suite of services.

The ability to quickly and reliably identify, qualify, measure and analyse a machine tool is essential to providing a high quality and, above all, efficient service to customers. This paper will demonstrate the present obstacles, how they have been addressed, and the potential for further work.

2 Aims and Objectives

With proper analysis and documentation, this paper aims to show that machine tool measurement can be made efficient, repeatable, and traceable.

Communication errors occur in all walks of life and can be costly, often preventable, mistakes that may prove highly embarrassing to all involved. This research work demonstrates that with proper analysis and a robust framework, the tasks of describing a machine tool and defining all of its Cartesian errors can be a largely automated task. The subsequent tasks of performing the measurements and drawing conclusions can be made much simpler because employees will be able to access the data through a computerised system and have much more confidence in the measurements and system as a whole.

2.1 Aims

This thesis aims to show that:

- It is possible to make large time savings by adopting a structured document control and revision system
- It is possible to automate some of the more complex and time consuming tasks in machine tool metrology that have previously been restricted to skilled analysts.

2.2 Objectives

There a several objectives within this project:

1. Investigate the present methods of data handling and identify areas for potential improvement.
2. Develop a data extraction and processing system to automate basic transcription tasks
    - This system should be able to interface and extract the measurement data from existing measurement templates and create the present summary documents
    - This system will not be required to perform any analysis on the captured data.
3. Implement a standardised document format and document control system within the machine tool measurement process
    - To minimise user impact the measurement and summary documentation should remain outwardly similar to the original documents

- The data extraction/processing system mentioned previously should be updated to maintain compatibility with the new formats

4. Create a standardised and flexible classification system for the identification of machine tool configuration
    - This system should provide the ability to unambiguously describe a machine tools axis configuration
    - This system should be aim to able to produce the relevant data for inputting into the analysis system in objective 4
    - This system should not cover the specifics of the cutting tool or table that is attached to the machine, only the axes that provide motion to it.
5. Develop an automated system for calculating all the possible freedoms of moment within a machine tool configuration
    - This system should take machine configurations described in objective 3 as an input and output a text based list of the errors present in the given configuration
    - This system should not have to deal with the errors present within the cutting/grinding tools or tables attached to the axes.

2.3 Evaluation strategy

In order to evaluate the effectiveness of the strategies and systems proposed by this research, different methods will have to be employed for the differing areas of development. Where the developments can be implemented in real world environments, the time (and therefore cost) savings introduced by the improved systems will be compared to the original methods.

For the evaluation of the automated error generation software, comparison of the outputs of the automated system should be compared to those of the traditional systems. Both the time taken and the validity of the results should be compared.

2.4 Benefits of proposed work

A more robust and universal system to store and analyse the machine tools and their measurement data would be beneficial to large machine shops where commonality between machines and tolerances could be exploited to allow large cost and time savings. It would also be extremely useful to manufacturers if reliable long-term data could be captured from real world environments.

Remote engineers would benefit from a more standardised and flexible method of capturing data relating to a machine tool's configuration and communication mistakes can be reduced commonality of the data format. Even ignoring the added benefit of an automated diagnostic tool, this alone would be an extremely beneficial outcome, as relaying the exact configuration of a machine tool is often a complex and error-prone task.

This thesis will also demonstrate that once the targeted machine tool has been comprehensively described, the process of determining all its degrees of freedom, and subsequent measurements of these, can follow a logical, automated and repeatable path. One of the benefits of this is that it reduces the dependence on human experts and the variation that can be introduced by human error.

Once the initial hurdles of robustly describing the machine tool have been overcome, further expansion of the system into a metrology planning, analysis and tracking suite is more straightforward. An overview of the steps required to develop this larger system will be outlined later in this document.

3 Literature review

There are a number of areas in which published research is relatively absent, mainly the development of flexible, full machine examination techniques. Much work has been done in areas such as novel utilisations of existing measurement equipment or new applications of existing machining technologies as detailed by Jywe (4), Axinte (5) and Khan (6), amongst many others. Although the new application of the double ball bar (DBB) system employed by Khan introduces a method of measuring freedoms of movement that were previously difficult to access (and with existing equipment), without prior knowledge that the errors need to be measured and how they affect the machining process; they are simply more unneeded data points. Machine tool measurement and calibration has also been discussed in depth by authors such as Wang (7), Knapp (8), and the ISO 230 (9) suite of standards to highlight a few. The situations and techniques discussed by Wang however are limited to the typical three linear axes found in the majority of machine tools, but does not venture into the more complex situations involving multiple rotary axes or unusual configurations. Conversely, the ISO documentation presents a detailed examination of various techniques of measurement, and the situations they can be applied to, but only regards each case in isolation. Similarly, error characterisation of specific machine tool features has been thoroughly detailed in further research such as Ibaraki (10), Khan (6)and Suh (11), amongst others. Again however, these concentrate on specific examples and relatively little look at the machine tool as a whole. Additionally, none of these specifically address the problem of what degrees of freedom are presented by all the axes in differing configurations of machine tool. Within this project, the error profile examples for the different machines have been utilised and expanded upon in order to extract the underlying patterns for use in a dynamic system. As discussed by Parkinson (12) (13), this is a pressing issue when attempting to efficiently produce measurement schedules for engineers to follow whilst in the field, the solution to which could potentially save the manufacturing industry large amounts of machine downtime, the cost of which is ever increasing.

Similarly, much research has been conducted, and a large industry has been created, to address condition monitoring through vibration, tribology and temperature monitoring amongst others, whilst relatively little work has been done on consistently monitoring the machine tool's output - the accuracy of a complex machine tool's full geometry. This could be attributed to the relative and increasing complexity of modern machine tools, but as they have evolved to become the standard when machining high accuracy or high volume parts, a more holistic view of machine tool measurement, covering the whole machine is required.

3.1 Historical development of condition monitoring/reporting

The history of modern machine tools can be traced back to the industrial revolution. Although wooden machines had been in use since biblical times, as discussed by Moore (14) it was not until early 1800 that the first commercially available examples were produced. The driving force behind these, and mass production revolution as a whole, was the concept of inter-changeability (14). The need for inter-changeability of parts (the idea that any 5mm thread bolt will fit any 5mm nut for example) helped drive the need for both standards, and the machines to produce parts to these standards. Prior to this all parts of machinery that had to mesh together (nuts and bolts, gears and screws, etc) were all made as unique pairs to such an extent that often different screws on the same machine were not interchangeable. This principle of interchangeable and compatible parts has been incorporated throughout the reporting system implemented in this project in order to achieve the same increases in efficiency and quality.

When operator-controlled machine tools were first introduced the positional accuracy and repeatability of the axes was down to the coordination of the operator and the accuracies of features such as axis straightness were still relatively low (2). At this time, the repair of a simple machine was not a troubling matter as production times were still relatively long and minor repairs comparatively simple, as machines were designed to "run to break" (15). With the introduction of Numerical Control, the increase in accuracy and complexity enabled manufacturers to reduce production times and increase the productivity of each machine (16). This increase in complexity came with an increase in cost, and also meant that the complexity, and consequently duration, of repairs invariably increased. Furthermore, the continued reduction in error tolerance (increased accuracy requirements) meant that repairs would be required more frequently, taking the machine out of production and costing the owners money in both repairs and lost production time.

As machine downtime became more of an issue, various solutions were created. Some manufacturers created heavily resilient machines that would run for long periods with minimal intervention and stayed with the traditional run-to-break approach. Others extended lifespans by setting run-time based intervals after which the vulnerable parts, which were now replaceable, should be changed, for example renewing guideways, instead of wearing out integrated ones. A further improved solution that was found involved periodic "health-checks" for the machines to determine whether repairs were needed to prevent further downtime. This was called was Condition Based Maintenance, first introduced in the 1940s by the Rio Grande Railway Company to prevent coolant and fuel leaks in a diesel engine (17).

3.2 Condition Based Maintenance

Condition based maintenance is the practice of replacing and maintaining parts of machinery as and when it is required by the status of the parts. Condition monitoring refers to the systems and technologies that are used to monitor the present operational condition of any number of systems of a machine tool. When multiple readings are taken over an extended period, the data can provide information on the rate of degradation of the machine tool as discussed by Sun (18), allowing preventative actions to be taken before problems arise. This does not traditionally cover the positional output of the machine in question however. The eventual aim of this project is to allow these principles of condition based monitoring to be easily incorporated into the system and allow the comparison of data sets over larger periods of time.

3.3 Condition monitoring approaches

Over the years, many approaches to condition monitoring have been developed to suit the various priorities of differing production facilities around the world.

3.3.1 Corrective Maintenance/Breakdown Maintenance

This approach aims to repair or replace failed components after failure has occurred. When dealing with non-critical systems where the repairs can be carried out quickly, this may be a viable approach. It has the benefit of having no additional monitoring or scheduling requirements, and no additional costs until something fails, but has the downside of producing unexpected downtime events and cannot guarantee zero failure situations (19) (20). When operating in environments that require both high levels of uptime and precision, this is not usually a suitable option.

3.3.2 Total Productive Maintenance (TPM)

TPM aims to improve machine availability through more efficient use of maintenance resources. In most circumstances this involves training the operators to carry out many of the day to day tasks involved with the assets maintenance, thereby reducing avoidable wear and increasing lifespan. This also means that the maintenance teams are released to perform more critical or complex tasks (19) (21). The theory was introduced in 1950s and is an integral part of the Lean Manufacturing philosophy (21). Many manufacturers are now implementing TPM strategies through skill/bonus incentives as the savings through reduced downtime and increased productivity, quality and staff moral can be significant.

3.3.3 Preventative Maintenance (PM)

Preventative maintenance is based around knowledge of mean time to failure (MTTF) figures for the wearing parts of a machine (22). This approach aims to reduce unplanned maintenance work and machine failures by replacing the required components before they fail. This method has the advantage of reducing the number of spare parts the owner has to keep on stock and requires no additional downtime for periodic measurements or data capture requirements, but as such cannot detect any unexpected changes in the machine (20). Additionally, if the process the machine is expected to carry out changes drastically, previous estimates for component lifespans may be invalid due to the new loads placed on them, requiring a complete timing plan overhaul.

3.3.4 Predictive Maintenance (PDM)

Predictive maintenance, often referred to as Condition Based Maintenance, relies on knowledge of the machine's condition to estimate failure times and produce servicing schedules to allow the wearing components to be replaced before they actually fail. This has the benefits of reducing both costs and downtime as the required resources can be put in place at the right times (as wear tolerances are neared) and aims to eliminate unplanned emergency repairs (20) (23). The downside is that some form of monitoring and data capture is required to provide the information that the system runs on. Despite this, predictive maintenance is slowly becoming more widely adopted in manufacturing due to the large benefits it can deliver through minimising disruption to production schedules and reducing costly emergency servicing (24).

The area of predictive maintenance and machine calibration in general is where the topic of measurement comes to the forefront as it is designed to catch drift in the output before it becomes a quality control issue.

3.4 Condition Monitoring/Measurement Tools

Due to the various types and functions of machine tools, many different methods of monitoring and recording various aspects of their condition have been developed. A selection of these are discussed here.

3.4.1 Vibration and Acoustic Emissions (AE)

Whilst other methods are available, modern machine tools are primarily powered by rotating motors and ballscrews, which, in turn, move elements of the machine along linear guide ways. Similarly, the spindles that move the cutting tools or workpieces are rotating elements, and they operate at either high or low speed. All these rotating bodies create vibrations at frequencies relative to their rotation speeds (15). Using accelerometers it is possible to create a vibrations signature of a "healthy" machine or machine part, and set tolerances that trigger alerts if the vibrations stray outside of them (25).

Acoustic monitoring is related to vibration monitoring and is described as transient elastic waves generated by the release of stress energy within a part or structure (26) (27). Correctly applied it can provide powerful diagnostic capabilities for a wide range of rotating machine elements and can fit neatly into a suite of skills and equipment available to maintenance teams (28).

3.4.2 Thermal

Monitoring the thermal emissions produced by a machine tool can give clues to multiple problems within the system and provide early warning capabilities. Problems such as worn bearings (29), lack of lubrication, or over-stressed motors (30) can be identified, or even the total heat output of a machine or facility could be monitored. One of the specialist areas of application of these systems is the monitoring of electrical components (such as motors or transformers in machine tools) as one symptom of over-stressed components is excessive heat build-up, leading to damaged insulators (31) and, in the case of machine tools, thermal errors being introduced into the machine (29).

3.4.3 Oil and Wear Particle Analysis

Oil analysis can range from its most basic form – a visual inspection to see if oil is present or looks contaminated, through to detailed spectral analysis of the fluid and its particulates (32). This can provide information about the parts they come in contact with by looking at the viscosity, solids content or particle count, amongst others, can tell us much about the condition of the fluid and the surfaces it is in contact with (33).

Analysis of the wear particles can tell us which part of a bearing gearbox or moving surface is wearing, and by how much (34). For example, checking for the presence of metallic particles suspended in gearbox or bearing oil can give a good indication of what stage of degradation the gears or bearings are approaching. This data could then be used to predict the oncoming occurrence of backlash in the axis drivetrain for example.

3.5 Present/Future Condition monitoring

As technologies advance and computing power and data storage have decreased in cost, many new and interesting methods of monitoring a machine's condition are becoming possible. In fact, one of the problems facing maintenance departments nowadays is the overabundance of data, leading to analysis backlogs.

The advancement of NC controller technology has opened the door for real time condition monitoring and adjustment technology. Many monitoring systems are built into modern CNC controllers and networks to allow emergency stoppages to be called if any one of numerous alarms or tolerances is breached (35). Tool wear monitoring is one area where this has been put to good use.

One such system, provided by Omative Systems (36), provides real time spindle monitoring and feed adjustment in order to maintain the cutting force on the tool within a set range, and therefore increase tool life expectancy. Similar systems are often built into the controllers to prevent motor overload, and various limits can be set to limit machine acceleration and further reduce wear.

3.5.1 Machine tool Accuracy

A high accuracy machine tool is a large investment for any machine shop and must be able to repay its initial investment. Modern machine shops are constantly competing to provide high quality services at competitive prices and timescales. In such an environment, a machine tool cannot justify its existence if it is:

1. Non-functional
2. Not performing adequately

As discussed by Ahuja (23), the majority of present CBM efforts are orientated towards addressing point 1 – minimising machine failures and breakdowns. Whilst this minimises downtime from component failure and can provide information for creating downtime schedules, it does not directly address a machine's output – its accuracy during cutting procedures. The task of measuring and verifying the asset is often left to the specialist calibration metrology departments who are viewed as a separate force to maintenance. The idea that metrology is an integral and productive part of the manufacturing process is discussed in detail by Kunzmann (37) and Perkins (38).

3.5.2 Large scope of the machine tool monitoring

The topic of Machine tool Accuracy is an extensive one covering many technologies, disciplines and sciences. The in-depth mechanics of measurement uncertainty, volumetric compensation systems and the strengths and weaknesses of various measurement techniques (for example) are discussed by the "GUM" (39), Longstaff (40), Bell (41) and Wang (2) (amongst many others) respectively. Many of the principles and techniques highlighted in the GUM are highly computationally expensive and can only be applied economically to data stored in a well-structured manner, further enforcing the need for an improved data storage system. Furthermore, a system that could control what measurements are scheduled to be undertaken could incorporate advanced analysis techniques, such as volumetric analysis, with relatively little increased human oversight.

Similarly, the various classes of machine tool, and the multiple arrangements of axes possible within these various configurations of machine have been discussed in detail by authors such as Bohez (42). The relevant Cartesian errors and offsets are not covered in detail, nor is the system particularly suited to enhancing commination in the shop floor environment. Flexible calibration planning and optimisation systems are under investigation and development, as highlighted by Parkinson (13), showing that the technology gap is being taken seriously.

3.5.3 Existing measurement tracking systems

There are a number of software packages available today that can provide assistance to the users in some of the areas shown above. The majority of these however are specifically produced by metrology equipment suppliers in support of their equipment.

Similarly, there exist multiple data collation and tracking suites for analysing large sets of measurement data, but these are often generic tools that would require customisation for each machine tool encountered.

The Renishaw Ballbar QC-20W double ball bar system is used to measure the interpolation abilities of two perpendicular axes (43). The software provides a number of measurements that are derived from the initial measurements and additionally allows users to track the variations of any of these over time using the software's history functions. Warning and alarm tolerances can be set within the software so operators can take measurements and only alert maintenance when the pre-set tolerances have been breached (Figure 1). This highlights the fact that the industry has responded to the need and is moving towards data tracking and tolerancing requirements. With the supplied software however, the ballbar can only supply information about the linear axes of a machine, and only within the limits of its working radius.

3.5.4 Minitab

For quality management and statistical analysis of large set of measurements or production statistics, Minitab is one of the most well-known software suites. It is used in many of the large blue chip production facilities within the UK and has many beneficial features and analyses such as regression analysis and Statistical process control (SPC) (44). It does not, however, instruct you on what variables or features should be recorded in the first place for machine tool metrology.

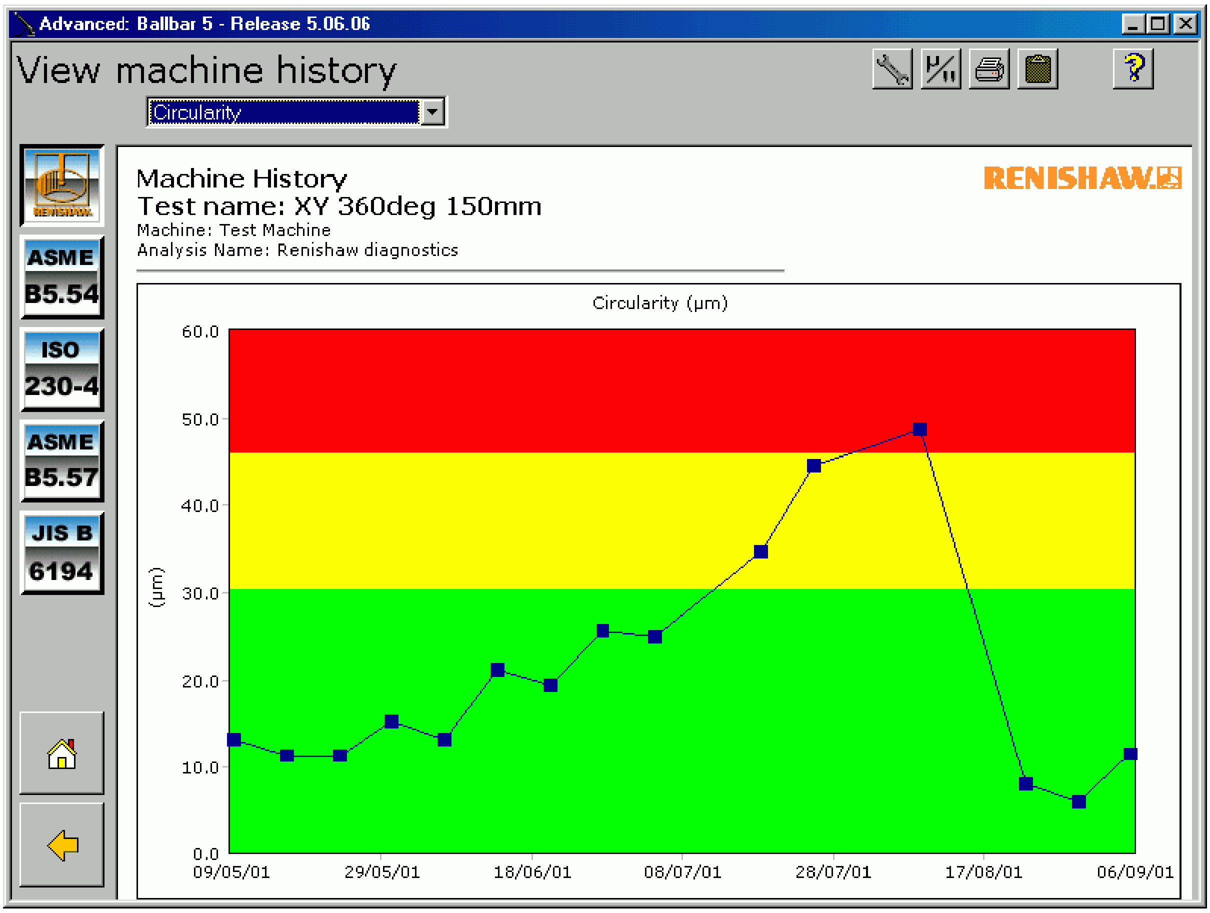

Figure 1: Renishaw QC-20 ballbar history function

3.6 Existing measurement equipment

Multiple solutions have been developed to allow specialists to measure the errors of almost every freedom of movement within a machine tool. These have advanced and improved as new technologies have become available and economical to deploy in the workshop environment and have been adapted to fill many roles. A selection of some of the more frequently encountered systems is presented here.

3.6.1 Precision artefacts

Carefully machined and calibrated artefacts have long been used to measure machine tool abilities. Granite squares coupled with precision Dial Test Indicators (DTIs) are still one of the most reliable ways to determine the squareness of a pair of orthogonal axes. However, data captured from these analog devices (DTIs) is subject to user interpretation and transcription errors when recorded on either paper or in digital format. Digital DTIs (linear variable differential transducers (LVDTs)) can alleviate the first issue, and software to record the results directly from the devices can be used to remove the secondary problem, however this is not as widely used as the traditional mechanical DTI due to the additional data capture and storage requirements (Laptop + software vs. plain paper).

Figure 2: Granite Squares

3.6.2 Precision Levels

Precision levels have also been used to measure the deviation of a machine's bed when compared to the earth level during installation and adjustments and they are still one of the few ways to measure the angular deviation of a linear axis about itself (the axis roll) as it moves along its traverse. Traditional bubble levels suffer from the same problems as analog DTIs, user interpretation and transcription errors, along with the limitations of the format itself (physical size and orientation limitations). Newer electronic levels, such as the BlueLEVEL from Wyler have accuracies down to 1µm/m (45) and computer interfaces to allow data to be captured digitally.

Figure 3: Precision bubble level Figure 4: Electronic inclinometer

3.6.3 QC20-W Ballbar

Renishaw's QC20-W (the wireless replacement for the QC10) is a telescoping double ballbar system that can be used to perform relatively fast measurements of the interaction of two linear axes as they move along a circular path. The sensor has a resolution of 0.1µm and a maximum sample rate of 100Hz (43) allowing various errors and control parameters to be calculated from the recorded data as the machine attempts to trace a perfect circle. Whilst the ballbar is extremely useful for checking whether a machine has changed from a previous condition, more in-depth measurement is often required for detailed problem solving.

Figure 5: Renishaw QC20-W

3.6.4 Grid Plate

The Heidenhain grid plate system involves the use of an optical encoder system and a high precision etched plate to relay the position of the head during motion. As the system is non-contact it eliminates any possible errors that may be introduced by the contact faces between the precision artefacts and DIT or the ends of the ballbar system. The system allows 2D movement within the limits of the plate and measurement resolution down to approximately 1nm (46) and is especially useful for examining complex contouring paths as any combination of movement is permitted within the plane and area of the plate.

Figure 6: Heidenhain Grid Plate+ Reader head

3.6.5 XL-80 Laser Interferometer

Renishaw's XL-80 measurement system is a laser interferometer system with a resolution of 1nm and additional environmental compensation to account for atmospheric changes during testing. It is capable of performing positional accuracy and repeatability measurements on linear axes, along with angular measurements about the perpendicular axes. The system can also perform linear axis straightness measurements and measure the squareness of two linear axes (47). Whilst the system can provide high resolution measurements of a wide variety of errors, the delicate setup procedures required for some configurations may warrant the investigation of more traditional methods if the highest degree of accuracy is not required.

Figure 7: Renishaw XL-80

3.6.6 XR20-W

The XR20-W is an additional piece of equipment to be used alongside the XL-80 to calibrate the positional accuracy of rotational axes. It contains an extremely high precision motor and measurement scale attached to an angular retro-reflector that, when combined with the XL-80 allows precise angular measurements to be taken.

Figure 8: Renishaw XR20-W

3.6.7 Agilent 5530

The Agilent laser calibration system is another laser interferometer system a measurement resolution of up to 0.25nm allowing the measurement of the same linear and rotational errors of linear axes and a number of the errors of a rotational axis (48). As with the XL-80 the system includes environmental compensation to eliminate the effects of thermal, pressure and humidity changes.

Figure 9: Agilent 5530 Laser Calibration System

3.6.8 Etalon LaserTRACER

In order to make volumetric compensations of a machine tool's working volume, detailed measurements are needed of all the errors within it. Capturing all the required data points can be a time consuming task when utilising traditional methods and has led to the development of faster methods. The Etalon LaserTRACER (49) is an example of new measurement tools that are allowing faster data capture from multi axis machines. By combining two rotational axes with a high precision linear measurement, the LaserTRACER can map the entire volume of a machine from a single location. As this removes the need for multiple equipment setups the time required to perform a full machine measurement can be significantly reduced.

Figure 10: Etalon LaserTRACER

3.6.9 Shortcomings

Although all these measurement devices provide the user with extremely high precision methods none of them advises the user as to which errors are present in their machine's configuration or which errors will be the most important to the process. This can lead to the situation where measurements are repeated (resulting is wasted time), improperly measured, or omitted completely, all of which can negatively impact production. Additionally, no one system, or even a combination of compatible extensions from the same manufacturer, can be used to measure all of the errors within a machine, as shown in Table 1. Neither is the data from the different equipment of accessories usually compatible any single piece of analysis software without further modification.

Furthermore, whilst the various systems presented here will produce data files to a number of international standards, only the QC20-W provides the user with the ability to track the measurements over time and set error boundaries within the data. For any further processing external applications must be utilised and further data processing or transcription systems created.

System \ Attribute	Linear Axis Positional	Linear Axis Straightness	Linear Axis Rotational	Linear Axis Squareness	Rotary Axis Positional	Rotary Axis Linear	Rotary Axis Rotational	Rotary Axis Squareness	Historical Data tracking	Operator advice
Precision Artefact + DTI	✗	✓	✗	✓	✗	✗	✓	✓	✗	✗
Precision Levels	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗
Heidenhain Grid Plate	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗
Renishaw XL-80 (+ XR20-W)	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗
Renishaw QC20-W	✓	✓	✗	✓	✗	✗	✗	✗	✓	✗
Agilent 5530 (+ rotary module)	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗
Etalon LaserTRACER	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗

Table 1: Commercial Calibration Solutions

3.7 Measurement uncertainty

Much research has been done on methods of measurement and their uncertainties. W. Knapp (8) highlighted the uncertainty of measurements that can arise in commonly found industrial settings, and how this may be significantly different to the stated or expected ranges. Whilst a thorough understanding of measurement uncertainty is a crucial to a robust measurement service, this is addressed more by the methods and procedures that are developed to take the measurements, not the process of defining what measurements we should take in the first place.

3.8 Conclusions

Much work has been done on the calibration of specific examples of machine tools, and even individual classes have been explored in depth. The error profiles presented by these specific cased will be used to investigate the links between the fundamental building blocks and the error profiles produced in order to uncover the principles governing the appearance of errors in different situations.

One of the key findings of this review is that due to the complexity of the situation, little has been published to date on the topic of all-purpose systems designed to address any machine configuration likely to be encountered in the modern machine shop environment. Work has been done on other areas of measurement and condition monitoring, as highlighted in the previous sections, but little on the problems presented by modern, complex, machine tool configurations.

Many commercial solutions have been developed to measure the various errors within a machine tool's geometry as shown in Table 1, but few address the problem of tracking the data over time, and none advise the operator which measurements are required in the first place. There are solutions to the problem of data tracking, such as Microsoft's Excel, of the widely used Minitab, but these are data management systems and do not provide advice on which measurements will be required in the first place. Table 1 also highlights that until recently (with the introduction of the updated QC20-W software) the focus of the calibration industry has been largely on the production of equipment with ever higher levels of accuracy and flexibility, not the management of data and tracking the measurement over a period of time.

Beyond the issue of data management, the problem of what data to capture initially is still left to experts who address the problems on a case by case basis using their previous experience and training. This thesis examines the development of this system and the foundations required to implement it in a real world environment.

4 Data Capture System Development

In order to remove the source of the most costly mistakes and consequently the source of a large amount of lost time, the problem of accurately communicating the machine configuration had to be addressed. A simple improvement was introduced, a verification step after the initial data gathering process in order to address the most simple omissions or mistakes. Once the engineers had delivered the machine description to the office, basic diagrams were constructed from the analysts understanding of the data, which were then returned to the engineers for verification. Whilst this did introduce a small additional delay, on average the time saved by reducing errors further into the reporting process greatly outweighed this. To reduce this delay even further, software could be developed to allow the on-site engineers to directly input and verify the initial machine description themselves, removing the possibility for communication errors at this stage. After this alteration, the logical sequence to repeatably produce a complete measurement schedule for any machine becomes as follows:

1. Fully record and verify the configuration of the machine tool using unambiguous terms
2. From this configuration produce a list of possible freedoms of movement within the machine
3. From this list of freedoms of movement, produce a list of tests to measure each of the aforementioned possible freedoms of movement

Following this step both the original manual process, and the improved, automated processes converge back to the same process of creating the measurement templates:

1. Produce a list of equipment and personnel (with the required skills) to carry out these measurements
2. Carry out the measurements in accordance with measurement best practices
3. Produce a report detailing the recorded measurements and conclusions that can be drawn from them

On the surface, the definition of the machine tool itself is a complex task given the multitude of different manufacturers and configurations of machines. Nevertheless, the benefits of creating a framework in which the majority of machine tools can be recorded and processed outweigh the cost of the initial development. Some of the immediately obvious benefits would be:

- The alleviation the problem of misinterpretation of colloquial terms for different configurations, or worse, machines that are describes as “kind of like” or “similar to” more well-known models or configurations.
- Fast and reliable comparison of machines produced by different manufacturers or of different ages or purpose
- Accurate predictions of time required to complete measurements or services, allowing owners to better plan downtime arrangements.
- More efficient use of resources as calibrations can be planned with higher degrees of accuracy – removes the problem of forgotten equipment or insufficient time
- Reduced cost to the customer through increased efficiency.

Once this initial data is recorded, whilst the methods of test used to capture the actual measurements may vary, the errors that we are testing for should never alter. The direct benefit of this is that is makes time-based condition monitoring of a machine tool’s output possible, as the results are comparable year on year. Historically this has not been possible as new errors may be added, removed or reclassified in future iterations, rendering the exercise uneconomical or impossible.

4.1 Selection of appropriate tests

Selecting the appropriate methods of test is the next step in the process of machine measurement. This involves examination of the arrangement of the axes in question, combined with the available equipment and the specific errors that we are trying to record.

Each measurement method has its own strengths and weaknesses, and may therefore be applicable in certain situations, but not others. In complex machine tools, there are many errors that must be measured, and often more than one way to measure them. Ideally, the most appropriate (fastest, safest, most certain, most repeatable…) tests should be automatically selected for each situation, but a more realistic approach is to present the suitable measurement methods for a particular error and leave the final choice up to the engineer that will be taking the measurements.

A large catalogue of measurement techniques and methods for a variety of situations already exists in the ISO 230 suite of standards which can be applied to a large number of situations. The range of different measurement equipment available on the market today complicates the situation slightly, as the ISO standards attempt to remain impartial and not reliant on any specific manufacturer. This leads to the situation where the methods applied in the field are a combination of the ISO best practice guidelines, coupled with the equipment-specific methods of operation.

In order to match the detailed measurement methods to each measurement situation, a database should be created. As this covers all the available measurement equipment, it results in a dynamic entity, constantly changing as new equipment or standards become available.

As the completion of such a database would be an extremely lengthy process, this work aims only to lay out a general structure for such a system, not to populate it in its entirety.

A complete archive of the various test methods was being compiled in an Excel spread sheet along with example diagrams and other relevant data. Precisely what data should be recorded along with the basics is to be reviewed as it will need to interface with any test selection procedure. After compilation of this list, a full review of all the elements of the tests should be undertaken to remove any/all errors that have accumulated over the years of upgrades, tweaks and re-writes.

Once this review is complete, a detailed investigation into the question “how do you know what test to select for each error, for each axis, for this specific machine?” must be undertaken to identify the rules that allow for correct selection.

4.1.1 What is important to the process/level of manufacturing

It is possible to measure certain errors in a machine tool in more than one fashion, and examination of the tolerances that the machine is working to allows us to define what measurement equipment is the most suitable for the present task. If the machine is only roughing out parts to +/- 5mm, it may be more suitable to use a precision bubble level with its lower resolution, than to use a laser interferometer with its higher levels of accuracy as the measurement can be taken faster and will fewer equipment requirements.

4.2 Machine tool configurations

Modern machine tools are for the large part built around the principles of “lines in space” (14). They aim to provide movement within multidimensional working envelopes with high degrees of accuracy, speed, and repeatability. Some axes provide movement along one of these theoretical lines (linear axes); others provide movement around them (rotational axes). Typically, though not exclusively, the more complex the final profiles of the required part, the more axes are required to allow the machine to approach from the required angles and create the required cuts (50). Additionally, the more axes a machine has, the more flexible it can be with regard to the machining tasks it can accomplish.

Unfortunately, as the number of axes in a machine increases, the more complex the task of deciding what needs to be measured to ensure that it is performing to its specified accuracy. If we take an example of a three-axis machine tool with the following conditions:

1. There are three linear axes, one tool, and one workpiece
2. Both the workpiece and the tool must be supported by 0-3 of the available three axes
3. All the axes must be used by the combination of the tool and workpiece

There are theoretically 24 different configurations of machine tool that could be constructed from these three linear axes. Not all of these possible configurations would produce sensible, or even practical, machines, but they are possible arrangements and most would require different documentation, diagrammatical representation and measurement methods for each situation. If we expand this to a four-axis machine the total becomes 120 possible arrangements, and for a five-axis, this becomes 720.

The number of possible arrangements of axis for a machine is described by the formula below

$$C = (A + 1)!$$

Where *A* is the number or axes and the outcome *C* is the number of possible combinations. As we can see, the traditional method of providing a set methodology for each configuration of machine becomes extremely inefficient as the machines become more complex and the number of variations increase. To this end, a system of analysing each machine tool independently has been developed in order to quickly assess each configuration individually.

Many standards have been written discussing the various measurement techniques, common machine configurations and the ways the former should be applied to the latter (9) (51).

When machine tools were confined to the classical roles and configurations such as the horizontal lathe, side boring machine, or vertical milling machine for example, list of tests could be prescribed and followed to allow machine shops to test their machines in accordance with accepted standards.

As part complexity, and subsequently machine complexity, has risen, the lines between these traditional types and configurations of machines have become increasingly blurred. Is a Mazak Integrex 650i a turning or a milling centre? Is a Hermle C50 a standard milling machine or a hybrid miller/VTL? Which set of tests should be performed to correctly qualify or diagnose the machine? This has in turn led to the need for each machine to be assessed on a case-by-case basis to ensure that each is fully understood and measured. This process, completed by skilled analysis personnel, is highly time-consuming, and extremely experience based.

In order to measure all the freedoms of movement that a machine may possess, a number of steps must be completed:

1. Define the component axes and interfaces of the machine
2. Define all the freedoms of movement for the axes
3. Select appropriate methods of test to measure all the freedoms of movement

As we can see, the first step in providing an efficient metrological analysis of a machine tool is determining the composition and configuration of the machine. In order to do this task repeatably, accurately and quickly, a method of describing all the component parts of a machine tool in an unambiguous manner is required.

4.3 Classification of machine tool elements

As discussed earlier, in order to uncover the processes and rules used to manually process the machine as a whole, all the inputs to the system that the human operator would take into account must be specified and recorded. Once the input data is characterised, deciphering the processes that follow becomes significantly easier.

There are many components that make up a machine tool. The control system, cooling, tool or workpiece spindles, linear or rotational axes; the list is large and increasing as new technologies are developed and applied. Whilst many or all of these may influence the accuracy of a machine tool, only those that are relevant to the geometric accuracies the machine are considered here.

The process of classifying the axis types of the machine is what produces the fundamental building blocks of the whole system – once we have classified the different types of axes, we should then have access to sufficient information to repeat the process and produce the same conclusions, given the same machine.

The classification process can be thought of as the construction of a type of “family tree” with each further subset of axes being a related but more specialised version of the one before. Before this process can begin however, we must clearly define what an “Axis” is. For the purposes of this document (and the subsequent automated system) an axis should be thought of as any part of the machine that provides useful motion to a Tool, Workpiece or Interface. A description of these three terms is given below.

4.3.1 Interface

This can be anything that is interacting with the workpiece. Examples include the machine Table (that the workpiece is bolted to), a Steady (as found on long bed lathes), or one of the tools mentioned below. A machine tool must have a minimum of two of these (a table of some sort, and a milling spindle for example) in order to perform a useful task, but can have many more. Without this interface between the machine and the external environment, there would be no way for the machine to interact, and no reference point to take measurements relative to.

4.3.2 Tool

In this situation the term "tool" refers to the part of the machine that will be removing material from the workpiece, or performing some action on it. This may be a milling spindle, a fixed cutting tool used on a lathe, a welding electrode, ultrasonic scanner or a laser – the list is extensive and increasing, so cannot be comprehensively described here.

4.3.3 Workpiece

This is the part or material that is being worked on. This can be a raw billet of metal or a near finished part but it is the generally inert, removable product that is extracted from the machine at the end of the machining process.

4.4 Axes

There are a number of ways a machine tool can produce movement and many ways in which they could be classified. As a starting point for the family of axes, the first branching of the tree is the differentiation between linear motion and rotational motion.

4.4.1 Linear axes

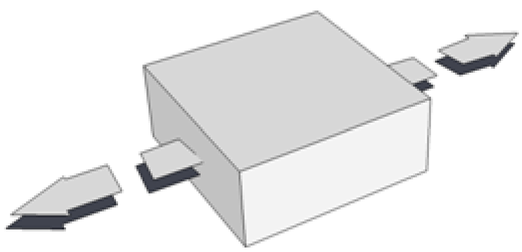

Figure 11: Linear motion

For a linear axis, the errors are very much as per the diagrams in the following section and although there may be many different methods of providing the motion to the axis, there seems to be only limited further levels of subdivision of the linear axis category. These are designated Type L1 and Type L2 – as displayed in the diagrams below.

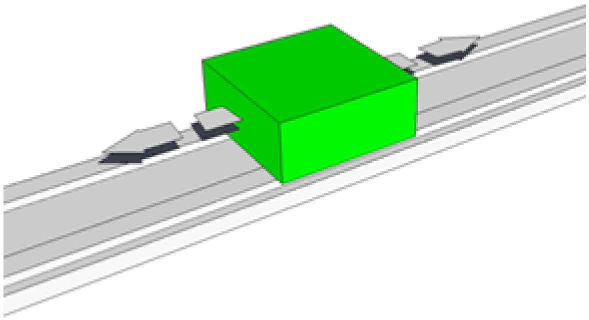

Figure 12: "L1" type linear axis

As you can see in **Error! Reference source not found.**, Type L1 involves the smaller shuttle or Saddle green) moving along a longer fixed bed (grey), whilst Type L2 involves a larger bed or column moving along a fixed anchor point. Along with these two subclasses of linear axis, a further type of linear axis is the Gantry.

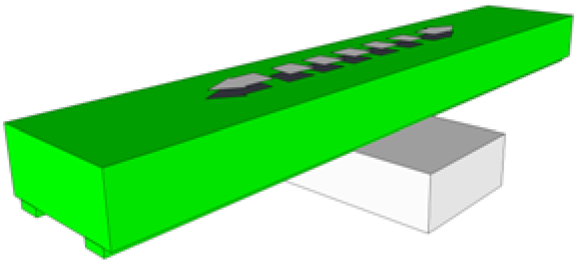

Figure 13: "L2" type linear axis

Please note that the orientations of these axes are not limited to those shown in the diagrams here - these are for illustration only, and can be found in either vertical or horizontal orientation.

4.4.1.1 Gantries

A further subdivision of a linear motion axes is the "Gantry" classification. The unique feature here is that the axis consists of two driving elements with a connecting beam or spar between them. Whilst this configuration provides the same function, and is subject to the same errors as a standard linear axis, additional errors such as the height between the two sides of the gantry and any positioning errors and servo mismatch in their movement could be taken into account when diagnosing problems.

Gantries, as with the previous linear axes, can be further subdivided into two subclasses, Type LG1 and LG2.

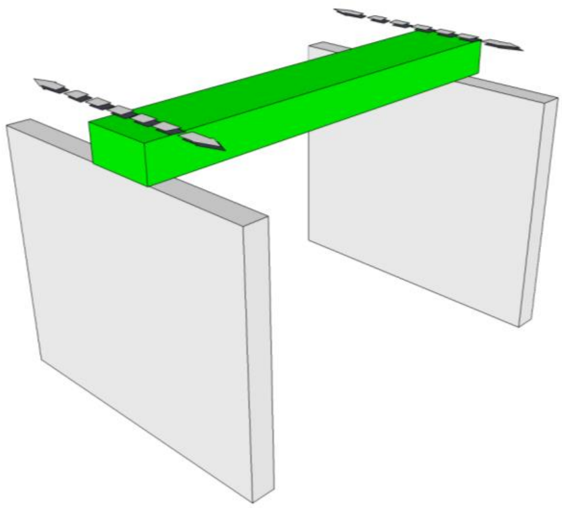

Figure 14: Gantry Type LG1

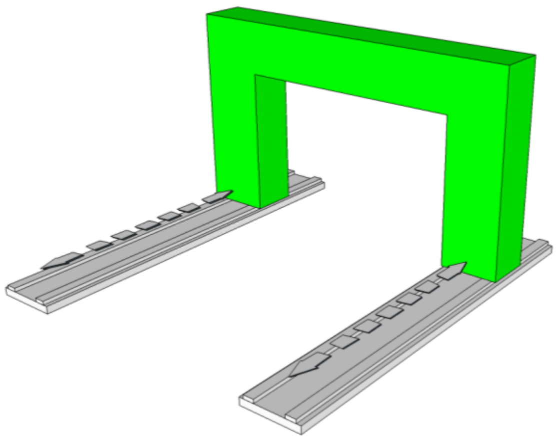

Figure 15: Gantry Type LG2

Both gantries perform the same function, but one is more suitable in some circumstances than the other. Type LG1, where only the beam itself moves, requires either walls (essentially) to be built, or a pit to be dug underground to accommodate the machines working volume. Type LG2 however merely requires space for the long machine beds to be laid down, however more of the machine is moved as the whole crossbeam and its support struts require moving. As with the standard linear axes, please note that we are not constrained to the orientations displayed here, for example, a Vertical Turning Lathe/Vertical Turret Lathe (VTL) crossrail can be considered as a Type LG1 gantry with vertical orientation and a limited range of movements (and accuracy).

4.4.2 Rotary Axes

The other type of motion that we can produce is rotary motion. There is some debate within this category about where to draw the line between a rotating axis, such as the rotary table on a Hermle C50, and a workpiece spindle with an indexing function, such as the headstock on a horizontal lathe. In either case, this differentiation is irrelevant to the basic geometry, and the "Virtual Construction" (within the following systems and diagrams) of the machine.

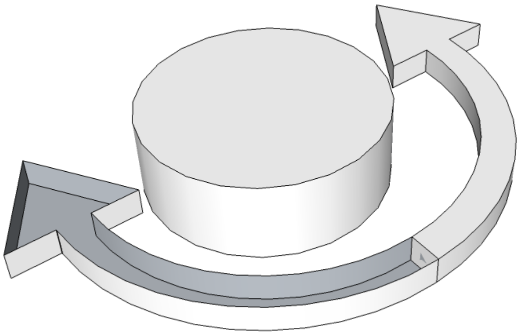

Figure 16: Rotary Motion

As with the linear axes, there are subdivisions of the rotary class into Type R1 and Type R2, displayed below.

4.4.2.1 Type R1

This configuration of rotary axis is commonly found as the main spindle supporting the workpiece in VTLs or standard lathe configuration machine tools.

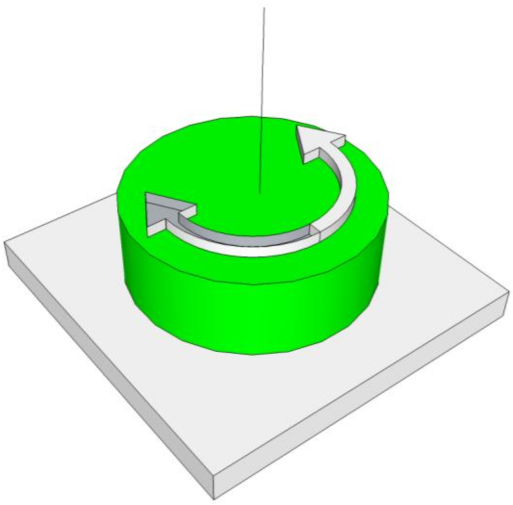

Figure 17: Rotary Type R1

4.4.2.2 Type R2

This configuration is commonly found in both fork head milling spindle arrangements and is the base of the “trunnion” type of rotary table.

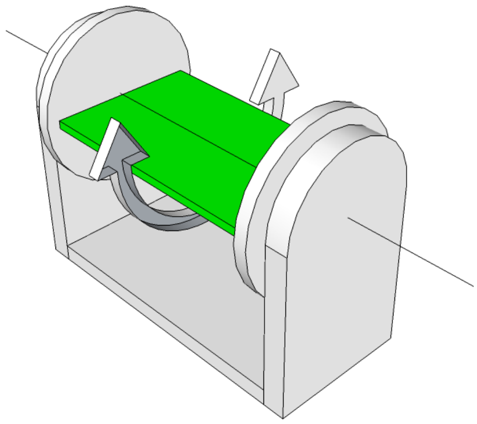

Figure 18: Rotary Type R2

The critical difference between the two types is the orientation of the interface plane[1] relative to the axis of rotation. With Type R1, the interface plane is perpendicular to the axis of rotation and therefore has rotational symmetry. These axes usually tend (though not exclusively) to have continuous, or at least 360 degrees of movement.

With Type R2, the interface plane lies *along* the axis of rotation and these axes usually have less than 360 degrees of travel. The R2 type (when coupled with a spindle or table) also introduces a new measurement that is relevant to the positioning calculations in the form of the Pivot Length; this is the distance between the interface plane/tooltip and the rotational centre of the axis.

[1] Interface Plane: it is called such here as it could be a table attached at this point, or the interface between the rotary axis and a further part of the machine.

4.5 Other axis types

Whilst the majority of machine tools are made up of a combination of these axis types, there are other variations that do not fit into this present classification system. One example of this is the combination of axes supporting the table on a Huron KX45, as shown in **Error! Reference source not ound.**. In this configuration, whilst the axis that rotates the table lies along one of the Cartesian axes, the one beneath that lies at 45 degrees to them. At present these lie outside the scope of this document and automated system.

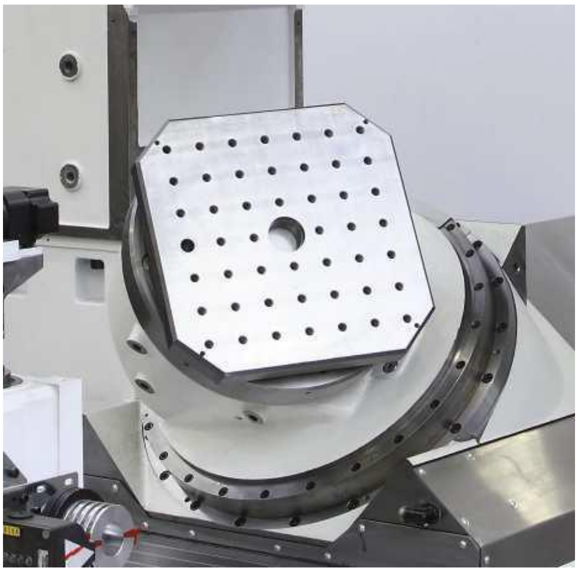

Figure 19: Nutating head table

4.6 Geometric Errors

In this section the different errors (and their designations) that could potentially affect the different types of axes are discussed and listed along with the errors found in some of the more common combinations of axes. This section does not aim to discuss the practicality of measuring these errors, nor whether they will have a direct effect on the process/part in question (this will vary), only that they exist as possible errors within the machine's abstract geometry. As such, it generally does not matter what subclass of axis these components are in the real world for this stage, this is only relevant for selecting methods of test to check the errors, but the way they are arranged is of critical importance.

As highlighted by Longstaff (52), Wang (7), and various machine tool specifications ((53) (54) (55)), traditional methods of stating the accuracy performance of a machine tool rely heavily on the positional accuracies of the various axes of the machine, but this is far from the true situation. Without performing further analysis these figures are often the only metrics that potential buyers have to compare different suppliers proposals, but rotational (angular), translational (straightness) and orthogonality (squareness) all play a large part in the accuracy of a machine, not to mention the impacts of thermal, non-rigid or vibrational effects.

Whilst all the sources of variation mentioned above may play a large (and ever increasing, as tolerances tighten) part in machine tool accuracy, the solution proposed in this thesis concentrates only on the geometric errors of the machine tool.

The two commonly used nomenclature standards for machine tool errors are detailed in the following standards:

- ISO 230-1 (9)
- VDI 2617 (56)

Both of these standards attempt to present a standardised way in which errors within a machine tool or Coordinate Measuring Machine (CMM) can be expressed but do not cover all the possible errors displayed by the various possible combinations of axes. The ISO standard seems the least efficient of the two as includes a redundant letter in each error code, the leading "E", making each error E**. For example the designation for the X translational error in the Y direction is "EXY"; the Y translational error in the X direction "EYX". If we take it as a given that we are recording errors relating to a machine tool, the first "E" is not required. Additionally, there exists the possibility of confusion as the error designation for rotational errors is "EXA" for a rotational error of X axis about the X axis. Whilst this is not incorrect, it does allow for possible confusion if an axis is not named according to the standard conventions; if rotational axis A does not in fact lie along the X axis but along Y, at first glance "EAA" would seem to relate to the positional accuracy of A-axis. This should in fact be denoted by EAB in this circumstance. Whilst these unusual namings of axes in machines are not common, the aim of this system is to reduce confusion and mistakes and this method does not support this.

The VDI standard make more efficient use of the available combinations by listing the axis that is moving, the type of error, and the direction of the error, for example, the same two errors described above become "XTY" and "YTX". This is the notation format that will be used throughout this document.

4.6.1 "Internal" errors

Each axis that exists in same three-dimensional Cartesian framework will have the same six "internal" freedoms of movement associated with it, three translational and three rotational, respectively along and about the three perpendicular axes. These six errors are present for each moving axis regardless of what type of axis they are or how they are organised with respect to any others. How these displacements and rotations are measured however differs greatly depending on the type of axis, therefore requiring different measurement procedure to capture the same errors based on the specific machine configuration.

The X, Y and Z-axes can be thought of as the fundamental dimensions of the three-dimensional world that we live in. The axes (for a standard Cartesian machine) will almost certainly lie along one of these virtual axes(X,Y,Z), regardless of what the physical axis is designated in the controller or documentation.

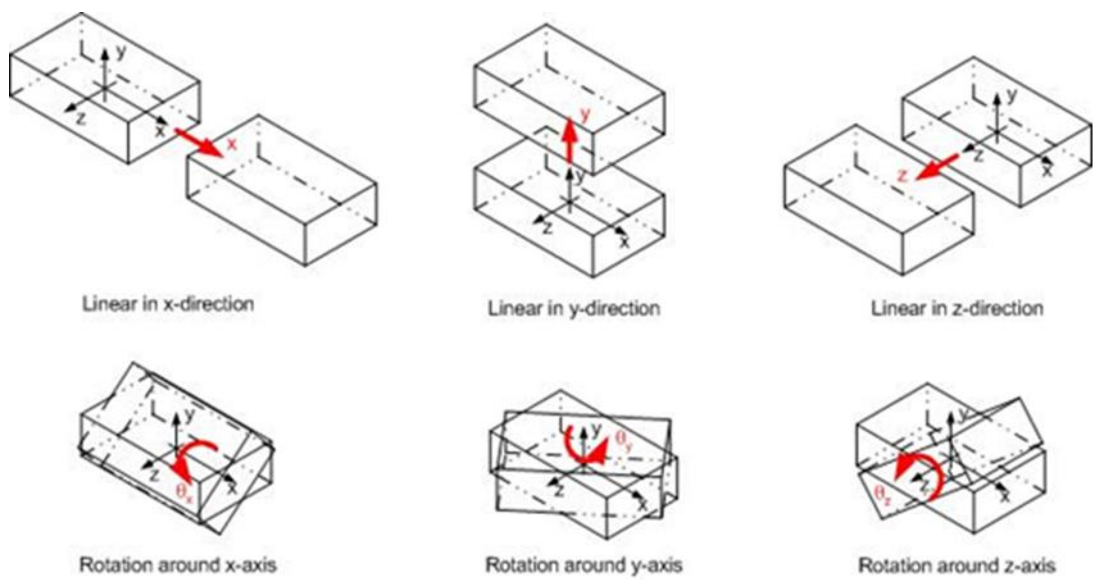

Figure 20: 6 degrees of freedom

4.6.2 Linear axes

As displayed in **Error! Reference source not found.**, a linear axis can have motion errors in any of the ix degrees of freedom as described in the previous section.

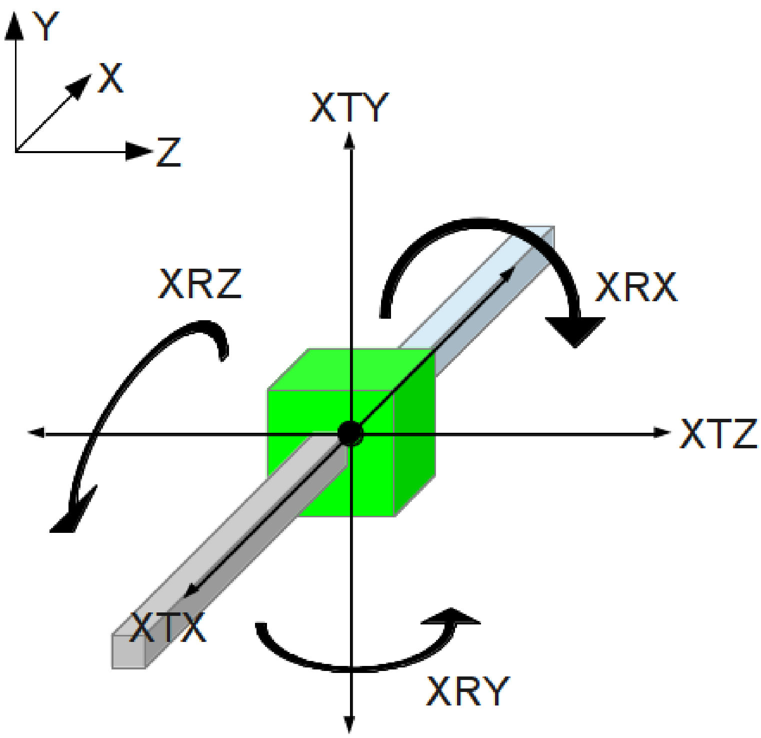

Figure 21: linear axis errors

The error designations in the VDI are as follows:

- "T" – translational error
- "R" – rotational error
- "W" – squareness error between two axes (detailed in the next section)

The geometric errors present for this linear X-axis when considered alone, with their VDI designations and standard interpretations are shown in **Error! Reference source not found.**.

Error designation	Description	Measurements
XTX	X translational error in X	X-axis Positional/Accuracy and Repeatability
XTY	X translational error in Y	X-axis Straightness in Y
XTZ	X translational error in Z	X-axis Straightness in Z
XRX	X rotational error about X	X-axis Roll
XRY	X rotational error about Y	X-axis Yaw
XRZ	X rotational error about Z	X-axis Pitch

Table 2: Linear axis errors

Each linear axis will contain these errors, but whether they are of relevance or not may depend on the machine purpose or axis type. For example the cross axis of a VTL will still exhibit a straightness error in the perpendicular horizontal direction, but this may not be of great importance to the process as the machine is mainly concerned with rotational symmetry which would be relatively unaffected by small errors in this direction.

4.6.2.1 Squareness

If two linear axes are present and perpendicular to each other (required in order to provide movement within a plane), then both axes have the 6 basic errors associated with them along with an additional error – the "Squareness" between them (how close the angle between them is to the true 90 degrees). This error goes by many names in the machine tool industry "perpendicularity," "90 degrees," "normalcy", "squareness" or "orthongonality" to name a few. It is one of the critical aspects of a machine tool if accurate parts are to be produced and can be subject to a large degree of measurement uncertainty due to the fact that the squareness between two linear axes is dependent on the straightness of the same two axes over a specific interval.

If the axes are not orthogonal it means that movement in one of them will produce unintentional movement in the direction of the other axis at the same time, as illustrated in **Error! Reference ource not found.**.

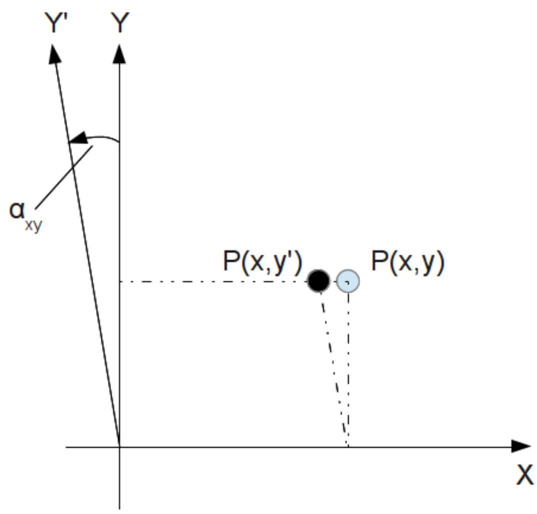

Figure 22: Squareness error effects

- Y is the ideal orientation of the Y-axis
- Y' is the true orientation of the Y axis, including the squareness error
- α_{xy} is the additional angular deviation in the Y-axis due to misalignment or damage
- P(x,y) is the expected location of the programmed point
- P(x,y') is the true location of the programmed point, including the squareness error α_{xy}

The squareness error is given the reference “W” in the VDI standard, meaning that the squareness error between the axes X and Y would be designated “XWY”. Squareness also applies to rotary axes, which is discussed in more detail in a later section.

4.6.2.2 Secondary Axes

Once the three dimensions of movement within our 3D machine are created, the full volume within them can be utilised. Sometimes however, additional linear axes parallel to these primary three are required. This could be in the form of an additional “quill” to project the cutting tool slightly further than the main axis (but at a higher degree of accuracy), or it could be a completely individual axis to allow the addition of a second tool (or even third in the case of the some long bed profiling machines).

These axes may be part of the main axis chain (**Error! Reference source not found.**) or may be part f a separate chain of axes (**Error! Reference source not found.**).

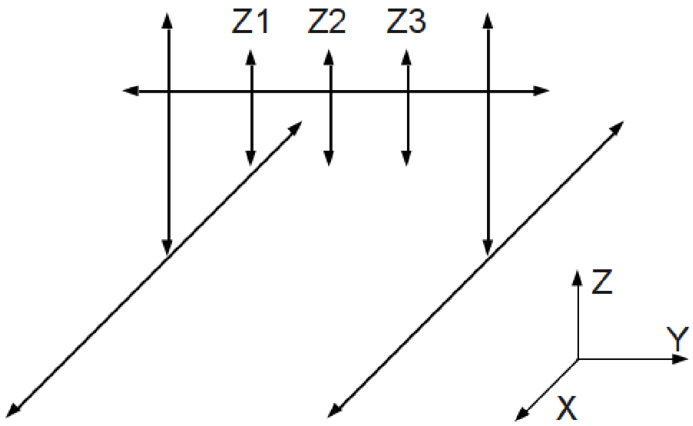

Figure 23: Three secondary axes

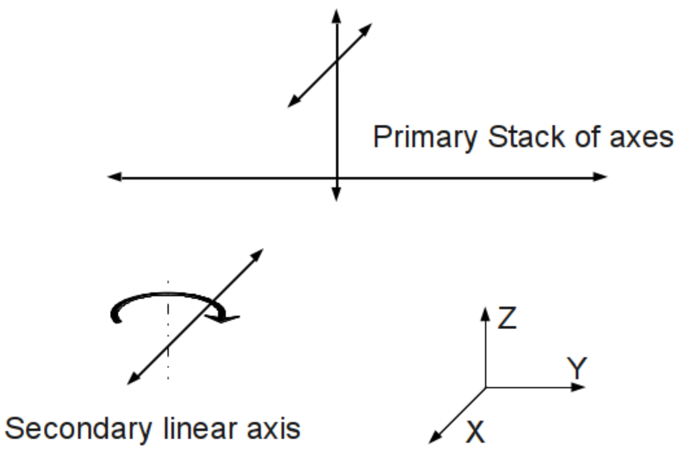

Figure 24: Separate secondary axis

Each additional secondary axis has the six “internal” freedoms of movement associated with it, along with two squareness errors. Depending on the machine’s situation and build type, they can be considered in either of the following ways

- Two parallelism errors – whether the axis is parallel to its “primary” axis of movement in both of the other directions
- Two squareness errors, as with any standard axis. These are the same squarenesses as the axis to which the secondary axis is supposed to be parallel.

Although technically both of these tests are referring to the angle between the axis and the two orthogonal ones, differing methods of measurement may provide benefits in certain circumstances.

4.6.2.3 Linear Totals

For a machine tool with three mutually perpendicular linear axes, this brings us to the familiar 21 errors (6+6+6+3). Adding secondary linear axes, an “X2” axis for example, would increase this number at a rate of 8 additional errors per axis.

Please note that this total of 21 errors does not include the errors or measurements associated with the spindle (or other cutting tools) or the workpiece holding element of the machine which must be addressed to make a full assessment of the machine. These are discussed in a later section.

4.6.3 Rotary Axes

Rotary axes are subject to the same six "internal" errors as linear axes are throughout their motion. These are interpreted slightly differently in terms of their meaning to the machine's capabilities, but the basic errors remain the same, but also introduce an additional three squareness errors. The axis' centreline must be parallel to one of the primary axis in two directions, and the rotary axis must have a starting "zero" position, usually aligned along one of the other primary axes.

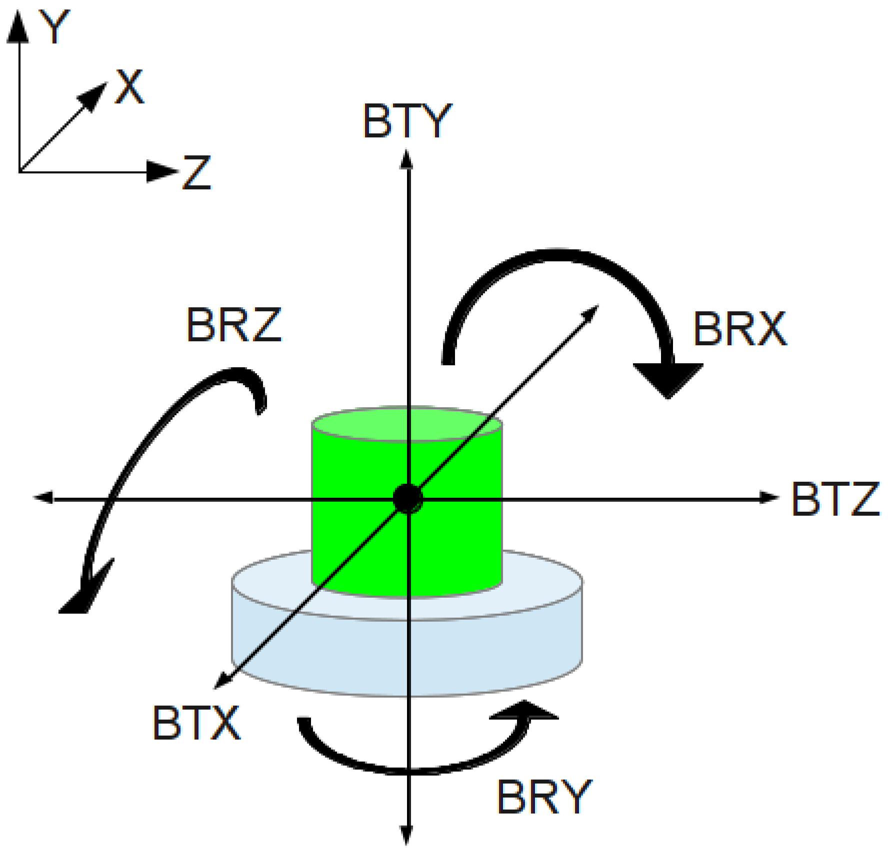

Figure 25: Rotary table internal errors

The explanation and interpretation of the internal errors is given in **Error! Reference source not ound.** below.

Error designation	Description	Measurements
BTX	B translational error in X	B-axis Radial runout in X
BTY	B translational error in Y	B-axis Axial runout in Y
BTZ	B translational error in Z	B-axis Radial runout in Z
BRX	B rotational error about X	B-axis angular deviation about X
BRY	B rotational error about Y	B-axis Positional/Accuracy and Repeatability
BRZ	B rotational error about Z	B-axis angular deviation about Z

Table 3: Rotary axis errors.

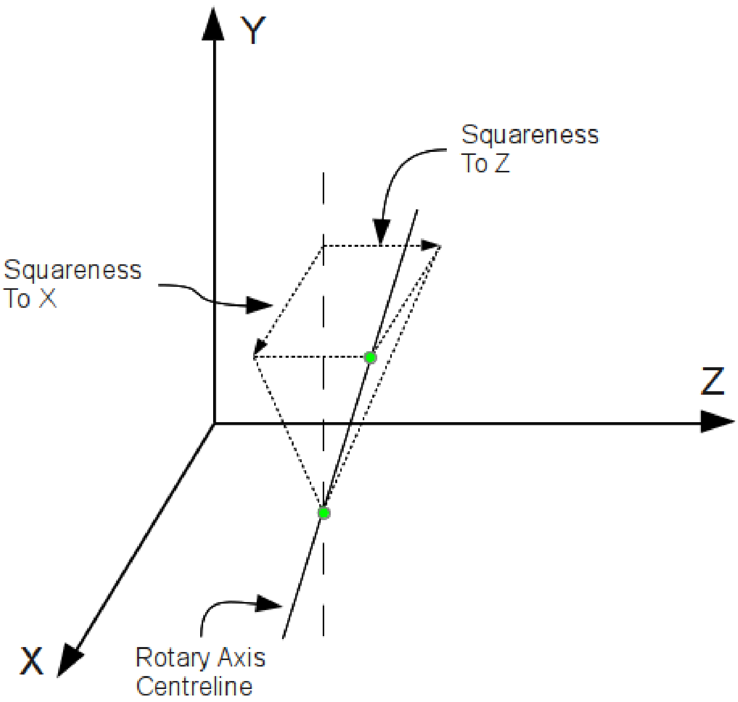

Figure 26: Rotary axis squareness errors

This leads us to a total of nine errors for each rotary axis, in the case of the B-axis above the three extra are added to the previous six:

Error designation	Description	Measurements
BWX	Orthogonality of B centreline to X	B centreline squareness to X
BWY	Accuracy of B starting position	B Zero position
BWZ	Orthogonality of B centreline to Z	B centreline squareness to Y

Table 4: Rotary Squareness description

Additional errors are introduced when the rotary axes are coupled with certain orientations of tools or workpiece interfaces, but these errors are not inherently part of the rotary axis. One example of this is the Rotary Axis Offset discussed in the next section.

4.6.3.1 Rotary axis offset

If a rotary axis is introduced on top of the first, and orientated so that the centrelines are perpendicular, a further error is introduced – the offset distance between the centrelines of these two axes, as displayed in **Error! Reference source not found.** below.

Figure 27: Rotary axis offsets

The identification of this error is important in five-axis machining applications as failure to do so can result in the machine being correctly calibrated whilst the rotary axis is in its home position, but producing a temperamental error during cutting processes as the axis rotates. This error is present in the fork head arrangement and the trunnion table arrangement and can often prove difficult to accurately measure if there is a limited range of movement.

This errors is denoted by the letter "O" in the "COB" format where this indicates the offset error between C and B axes.

4.6.3.2 Concentricity

When dealing with machines that have multiple rotational axes further alignment measurements may be required. If a second rotary axis is present and lies along the same axis as the first, the concentricity of the centres of the two axes should be measured in both perpendicular directions, X and Y in the case of **Error! Reference source not found.**. This arrangement is particularly relevant to athe configurations and the use of a tailstock or steady for supporting longer workpieces.

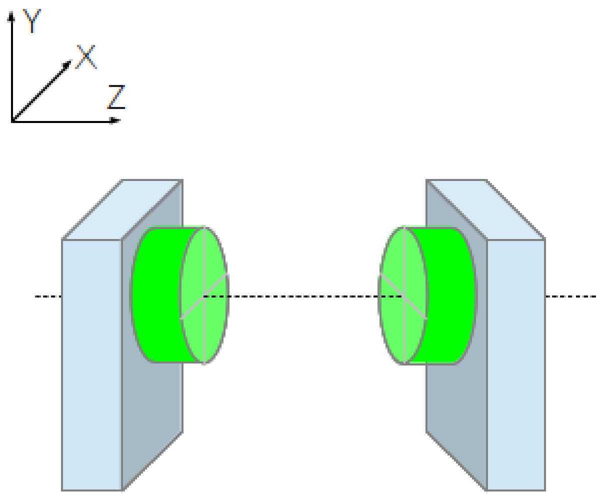

Figure 28: Concentricity

4.6.3.3 "Fork" Head

A common feature in milling machines is the "Fork" Head – called such because the second axis is suspended between the arms of the first like the tines on a two pronged fork. When combined with a milling spindle this produces a large number of possible errors, illustrated in the **Error! Reference ource not found.**.

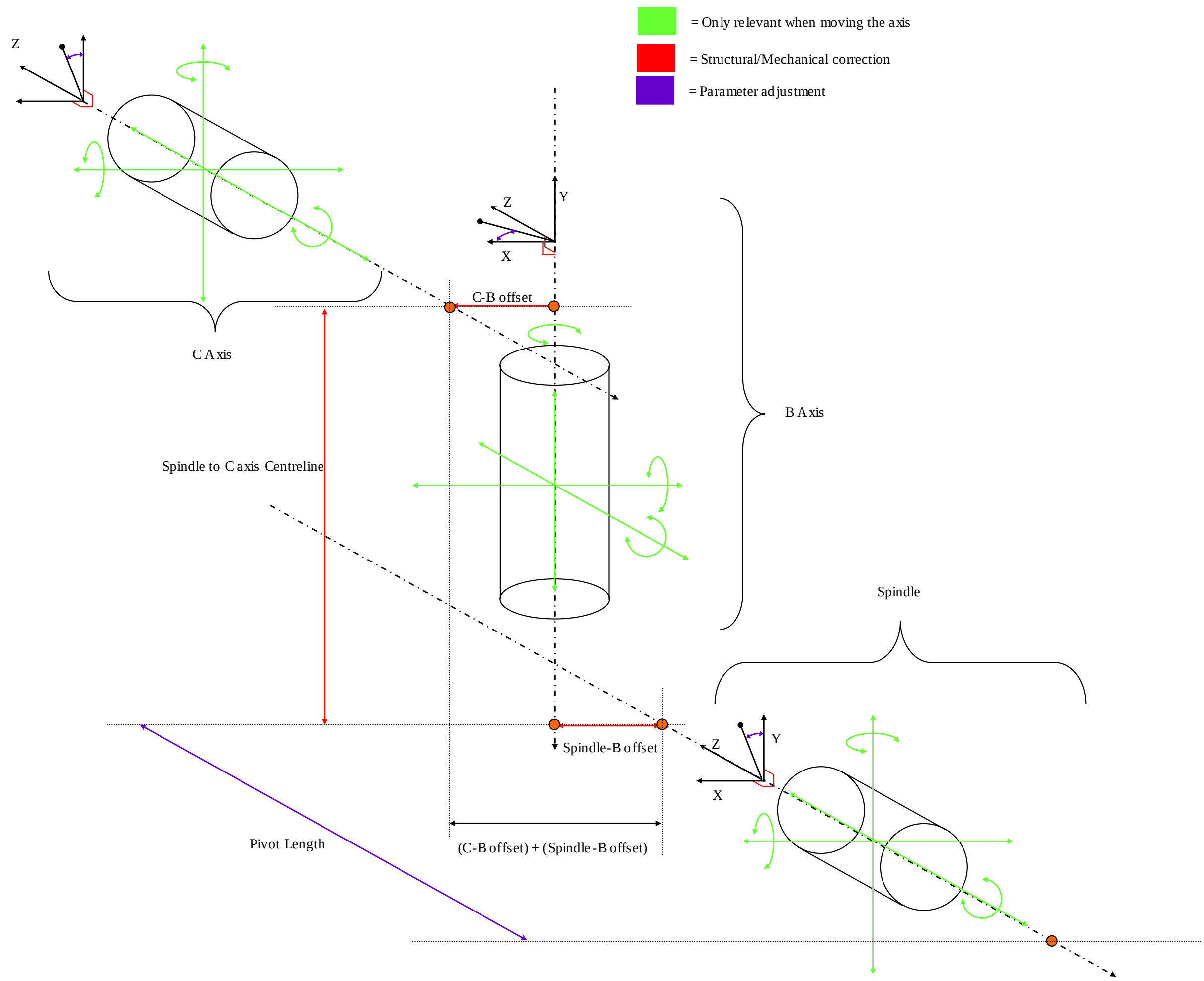

Figure 29: Fork Head errors

This common, but complex combination of axes produces an error count of 31 if all the possible errors are accounted for. These are detailed in **Error! Reference source not found.**.

Error	Description	Error	Description
CTX	C translational error in X	BWY	B Zero position
CTY	C translational error in Y	BWZ	B centreline squareness to Y
CTZ	C translational error in Z	COB	C to B axis offset
CRX	C rotational error about X	SpTX	
CRY	C rotational error about Y	SpTY	
CRZ	C rotational error about Z	SpTZ	
CWX	C centreline squareness to X	SpRX	
CWY	C centreline squareness to Y	SpRY	
CWZ	C Zero position	SpRZ	
BTX	B translational error in X	SpWX	Spindle errors
BTY	B translational error in Y	SpWY	
BTZ	B translational error in Z	SpWZ	
BRX	B rotational error about X	SpOB	
BRY	B rotational error about Y	SpOC	
BRZ	B rotational error about Z	SpPL	
BWX	B centreline squareness to X		

Table 5: Fork head error details

Coupled with the standard 21 errors for a 3 linear axis machine this would give us a total of 52 errors for a 5-axis machine with a spindle. Here “Sp” denotes the rotary Spindle axis.

4.6.4 Interfaces

As discussed earlier, the point where the machine tool contacts the outside world can be called the interface. This could be the tool taper, the chuck of a lathe or the table that supports the workpiece. Each classification of interface has its own unique impact on the machine and introduces unique errors. Because of this, the interface elements will require a small database to manage the different errors and measurement techniques required for each instance. This database was not included in the final system due to stability issues.

4.6.4.1 Pivot Length

This is not a property of the rotary axis itself, but of the combination of the rotary axis and (in the case of the "fork head" arrangement in **Error! Reference source not found.**) the face of the spindle aper.

This is the offset distance from the centreline of the perpendicular rotary axis, to the spindle face that the tool will interface with. This parameter is important in contouring applications and must be carefully calculated to correctly inform the machine of the effective length of the tool.

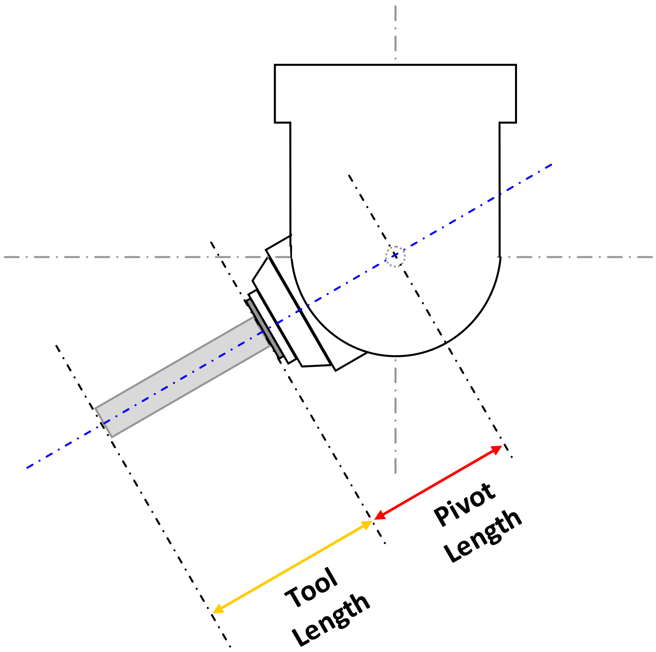

Figure 30: "Fork Head" Pivot Length

This type of error is also present when a table is positioned so that its surface plane is parallel to the axis of rotation, as shown in **Error! Reference source not found.**.

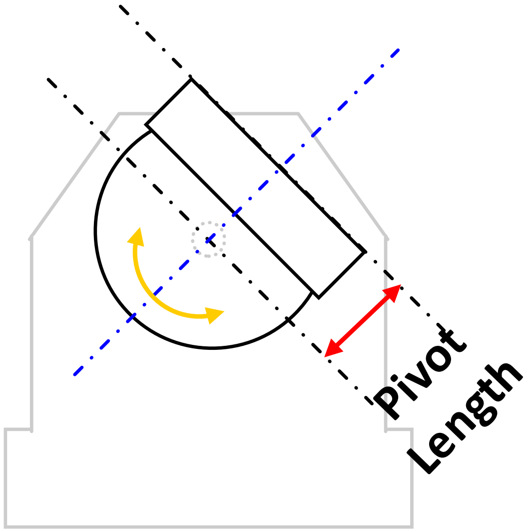

Figure 31: Rotary table Pivot length

The pivot point can be either in front of the tool/face or behind it, giving either a +ve or –ve pivot length.

4.6.4.2 Spindle Taper

The spindle taper is the interface between the tooling and the rotating spindle. At present the spindle taper test is to measure the surface deviation with a mechanical dial test indicator (DTI) by contacting it into the inner face of the spindle.

4.6.4.3 Table flatness

Table flatness is a property of machining tables, usually found in milling or boring type machines. The table surface is measured in a grid-like pattern as shown in **Error! Reference source not found.**, aken from the ISO-230: Part 1 standard.

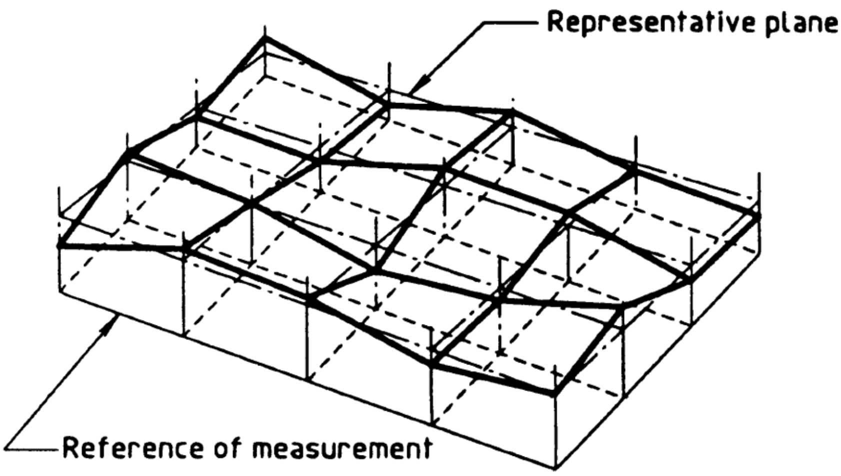

Figure 32: Table flatness (9)

5 Problem definition and industrial background

As high-accuracy machine tools have become the norm in modern machine shops, the owner's reliance on these tools to perform as they have been advertised has grown. As the complexity of these machines has increased, the ability to fully understand the errors contained within them (and the effects of these) has decreased. In order to fill this gap, the calibration houses and the machine tool service industry have provided facilities to measure these machines and deliver detailed calibration reports to the owners. This in turn has led to much time and effort being invested in the business of producing these metrology and calibration reports quickly and, importantly, to a high and repeatable standard.

Due to the varying skills, training, backgrounds and opinions of different organisations and individuals, asking the same "question" about a machine tool's accuracy and degrees of freedom will often result in different "answers", given the same starting conditions.

The sources of these deviations can often be traced back to simple sources, and do not necessarily result in any detriment to the end user. For example, an engineer with a more Coordinate Measurement Machine (CMM) background may advocate a laser interferometer system to measure angular pitch of a linear axis, whereas an engineer with a more machine installation related background might advocate the use of precision electronic levels to take the same measurements. Both of these approaches will provide the ability to perform the required measurements and both may perform to the accuracy standards required by the customer.

When it comes to deciding what measurements to perform in the first place however, there should not be any variation in what the potential errors within the machine are. The freedoms of movement of each axis, or combination of axes, are described by the three-dimensional coordinate system of the real world. Therefore, using a systematic approach, a single unambiguous answer should be obtainable for each configuration of axes. From this point, the methods used to measure these movement errors can differ, but they must be able to provide numerical results for each of the specified error movements. Driven by the manufacturing industries increasing drive for reliable information, this where the difficult process of converting this *Tacit knowledge* embedded in the experienced individuals into *Explicit knowledge*, documentable and distributable, is first encountered.

5.1 Metrology analysis process

During a placement with a leading machine tool service organisation it was possible to gain a lot of insight into the methods and systems used to create the necessary calibration and service reports and the problems and issues they encounter on a daily basis.

The service provided by the organisation was to examine any machine and produce a report detailing the mechanical, electrical and metrological issues that may be affecting production. Targeted repairs are then carried out, at the customer's discretion, in line with the suggested repair plan constructed from the reported findings.

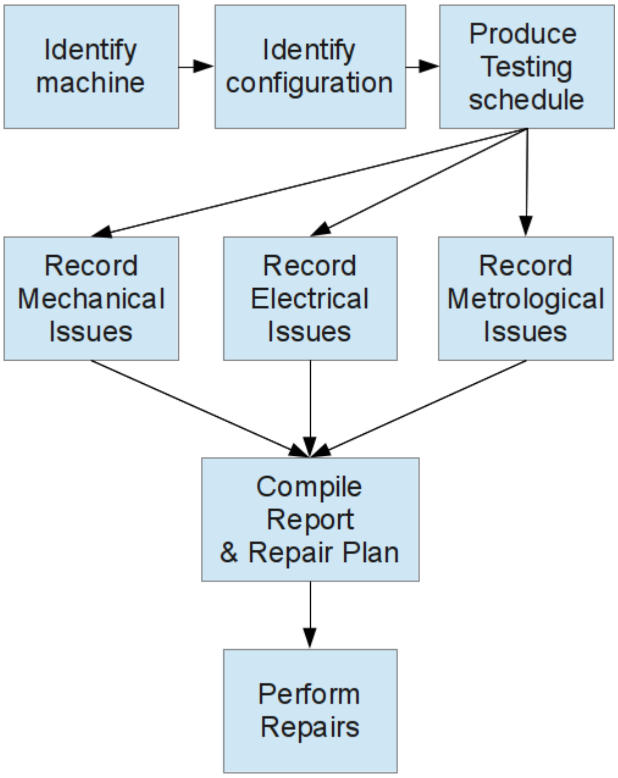

Figure 33: Process flow

Something that quickly became evident was the fact that each machine visit was treated as a unique product. This meant that a largely fresh set of documentation was created for each service activity with little interchange-ability between calibration reports for different machines of similar characteristics. The primary cause for this was the highly manual nature of the system and lack of a structured data management system and document control. One of the other largest areas of interest was the transmission of data between each of the stages in the system. At each of these, the lack of a formal data storage or transmission format meant that communication errors could be introduced, rendering all following outputs either inefficiently or incorrect.

During the investigation, methods of improving efficiency were identified throughout the system, the main areas of which are addressed in the following sections.

5.1.1 Machine identification

The initial machine identification step (where the correct target machine is physically located), whilst seemingly simple, and usually completed without issue, has the possibility for extremely detrimental mistakes to be introduced. As an example, if multiple similar or identical machines are being assessed as part of a machining cell, unless each machine is assigned a unique identifier, there is the possibility that work could be carried out, or corrections applied, to the wrong machine. This problem becomes more critical if different engineers are working on the repair actions than were assigned to the initial measurement procedures. This could not only create the situation where a machine is not corrected to the levels required by the owner, but also that another machine may be rendered unfit for production by having the wrong compensation values applied to it. This situation mainly arises due to the differences in asset naming procedures used by different companies, coupled with a loosely applied machine detail collection process.

5.1.2 Metrology Index

After machine identification issues, one of the most significant and time consuming issues was the problem of variation of the test schedules for machines over time. This was highlighted by the periodic re-examination of “Metrology Index” (MI) associated with machines as they were subject to annual recalibrations. The term “Metrology index” refers to the “master list” of tests that were performed, or should be performed on each machine as part of the in-depth audit.

During the research, the MIs of machines that had been previously calibrated were periodically re-checked during creation of fresh reports to ensure that mistakes had not been recorded at earlier stages. This was performed to ensure the correct machine was being assessed, but occasionally fresh information (possibly contradictory), from a different attending engineer perhaps, meant that all the information about the machine had to be re-examined, updated, or extended. At this point it was discovered that although the MI was recorded for each machine, at no point was the fine detail regarding the machine’s definitive axis configuration recorded. The consequence of this was that unless the methods of test that were being used were completely understood by the members of staff creating the reports, and able to be deconstructed, verifying that the correct configuration had been recorded, or was even that the correct machine was being worked on, could prove difficult and time consuming.

In most cases, the machine configuration could be recovered from the machine details, MI, and machine diagrams, but these were not always free from the errors or contradictions. In these situations the next course of action was often to attempt to retrieve the information from the engineers who had been attending the site, but if they were unavailable, or provided unreliable information, the only suitable solution was often a re-visit to the machine, which was an extremely costly procedure in both time and financial terms.

The typically observed method of producing a MI and measurement templates adhered the following steps:

1. Communicate with on-site engineer to extract the machine configuration. Typically involving a description of an accepted machine configuration such as “Vertical machining centre” or “Side borer” with additional axes.
2. Document configuration in some format, typically with simple line diagram or brief machine description.
3. Deliver machine configuration to Metrology analyst via either email or verbally.
4. The MI would then be produced by Metrology Analyst
5. The MI would then be delivered to report assembly team
6. Report team would then create measurement templates as dictated by MI
7. Measurement templates delivered to engineers for completion

Between steps three and seven a significant number of man-hours (from 4 up to a possible 20, depending on the complexity of the machine) could be spent constructing the unique set of documents for the machine in question. This can create a number of issues as, from the outline above, it can be seen that the only contact with the field-based engineers, who were actually in contact with the machine, is at the very beginning and end of the process.

Often, communication errors at stage 1 were not identified until stage 7 when the measurement templates are returned to the engineers. This could render a large portion of the work incorrect and the whole process must be restarted. Alternatively, engineers could correct the mistakes in the field and return the measurement templates with or without additional notification of the changes. In this scenario, the alterations made by the engineers may not be noticed until additional processing has been carried out on the data. Whilst this would provide a corrected document, it could result in further wasted time as subsequent documentation, based on the original erroneous data, was now incorrect.

Under closer inspection it was found that the MI for numerous machines had often evolved over a number of re-visits depending on a number of reasons:

- Customer requests
- Availability of new measurement equipment
- Correction of errors within previous work
- Numerous other reasons

Whilst the alteration of the test schedule to fit customer, time, or equipment constraints is perfectly valid, this introduced secondary problems when we consider that these test schedules were also functioning as a machine description. This apparent alteration of machine configuration has the effect of making time-based comparisons of machine condition difficult or impossible, as we cannot be certain that the readings taken at different times are indeed comparable and introduces doubt surrounding the previous work if further identification details proved insufficient.

The consequence of this is that any comparison of measurement, from yearly reports for example, would again be an entirely manual process with either non-repeated measurement omitted (losing possibly important data) or including empty data fields, highlighting the fact that the number of measurements had changed, or not been completed (therefore prompting further questions from the customer). This meant that any attempts to plot the degradation of a whole machine, or individual aspect of, over time was not possible without a substantial amount of additional effort. As an example, the relatively simple task of plotting the variation between a pre and post repair calibration and verification for a single machine could take upwards of 5 hours for a relatively simple machine configuration, or anything up to 16 hours for a complex machine with incomplete data sets.

5.1.3 Data formats

The format in which the data was recorded and stored provided a further area for investigation. Historically machine tool calibration data was often recorded on manufacturer supplied paper templates and stored either with the machine or with the maintenance department. As this is impractical when dealing with a nationwide network of service engineers, electronic equivalents had been created in Microsoft Word. Whilst these provided the ability to transfer the measurements to the central office efficiently and allowed paper copies to be easily created, this caused additional problems in later stages.

In order for the experienced analysts to make efficient use of the measurement data recovered from the service activities, it was processed into multiple summary documents. Unfortunately, as the measurements were recorded as plain text within Word documents, the data contained in the measurement reports remained almost as inaccessible as though it was on paper. This resulted in a large amount of time being devoted to manually transcribing the measurements into the summary documentation and manual checking of the values against the prearranged tolerances. Not only does this take up a considerable amount of time, but also introduces the very real possibility of human error into the system. Whilst there are methods that can be employed to minimise the errors introduced by manual data inputting, these can drastically increase the processing time required to complete the tasks (57) - something that is not usually available in time critical, machine tool service environments.

5.1.4 Tolerances

Throughout the measurement procedure we must not lose sight of the end-goal of the procedure; to measure and qualify the machine tool against a set of pre-defined criteria. Simply measuring a machine and presenting a set of numbers is often a waste of extremely valuable machine downtime. Is 73 microns of deviation acceptable or should it be cause for alarm? Is this a large deviation from a previous reading? In order to draw useful conclusions about a machine's condition, it is necessary to know what levels of accuracy it is expected to perform at. If the tightest tolerance the machine is expected to function at is +/-500µm, a deviation of 73µm is well within tolerance. However if the machine is expected to be accurate down to +/-5µm, this is cause for alarm. Because of this requirement to perform numerical comparisons on the measurements, an additional consequence of the inaccessible format of the data became apparent when attempting to manually apply the process tolerances to the measurement data.

The need for tolerances to be available and compatible with the measurements that are taken was highlighted when multiple measurements were found to be measuring the same error in the machine's geometry. Although the measurements were presenting the same data regarding the particular errors, the units they were recorded in, and subsequently the tolerances that were applied to them, were different. Comparing the duplicate sets of measurement was further complicated by the need to manually convert between different measurement units each time a comparison or conversion was required.

5.1.5 Measurement methods

Because of the format the measurement procedures and methods were stored in, editing procedures or diagrams to more closely match the machine in question, or correct errors in the procedure, was possible for both office staff and field engineers. Whilst this meant that often the measurement procedures were more tailored to each machine, it had the unfortunate consequence of greatly increasing the time required to create the measurement documents as they could not be generated from a central template database. Additionally this conflicted with any attempts to instigate a document control system or register as the numbers of minor variations of each basic template were very large.

5.2 Common Sources of Variation and Uncertainty in Machine Tool Measurements

When looking at a machine tool assessment as a whole, there are many areas that can and do contribute to uncertainty in the final outcome. The ISO 230 (9) standards and The Guide to the Expression of Uncertainty in Measurement (GUM) (39) have laid out a number of best practices when it comes to taking individual measurements of an axis' straightness or angular deviation for example, but how do we go about deciding what measurements are needed in the first place? The aforementioned standards have detailed examinations of various individual parts of a machine, but not the whole and varied combination encountered today.

The component axes of a machine tool, combined with simple mechanics, dictate what movements the machine can perform. Mechanics dictates that, within a three-dimensional space, each linear and rotary axis is subject to a finite number of freedoms of movement. Therefore, deciding the freedoms of movement for the machine as a whole, and subsequently the measurements required, are specific to each machine. The process for calculating this should be able to provide a unique answer for each configuration of machine.

Once it has been decided what measurements are required for the machine in question, there are still many factors that can affect the measurements themselves. Whilst dealing with these influences directly is not the main focus of this investigation, ways to minimise or measure their effects can be considered within the system.

5.2.1 Environmental

Environmental factors can have subtle but important effects of measurements that become more and more important as the scale of the measured errors decreases. One of the greatest challenges to modern high accuracy machine tools is temperature variation during operation. Even when not performing cutting tasks, temperature can affect almost all aspects of a machines geometry and any measurement equipment that is operating on or near it. As production tools chase single or even sub-micron accuracies, factors such as internal and external vibrations, localised air turbulence, humidity and pressure or even old fashioned dirt can all play their part in drastically increasing the uncertainty associated with a measurement. Whilst it may not be possible to completely control many of these factors, it is often acceptable to record them and compensate for their effects using mathematical models.

5.2.2 Process

As discussed previously, the existing standards provide good techniques and best practices for taking any or all measurements that may be required when diagnosing a machine tools problems, or qualifying its condition for production. These guides however require a large amount of background knowledge to be fully understood and implemented. The time and financial investment required to bring all the staff that may be required to take measurements may simply not be feasible in many situations, so, where the situation allows, can lead to the creation of metrology departments (37). Metrology departments however, are still subject to the same human and resource limitations as all others so cannot be everywhere at all times. This can lead to the delegation of less technical tasks to other staff members or departments, and re-opens the door to uncertainty.

One answer to this is to have a specialist create in-house procedure documents that can be distributed and followed each time a measurement of this type needs to be taken. If all the influences that are likely to have an impact on the measurement are addressed by the approved method of test (and subsequently recorded) they can be monitored along with the critical measurement itself.

This does not mean that a comprehensive method of test is a suitable replacement for a skilled metrologist, but it does mean that some of the more day to day monitoring tasks can be delegated to other members of staff with a reduced risk. Without a suitable analysis and tolerancing structure in place however, the entire captured data set will still have to be reviewed by the appropriate personnel.

5.2.3 Human

The engineer or technician carrying out the measurements is another potentially large source of measurement error, as discussed in the "GUM" (39). To combat this, an in-depth understanding of measurement, uncertainty, and machine tool geometry can be given to the people that require it. Unfortunately, although training members of staff in the relevant techniques can allow them to perform more complex measurements or use new equipment, it often comes at a large additional cost in both financial terms and lost time. Additionally, this will not entirely guarantee the consistency of the measurements taken by different people, even though they are both now trained in the same techniques (57).

The use of approved procedures and documented data recording practices was used to help reduce these variations, but high quality training and a good understanding of the principles that are being applied are still required if situations outside the current documentation are likely to be encountered.

An additional area of interest with human operators is that of data transfer; Communication. Even when dealing with highly trained and experienced staff, communication errors are possible, and were found to be relatively common. Time constraints, differing experience levels, background noise, and even illness can influence how well a machine's description is conveyed over the phone from an engineer. Photographs helped to alleviate the situation somewhat, but there is still a lot of room for interpretation without observing the machine proceed through its full range of motion. This is an area of great concern when efficiency is important, as an incorrectly described machine can cost a large amount of time depending on how far through the process the mistake is noticed. If it is picked up at an early stage – when a basic diagram is constructed for verification – only tens of minutes may be lost. If the error goes unnoticed until a full suite of test diagrams, methods and data capture sheets are created, potentially days' worth of work may have been wasted.

A common format for recording the machine configuration would at worst reduce, and at best eradicate errors of this type, improving overall system efficiency and traceability.

5.2.4 Equipment

As technology progresses at ever increasing rates the range of measurement equipment available is increasing quickly. Traditional methods such as granite straightedges coupled with a DTI or high precision levels are still widely used and are the only options in certain circumstances, but there are now many additional options. Laser tracers such as the Etalon can fully map the entire three dimensional volume of a machine to a high degree of accuracy, but incur a very high initial investment cost. Laser interferometer systems such as the Renishaw XL-80 or Agilent Laser Interferometer system can provide very detailed information about individual axes, but take larger amounts of post-processing to provide a volumetric analysis of a machine.

One of the major benefits of the digital systems over the analogue counterparts is that the data capture process does not involve the human operator directly, therefore removes the potential to introduce human error when physically reading or recording results.

5.3 Traceability and document control

As the pressures on manufacturing industries to increase their efficiencies and their flexibility grow, the requirement for traceable measurement and maintenance techniques has come to the forefront. This has been driven by the need to understand the systems in use and be able to trace sources of mistakes or inefficiencies.

Traceability of measurements is becoming a key aspect of many areas in machine tool production and maintenance. If clients request a certain manufacturing accuracy tolerance, how can they be assured that the reported measurements are accurate? If the organisation is attempting to reduce production part variability, how can they be assured that variance in repeated measurements cannot be attributed to measurement errors or method variation? If the production facilities are attempting to implement a preventative maintenance system to reduce downtime and maintenance costs, how can they be assured that the drift in measured errors is not attributable to measurement error or equipment degradation? These factors, amongst many others, are highlighted by W. Knapp (8).

Ensuring that measurements, methods and equipment calibrations are traceable back to national or international standards is a key aspect in all these situations and services to these ends are provided by various calibration establishments around the country.

Traceability can also be applied to supply chains where documentation and control are required for each step in the production chain. This can be a distinct advantage to organisations, as the more information that is available about a process, the more control you have.

As an example, the system to track the progress of report production within the host organisation can be used.

In order to track the progress of reports prior to their delivery to customers a spreadsheet was used to record basic information relating to the machine in question. Whilst general information was recorded, such as the organisation the machine was owned by, a serial number for the machine, and the stage of completion that the report was presently at, only the most recent version of the data was retained. This meant that efficiency figures that could be used to track down bottlenecks in the report processing could not be identified, and improvements were not made. Additionally, various different types of identification could be used to identify the machine tool in question, but what type of ID was recorded was not known. This presented a problem when different organisations may monitor machines by the manufacturers serial number, an independently assigned internal ID number, a model number, or a combination of these and more.

Similarly, if a MI is composed for a machine with specific customer requests taken into account, this then becomes the default test list for all future reports on the same machine. If for example the requests are to remove a number of measurements in order to save time, this reduced number will be used for the next measurement cycle even though there may be enough time for a full suite of tests. This is because there was no procedure in place to record both the full metrology index and the amended one with the reasons for the additions/alterations.

The combination of these and other issues led to the situation where data was frequently lost or its reliability called into question, limiting the ability to analyse and improve the system.

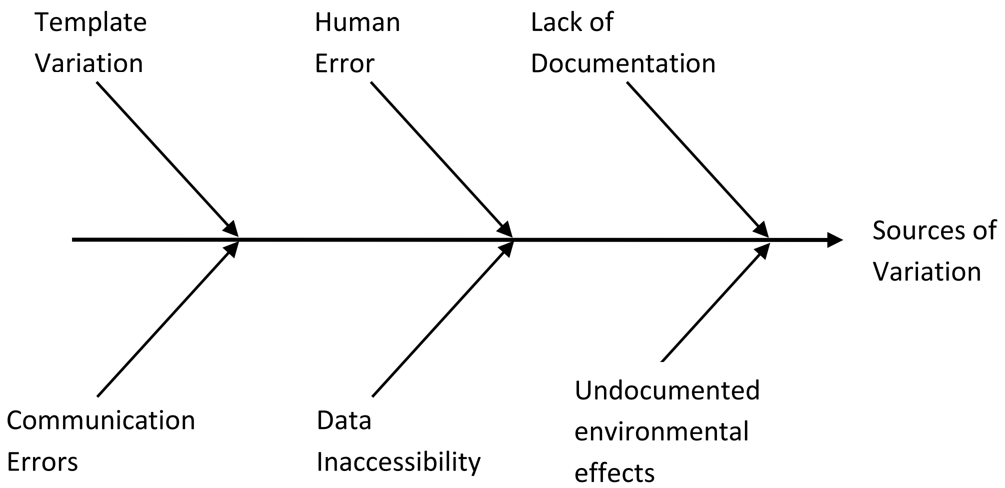

Figure 34: Sources of variation

6 A framework for implementing ongoing improvements in an industrial setting

Throughout the research project a number of improvements were proposed and implemented based on the findings of the report. The impacts of both the improvements that were implemented and those that have yet to be released are discussed in the following sections. Through these improved data capture and storage methods large improvements both internally and externally to the organisation were achieved.

In order to provide the best possible service to the customer, fast, reliable and consistent access to measurement data is crucial. If widely available, this would allow deeper integration into existing preventative maintenance programs and allow the machine shops to further improve their production accuracy. This, in turn, could further assist in securing additional business for the organisation, and free up large amounts of internal human resources to work on additional projects.

Multiple improvements were implemented throughout the course of the research project, with further scope for improvement remaining. The individual improvements and their benefits, both direct and indirect, are discussed here

6.1 Document tracking and traceability

As discussed previously, the lack of information relating to processing times meant that uncovering bottlenecks in the report processing system was a difficult task. To this end, a system to track the progress of reports through the different stages, and provide the information required for successful delivery was developed and implemented. When working in situations that demand high levels of confidence, the benefits provided by a fully robust and traceable system far outweigh the costs.

Benefits:

- Standardised methods and documentation – lower variability between measurements
- Improved change management
- Greater confidence in equipment and results
- Systems can quickly be analysed

Costs:

- Additional overheads
- Changes can take longer to implement
- Reduced flexibility

By recording (and importantly, retaining) the times and dates when the various stages of report processing were completed, and by whom, the slowest areas of the system were able to be identified and addressed. An additional benefit of the improved tracking system was the standardisation of the various machine records, allowing the machine identification data to be correctly categorised and stored. This reduced the number of mistakes associated with incorrect or incomplete machine record selection as the differing identification formats used by different organisations could now be accommodated separately.

6.2 Data extraction algorithm

After the on-site measurements and data capture was completed, as highlighted earlier, one of the most time-consuming processes was the transcription of the raw data into more condensed documents. Because of this, one of the first changes to be implemented was the introduction of a basic “find-and-extract” algorithm to parse the relevant parts of the main report and produce the summary document.

This was relatively limited in the initial stages, as there was a large degree of variation within the source data documents. The same results could be displayed in the arrangement shown in Table 6, but also in the arrangement shown in Table 7. Additionally, the results may or may not contain the measurement units as part of the reading (Table 7) or as a specified format for all related measurements (Table 6), or as a (potentially contradictory) combination of both. The system had to be able to locate key markers (often the word “result(s)”) followed by a set sequence of text or cell contents. Multiple try/catch routines were attempted to match to a known configurations and keywords for data extraction before moving on to the next “results” location. This initial version was also designed with caution in mind, as data transcription errors introduced by software mistakes would have a far greater consequence than the existing delays caused by human intervention. To this end, the system was designed to alert the user when data was incorrectly formatted or located, rather than produce an answer that may be incorrect, allowing the operator to manually find the missing values and correct the summary document.

Results (MM)		
Position	**A**	**B**
Reading	0.010	0.015

Table 6: Data format example 1

Results			
A	**0.010mm**	**B**	**0.015**

Table 7: Data format example 2

This initial implementation, even including the errors requiring human intervention, saved large amounts of time for each report produced. For smaller reports (simple 3 axis machines for example) with 20-30 tests, the time required to produce the metrology summary regularly decreased from 1-2 hours, down to 10-15 minutes, including corrections for omissions and formatting errors introduced by the program resulting in a saving of 75-83%. For reports on larger machines (6 axes +) with upwards of 80 tests, the time required regularly decreased from 4 hours per report (or potentially more) due to the large number of 3 decimal place numbers to transcribe, down to 15-20 minutes, resulting in a saving of 91-94%. Unfortunately, it is quite difficult to attach exact figures to the time savings for all reports as, in the initial formats at least, each report was unique and the number of errors introduced by the human based copying technique was extremely varied.

6.3 Template standardisation

The next stage of improvements was aimed to address the source of the variation that limited the data extraction program – the large variation in document content, layout and construction. The task of migrating the basic documents used to produce data capture templates away from the unique, initial "hand-crafted" format to one that could be created, navigated and edited programmatically was time consuming, and could potentially have affected a large number of users throughout the organisation. The direct benefits of this conversion, as with the standardisation of machine tool parts at the birth of mass production (14), are reduced design time and increased interchangeability.

One requirement was that externally, the layout and function of the original documents was to be retained, but the underlying structure could be re-written. This was accomplished by basing all the new documents on the "table" element within the Word documents. This allowed the outward look and feel of the documents to be retained, but meant that instead of each machine requiring the re-use of the previous year's uniquely customised documents, the relevant data could be inserted into blank, standard framework, documents using automated routines.

During this process commonality between documents was identified and the number of template documents drastically reduced. For example, the measurement of a linear axis with a laser interferometer required a specific measurement document template. As there was a high probability that any machine encountered would have a least two of the three axes named X,Y and Z, previously, a complete suite of documentation had been generated for each permutation of these axes; X vertical, Y front to back, Z left to right; Y vertical, etc. If only two axes were required, the documents relating to the other could be quickly removed, but of differently named or orientated axes were encountered, a large amount of time was required to adapt the templates to the new layout. This led to the situation where there were six fully compiled sets of documents for all the possible arrangements of these three axes with only minor text variations between them.

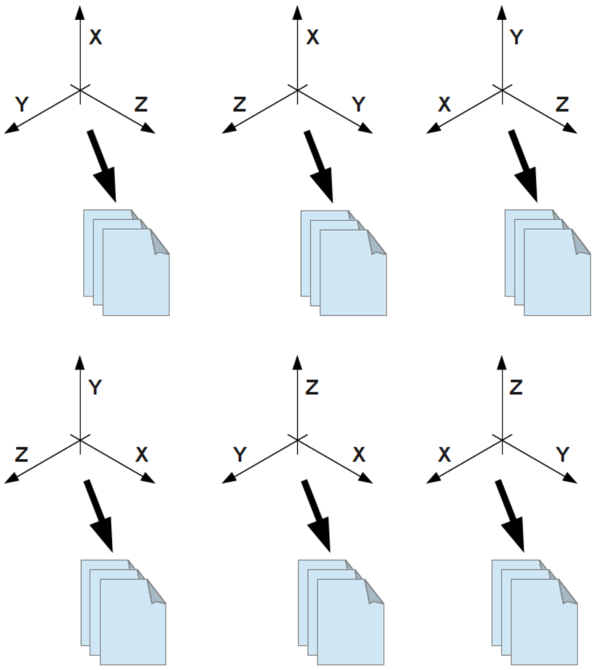

Figure 35: Multiple unique documents

After examining the variations between the documents a common template set was designed, and a report generation program created to populate them based on the users inputs. This approach reduced the number of documents for two linear measurements (a single bidirectional positional test and a 5x-bidirectional accuracy and repeatability test) and two angular tests per axis from 72 fully completed documents, down to three document templates. These three templates could then be automatically populated with the relevant data to create all the required arrangements of axes with little human interaction and no errors.

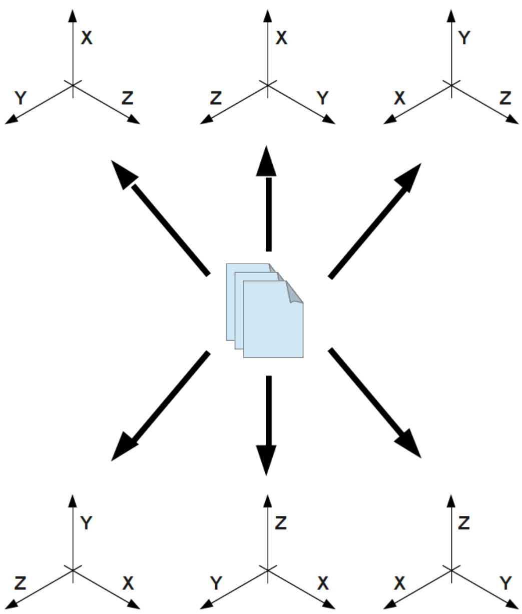

Figure 36: Single source template

There were number of additional benefits to this approach when applied to the wider system:

- Enhanced document control
  - Reduced burden on human resources as changes only need to be applied to a small number of templates rather than a large suite of documents
  - Reduced the number of mistakes present throughout the system due to human error, as any alterations are only made once, rather than repeated numerous times
  - The creation of the template documents allowed a basic version control and change-log system to be implemented, further reducing mistakes and duplications, and allowing improvements to be assessed and discussed before implementing
- Enhanced document design and quality control
  - Additional free time for the system maintainers allowed more resources to be applied to the quality checking and document design, rather than maintaining the collections

After demonstrating the advantages and compatibility of the new system, the upgrade process was extended to the rest of the documents commonly involved in report creation resulting in wider time savings and virtually eliminating typing errors.

6.4 Data collection template assembler

The implementation of the standardised template format and the reduction of the number of unneeded variations allowed the creation of a system to allow automatic assembly of the most common reports. This was achieved by creating an Excel based input form in which the required measurement templates could be selected and the machine's basic details entered. One direct and instant benefit was that it removed the need for human operators to enter the machine's details on each page (manufacturer, owner, serial number) and therefore eliminated the problem of data contamination caused by incomplete removal of data from the report that the documents may have been initially extracted from. Whilst this may seem a relatively minor error as it does not directly affect the measurements, it could previously have led to embarrassing situations when customers notice incorrect machine details in reports and raise further questions, or could even led to the exposure of sensitive data, depending on the report the original documents were taken from.

Once the document components were selected and the machine details entered, the program would then compile these templates (combined with the axis details relevant to the measurements) into complete documents fit for delivery to engineers.

The implementation of the report-generating program reduced the time required to compile a blank report for delivery to the service engineer from 4-20 hours, down to 7-10 minutes where the common templates were applicable. Aside from reducing the time demands on the office staff by up to 99% and effectively eliminating transcription and data entry errors, this had a number of additional benefits

- Lower machine configuration error rate; On-site engineers could now identify any issues with the machine configuration much more rapidly and report them back to the office before further time was lost

- Reduction or elimination of on-site time wastage; Engineers no longer delayed by waiting for documentation from the office, saving valuable on-site time (machine downtime)

- Reduced persistent error rate; Engineers were much more likely to highlight errors (small or large) as they no longer had additional delays to be concerned about, nor had to worry about upsetting the office staff as large amounts of time could have previously been wasted creating incorrect reports.

6.5 Data processing program – Second implementation

The introduction of version controlled template documents combined with the improved underlying structure of the documents meant that it was possible for a more advanced data extraction program to be developed. The contents of the table cells (where the relevant data was stored in text strings) were now accessible through an easily accessible document element (the ".table" element in the Word 2007/10 format), in a sequential numerical order, rather than a varying depth and order combination using graphical objects with several other objects embedded within them.

Another immediate benefit of this was that the number of cells in the table could now uniquely identify each template structure. Combined with the knowledge that the structure of the document was now unlikely to change from report to report (without prior notification) this meant that the cells containing the relevant data could be accessed directly without an extensive, and error prone, text parsing routine. Once the data extraction algorithm was re-designed to recognise specific template formats no further analysis was required to locate the relevant information within the document. This in turn meant that the length of cpu time required to run the data extraction and manipulation algorithm was drastically reduced, along with a much higher degree of confidence in the extracted data. This second version of the data extraction routine further reduced both the time required to produce the metrology summary documents (compared to the initial situation) and the errors present in the document.

The changes brought about by the incremental improvements altered the machine tool data processing and reporting system from the structure shown in the “Original System” in Figure 37 to the structure shown in “Updated System”. The work presented in the following sections attempts to automate the first two steps of the system, with a view to eventually limiting human interaction to data capture, template design, and decision making tasks in order to minimise the introduction of human error.

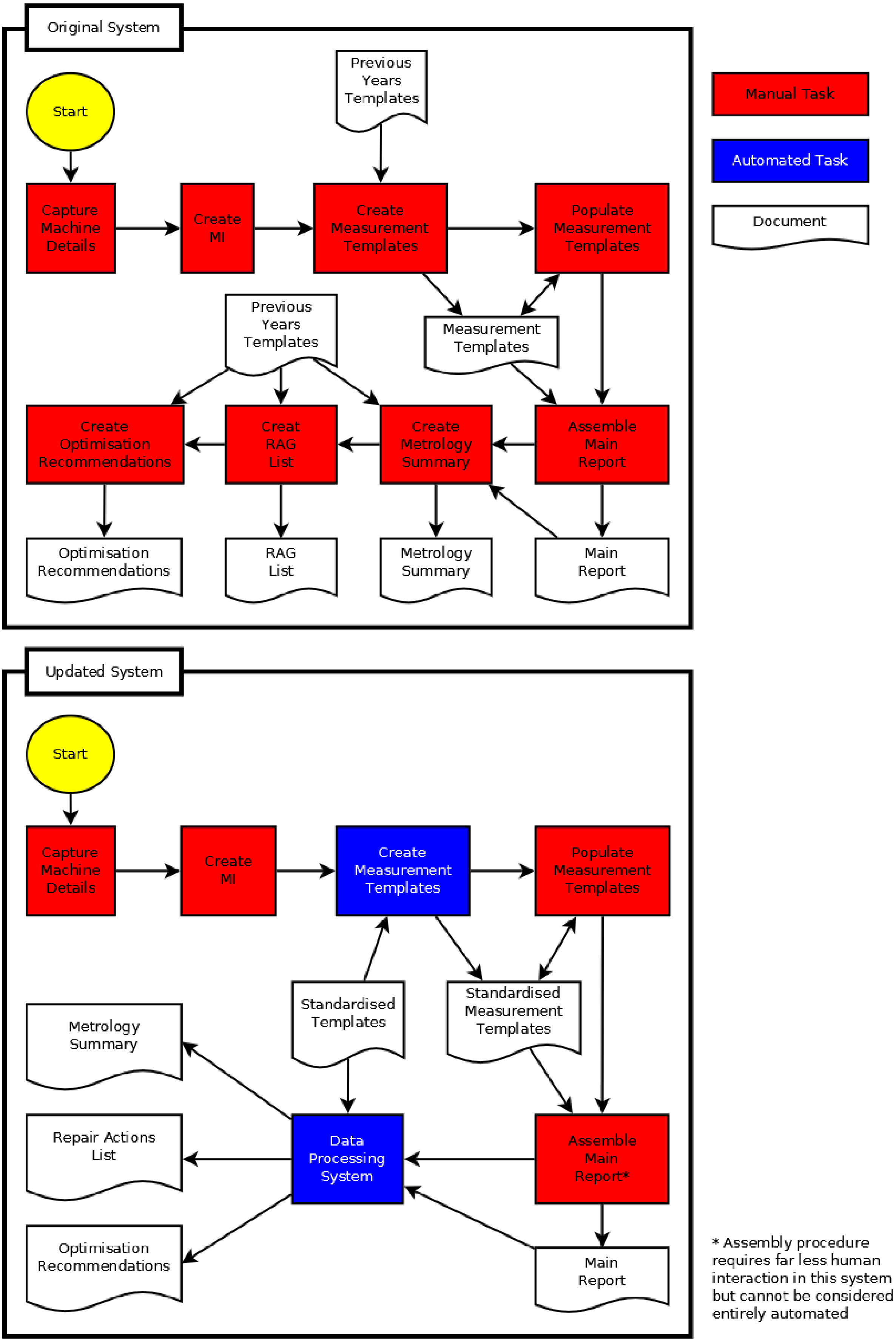

Figure 37: Measurement data processing system comparison

7 Software design and development

Initial test versions of the software were written in Visual Basic as it can be heavily integrated into the Microsoft Office suite of software that is commonly used throughout the business world. After initial testing, however, it was found that certain aspects of the program would be significantly easier to implement if the features of a fully object orientated language were available. To this end C# was chosen as the language in which to implement the system of rules presented in the previous section. It also has the advantage of being portable to multiple operating systems and has numerous, highly functional development environments available.

7.1 Inputs

The data collection table discussed in the following sections, and displayed in **Error! Reference ource not found.**, served as an input structure for the program. The plain text file format was selected as it provides the most flexible method of inputting data at present. One negative consequence of this is that there is no data validation feedback provided to the user to prevent mistakes, however these downsides were deemed acceptable at this stage in order to retain the portability of the original code.

Future versions of the system will ideally include a Graphical User Interface (GUI) version of the data collection framework in order to validate inputs and prompt users for corrections and omitted data prior to running the error selection algorithm. A full description of each of the data input types is given in the following section, 7.2.

Axes									
	Name	|| to	Type	Ref	Orient	SitsOn	Base.	Co-Ax	CNC?
1	X	X	L1	*	S	Y	-	-	*
2	Z	Z	L2	*	V	X	-	-	*
3	Y	Y	LG1	*	F	-	*	-	*
4	B	Y	R2	-	-	C	-	-	*
5	C	Z	R1	-	-	Z	-	-	*
6									
7									
8									
9									
10									

Table 8: Axis information capture

Interfaces				
	Name	Type	SitsOn	CL || to
1	Spindle	1	B	Z
2	Table	2	-	Z
3				
4				

Table 9: Tool/Workpiece interface capture

	Description
L1	Linear Axis type 1
L2	Linear Axis type 2
LG1	Linear Gantry Axis type 1
LG2	Linear Gantry Axis type 2
R1	Rotary Axis type 1
R2	Rotary Axis type 2
S	Side to Side
V	Vertical
F	Front to Back

Table 10: Key to Table 8: Type column

7.2 Information Requirements

So far, we have illustrated that there is certain information required about the machines axes to enable us to correctly identify each type and perform useful actions on it. At present, the minimum data required for all axes is as follows:

- The axis name
- Which primary axis it lies along (may or may not be the same as the Axis name)
- What axis type it is (from the previously mentioned options)
- Which axis it sits on (if any at all)
- Whether it is a vertical axis
- What axis it is co-axial with, if at all (in the case of some rotary axes)
- Whether it should be treated as the reference base for the machine
- Whether it is a fully CNC controlled axis or not (some are just hydraulic pushers for example)
- Ideally, what the drive method is

This list only covers the requirements for machine axes and does not cover the various interface/tool types or the data that should be collected about them. The machine error discovery procedure can be run without this additional information, but it will be required to fully complete the procedure as the Tool/Workpiece interfaces are a key aspect of the machine tool.

The justification of each piece of information is discussed in the following sections.

7.2.1 Axis name

The name that the axis is given in the controller or documentation is essential to relate the errors and subsequent measurement procedures back to the machine with minimal confusion. Naming conventions may vary from manufacturer to manufacturer, or between applications, so giving the system the flexibility to adapt to these situations is a key feature. Axis parallelism

Each axis provides either motion along or about one of the primary axes. This variable is required in order to specify which of the three primary axes the axis is parallel to: X, Y or Z.

7.2.2 Axis type

The axis type lets us decide what freedoms of movement are possible within the axis. For the purpose of extracting the theoretical errors, usually only the part of the designation that specifies whether the axis is linear or rotary is important, the further differentiation however is important for method of test selection at a later time.

7.2.3 Primary reference axis

This flag is required to identify the “first” axis that is present along the direction of one of the three primary axes. This is required in order to differentiate primary and secondary axes; which axis the parallelism is measured relative to, rather than from.

7.2.4 Virtual axis

Additionally there is the concept of “imaginary” or “virtual” axes. These are directions of movement that the machine does not deliberately move in, for example a VTL with only vertical and side to side movement, but that errors can occur in. As is shown in Figure 38, the machine’s axes all move along axes that are parallel to either X or Z, with no deliberate motion in the Y direction. Although the machine does not deliberately move in the Y direction, the straightness error of each of the axes will produce motion in this direction, as discussed earlier in section **Error! Reference source not found.**.

In order to make use of the program as simple as possible, it is configured to automatically include a virtual axis in any of the primary directions (X,Y Z for example) that are not included by the user, so that a 3 dimensional framework is always created. The “virtual” flag excludes the axis from being used as an axis that could be a source of errors, but included as one that errors can occur in.

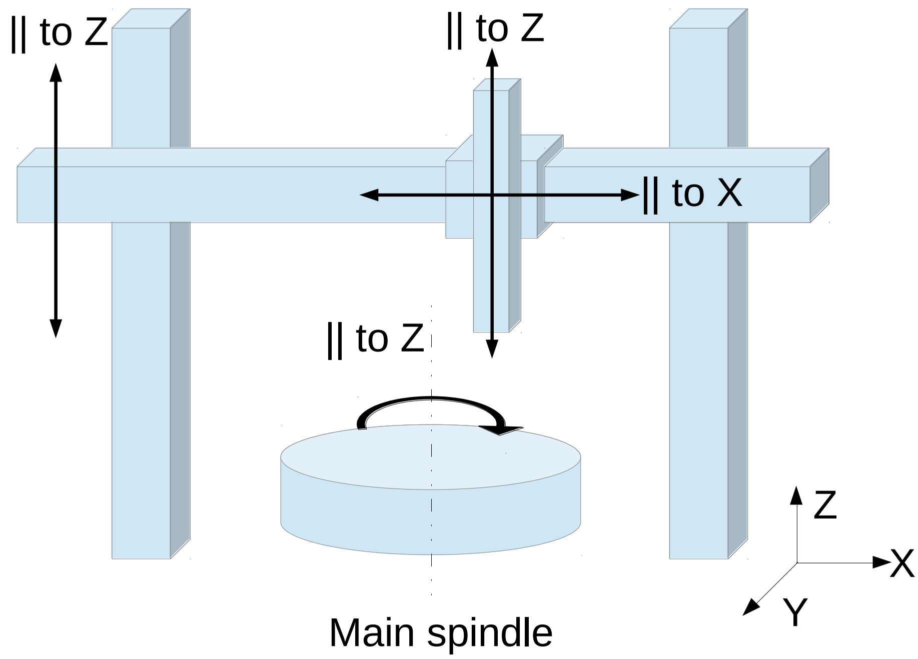

Figure 38: Vertical Turret Lathe

7.2.5 Sits on

The “Sits On” reference links the axes together in build order. This is arguably one of the most important pieces of information about the machine as it allows us to extract the more complex inter-axial errors from the collection. An axis that does not sit on any other axis is usually connected to the ground, and an axis that has no axis on top of it usually supports a tool or workpiece interface.

7.2.6 Orientation

From the theoretical, error determination perspective, whether the axis is vertical or not is unimportant, as we are dealing with lines within a virtual space. It is however a crucial piece of information when it comes to selecting a method of test for some errors. For example, axial roll (XRX) is simple to determine when the axis is horizontally orientated, as precision levels can be used. If the axis is vertical however, more complex methods have to be employed as measurements against gravity are not possible.

To this end, the orientation of the primary axes are required to enable test methods to be selected, and to potentially allow the automatic construction of simple diagrams to illustrate the machine’s layout to users. Axes can be either Vertical, Front-to-Back, or Side-to-Side, with whatever axis designation is appropriate assigned to them. Although this does potentially allow for different information to be entered depending on the viewer’s location, it should not impact the errors present in the machine, only the diagrams and, potentially, the measurement methods.

7.2.7 Reference base

One axis must be specified as the base axis for other measurements to be taken against. Once the type and arrangement of the machine's axes has been determined, the next crucial piece of information is determining which axis is the "base" for all the measurements to be taken against. This does not affect the freedoms of movement present in the machine, only how these are interpreted when it comes to producing a list of measurements. It is required in order to define which axis should be the "master" axis in measurements that involve two machine axes, such as parallelism or squareness. This is usually the axis that is placed on the machines foundations first and is often the most difficult to adjust. It is also how we are able to simply identify some of the larger families of machine tools. The differences between a Vertical Turret Lathe (VTL) for example and a 5-axis milling machine can be used to illustrate this point.

The VTL is primarily used to create large diameter parts with rotational symmetry. As such, it usually takes the centreline of the spindle as the centre point for the machine as this is the point that the rest of the machine will, in effect, move relative to. This means that instead of measuring the parallelism of the spindle centreline to any parallel linear axis, we would measure the parallelism of the linear axis to the spindle centreline. This seemingly minor differentiation has a more significant impact further down the measurement/repair sequence of events, as any adjustments or alterations to the machine would usually be to make a linear axis parallel to the centreline. If we were to alter the orientation of the spindle instead, this would then invalidate any further measurements that were taken relative to this centreline. A five axis milling machine further illustrates this explanation.

If we take the 5-axis gantry milling machine displayed in Figure 39, the machine is constructed of 3 linear axes and 2 rotary. The first axis that is connected to the earth is the Y-axis.

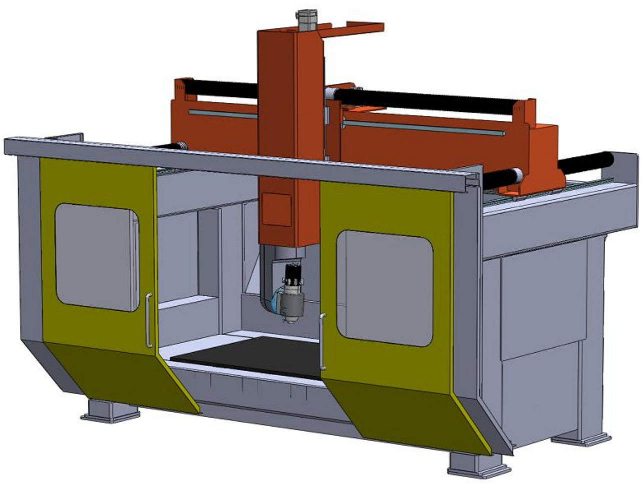

Figure 39: Geiss 5-axis machine tool

This consists of the left and right had sides of the gantry (Y master and slave) on top of which is placed the X axis (left to right) and on top of that the Z-axis (vertical column). These three axes aim to be perpendicular to each other and therefore provide 3-dimentional movement within the machine's working volume. This configuration provides us with three squareness errors; X squareness to Y, Z squareness to X, and Z squareness to Y. The build order of the machine (X on Y and Z on X) means that if we were to detect an error in the squareness between the Z and Y axes, we would proceed by altering the alignment of the Z-axis, rather than the Y. If we were to alter the Y-axis to make it square to the Z, this would potentially require re-levelling of the entire machine and invalidate the rest of the measurements taken from it, altering the Z-axis only affects the axes that are sitting on top of it, and leaves the Y and X untouched.

Although this is a relatively straightforward concept, an explicit declaration of which axis is the base of the measurements is required for the analysis routine to quickly determine the correct master slave relationship between the axes. This is due to the fact that it is not always the most obvious "bolted to the ground" axis that is the most important, or there may be multiple axes that are attached to the ground.

7.2.8 Co-axial with

Within certain configurations of machine (usually Lathes) rotary axes may sometimes be aligned so that they both rotate about the same centreline, for example a horizontal lathe may include a tailstock to support longer workpieces. However, the coaxiality of two rotary axes that are parallel to the same primary axis is not guaranteed, so it must be specified on a case by case basis.

7.2.9 CNC controlled

Within a machine tool, not all axes are under full positional control of the CNC. Some axes are designed to simply progress or extend until they meet an obstacle or the end of their travel. Whether the axis is fully CNC influences whether the positional errors (XTX for example) are relevant to the machine; if a tailstock is a hydraulically activated axis that simply moves until it contacts the workpiece, we are not interested in its positional error, only that it does move through its full travel.

7.2.10 Secondary information

Additional information that does not relate to the theoretical errors within the machine is required in order to make accurate assessment of the measurement methods available to the engineers. This information will not impact on the presence of the errors in the machine, but could potentially be used in automatic setup of data capture fields, equipment and time scheduling.

7.2.10.1 Drive method

Similarly to the CNC control variable, the drive method of the axis does not influence the errors present, but may highlight additional mechanical or electrical testing that may be associated with the particular drive methods.

7.2.10.2 Axis travel limits

The positive and negative limits of travel for an axis are essential to selecting the most appropriate methods of test for the axis. For example it would not be possible to use a 600mm granite square to measure the squareness of two linear axes that are 400mm long, as it probably would not fit. Similarly, it would not be possible to measure the straightness of a linear axis with 20m of travel using the standard optics for a XL-80 system, as they have a maximum range of 2m.

7.2.11 Data capture form

In order to provide a simple method of capturing the required data whilst on-site, a simple data record sheet was constructed. A sample of this, suitable for a machine with up to 10 axes is shown in **Error! Reference source not found.**.

Figure 40: ASCII Text file input extract

The information captured here can then be used to develop a virtual model of the machine and, with the details of the next section, determine the errors present within it.

7.3 Outputs

Similar to the input method, the output of the system is a plain text file detailing each of the errors present within the given axis setup. The file details both the error code (eg. XTY) and the human readable version of the error (X translational error in the Y direction). Again, the plain text format is to allow the greatest amount of flexibility in the present situation. This allows the relatively small program to be included or utilised by both human operators, and additional software or systems, should the need present itself.

This file is accompanied by an additional, more detailed file containing the initial error code, and the provisional test titles that can be applied to measure the error in question. This is a limited demonstration of the next step of linking each error with one of the suite of test methods available to the organisation. A fully integrated version would require a simple database to store the test methods and all relating materials, with a more advanced selection algorithm based on whichever weightings are deemed most appropriate.

7.4 Design detail

Once the axis details are entered into the data input file, the software can assess the arrangement and produce the full list of freedoms of movement present in the machine. As the geometry of the 3-axis machine tool is well understood, the focus of the software is the more complex and extensive configurations of machine tools.

Automatically assigning the six “internal” degrees of freedom to an axis is a simple process of iteration through the listed axes and will produce the majority of the freedoms of movement. Once the three “reference” axes have been assigned, each of the axes in the machine is assigned an error along and about each of these reference axes. The program flow detailing this is shown in Figure 41.

The first step in the process is to read in the machine details from the input structure discussed earlier, and store them in the internal Machine Axes class structure. From this point, the program iterates through each of the axes until all have been processed, adding a translational and rotational error in the direction of each of the primary axes. At this point, there should be six errors for each axis present in the configuration, three linear and three rotational. These are later processed into the more “human readable” format of Straightness, Positional Error, Axis Roll, etc.

The more complex interactions between the axes required more complex examination, as detailed in the next section.

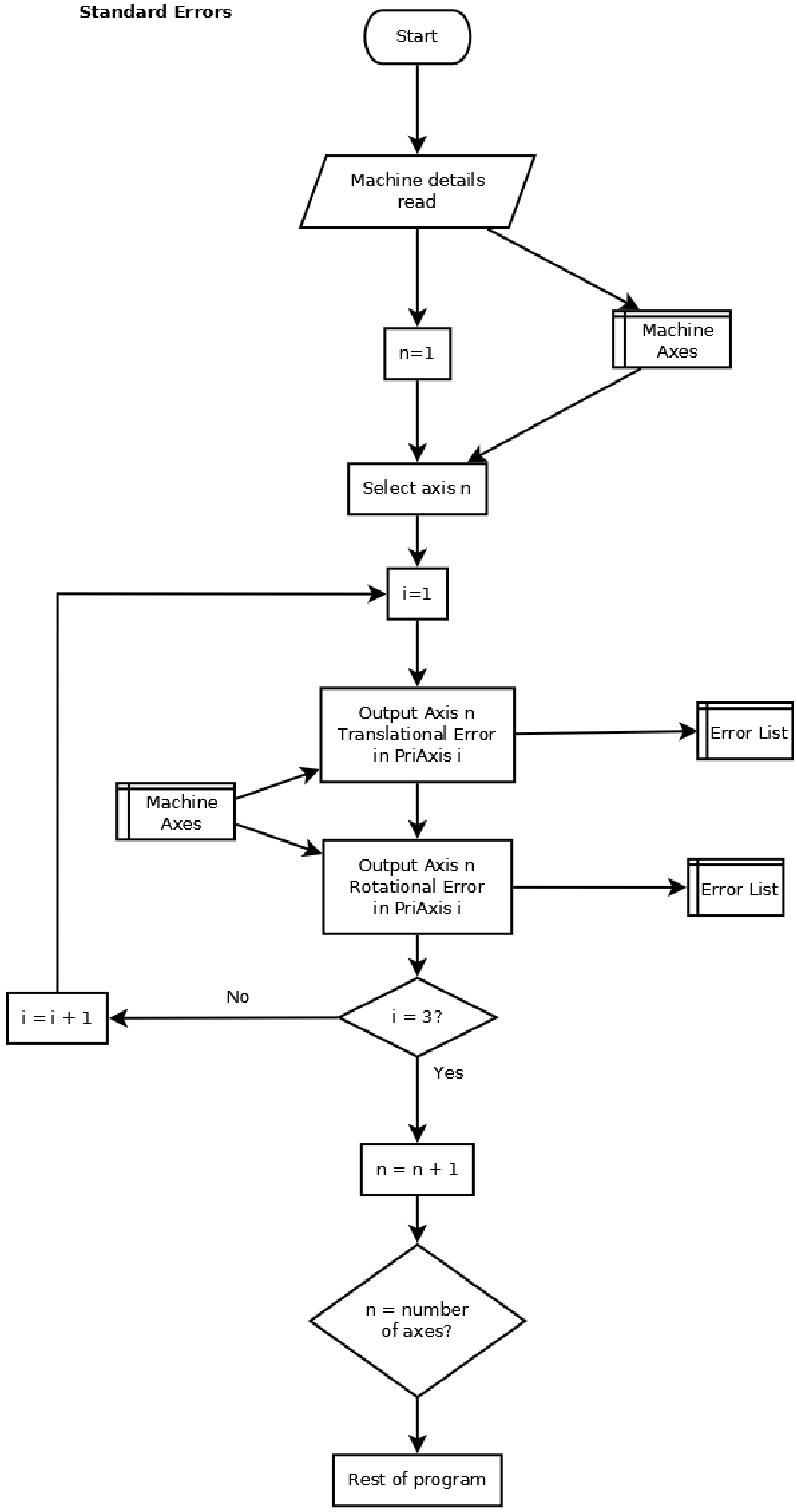

Figure 41: Method for determining standard “internal” errors for each axis

7.4.1 Squareness

The squareness errors between the various axes are dependent on both the type of axis involved and the order in which they are linked. Initially the method required to correctly assign the squarenesses seemed extremely complex. A single axis has no squareness errors as there are no further axes to be aligned to. Two axes have one squareness error – the squareness of the one with lower precedence to the one with higher. Three axes have three squareness errors:

- None for the first axis in the chain
- One for the second axis in the chain (to the previous axis)
- Two for the third axis in the chain (to both of the previous axes)

The situation for rotary axes is different yet again, as they have the two alignments of the rotational centreline to consider in all cases. When additional, parallel axes are considered however, the situation becomes more clear, as they also always possess two squareness errors.

If, rather than a three axis machine, we consider instead a large machine with seven linear axes and six rotary axes, it becomes clear that the majority of these axes have two squareness errors (11 axes out of the total 13), and in fact it is the base axis and the next lowest that are the exception. The flowchart displayed in Figure 42 details the program structure required to implement this.

The system steps through each of the axes in the machine tools configuration and tests each against a simple set of conditions. Virtual axes are ignored (they do not really exist), as is the base axis for the machine, as this is the one that all others compare to. After this, as long as the axis is a rotary axis, or is a linear axis that is not one of the three base axes, two squareness errors are added by the right-hand branch of the program.

The more complex decision tree is to distinguish between the other two reference axes that may be possible in the machine. The "highest" axis of the two (the one furthest up the chain of axes) is treated the same as the others and has two squarenesses added, and the other has just one added (between itself and the base axis).

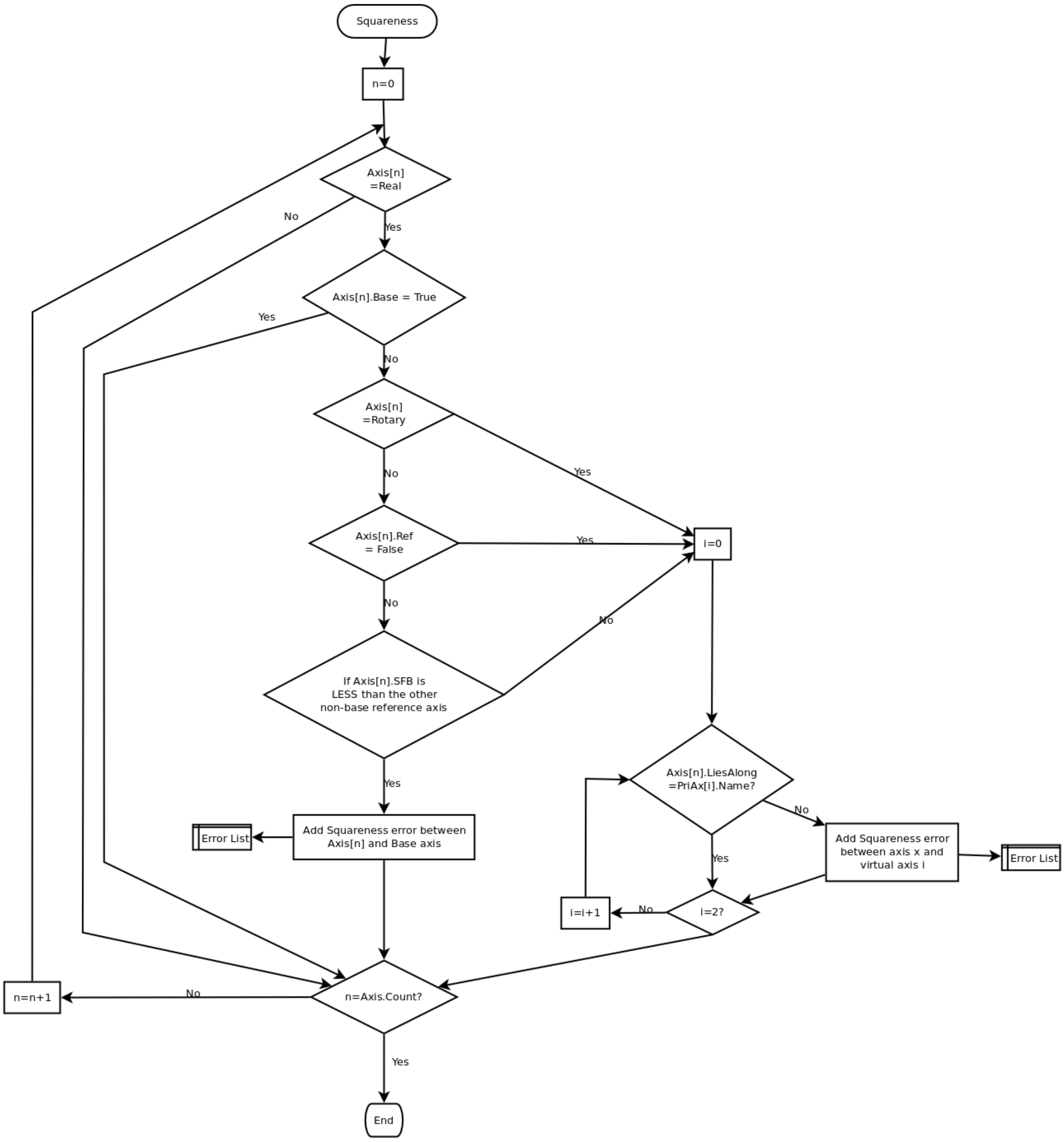

Figure 42: Decision process for selection of squareness error

7.4.2 Rotary Axis Offset

The addition of the rotary axis offset error is a relatively straightforward process. If a rotary axis is on top of another, non-parallel rotary axis in the chain of axes, the offset error is included in the listing.

7.4.3 Rotary axis concentricity

The application of the concentricity is still largely an operator decision, as there is no way to automatically distinguish whether rotary axes that are parallel to the same primary axis are meant to be concentric or not. To this end, the software adds offset errors between the primary rotary axis in question and the ”concentric” axis only when specifically instructed to via the input data file.

7.4.4 Interfaces

The machine interfaces are dealt with largely on a case by case basis, as each has a specific set of characteristics to observe. One of the most complex is the high speed milling spindle, but this can be sub divided into a standard rotary axis, and the spindle taper. This lets us use the existing system to process the rotary axis part of the spindle, and allows is to add a spindle taper test as the only new addition to the system.

7.4.5 Source code

The full project file and source code, along with example input files and a pre-compiled version of the system are included in electronic format.

7.5 Graphical User Interface

Although no GUI was developed for this version of the software, there are a number of benefits to its future development, mainly in the area of data validation.

A simple system to limit cross referencing of axis data (such as the “Sits On” field) to axes that have already been entered would eliminate basic data entry errors and make the system more robust.

The addition of a system to produce a simple line drawing of the configuration that is being entered would also provide a useful visual feedback system to the user, allowing them to quickly identify any mistakes in the configuration that they are inputting.

8 Validation Case studies

In order to validate the efficiency of the system, "Metrology Indexes" created using the traditional manual method, detailed in section 5.1, were compared to the error lists and test schedules created with the automated system. These were checked for correctness, completeness, and the time required measured for both methods.

Omitted tests from the manual process are not necessarily detrimental to the machine audit as they may have little impact on the specified machine or process, but they should be noted and the reasons for removal recorded for future reference.

A range of machine types and complexities are included in order to test the system with real world examples and highlight any strengths or shortcomings of the new system in varying situations.

The comparison metrics used are detailed below.

1. Data capture/entry time (mins)

This is the time required to note down the configuration of the machine either on paper or using a basic diagram (using the traditional manual system) or to enter the details of the machine into the table ready for processing with the software.

2. Data capture errors

In this area an error could be an axis being recorded as sitting on top of another when in reality they are separate, or recording an axis as vertical rather than horizontal. The number of errors introduced at the data capture stage is important, as this is the data that forms the basis of all the following work and measurements. Errors in this stage can be highly costly if not discovered until later in the process.

3. Error list production time (mins)

The error list production time is a key metric. If large amounts of time are taken to produce the list of errors in the configuration, this means that more time is being wasted on site, extending already costly downtime.

4. Error list omissions

Omissions in the error list are missing freedoms of movement. The number of omissions (or incorrect additions) in the completed error list is another important metric as missing measurements could prove crucial at a later date. Additionally, site re-visits to collect additional data become extremely expensive when additional travel time and machine downtime is factored in.

5. Test schedule production time (mins)

This is the time taken to create (by hand in the traditional system) the production of the Test Schedule, or Metrology Index (MI), and is presently a time consuming and highly repetitive task. Comparing the time savings in this area can again translate directly into cost savings as downtime is again reduced, as is office workload.

6. Test schedule omissions/errors

This is the number of errors introduced by the operators of the system. The direct costs of each error are hard to quantify as each machine has different requirements placed on it, emphasising different areas of its performance. This metric mainly highlights the errors caused by differing personal judgment and genuine human mistakes, often caused by time pressures.

One area not measured in this section errors introduced by the communication of the machines configuration from the site to the office. The process communicating the configurations from the engineers to the analysts is often where mistakes are introduced, with little in the way of verification until the full test schedule is returned to them. The number of communication errors depends largely on the experience of both parties involved and the complexity of the machine in question. This is another area where the creation of a data language to fully describe the axes of the machine will save more time and reduce (or hopefully eliminate) communication errors.

Full metrology indexes for each of the cases can be found in Appendices 2 and 3.

8.1 Cincinnati 500

The Cincinnati 500 is a good example of a standard 3-axis machining centre commonly encountered in smaller machine shops around the world. Even so, as stated earlier, there are potentially 24 possible combinations of these axes with one tool and one workpiece. Although this is one of the more straightforward machines to generate the error list for, the tailoring of the measurement list for the precise arrangement of these axes makes the process more time consuming.

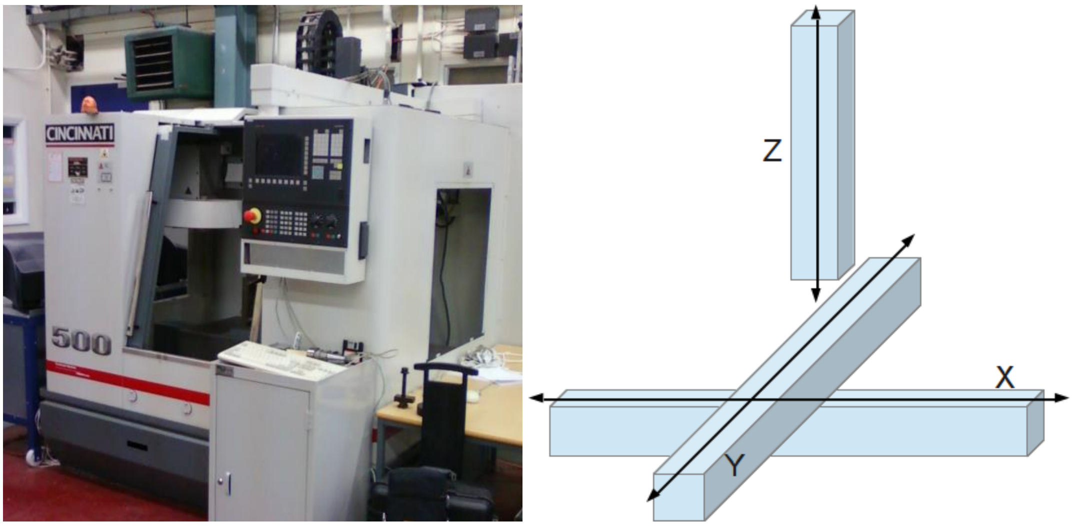

Figure 43: Cincinnati 500 and axis configuration

8.1.1 Manual method

The traditional manual method of metrology index creation allows the engineer to capture the initial machine data slightly faster as the only requirements are at most to record a basic line diagram or a short list of axis names. The creation of the test list from this data however takes significantly longer than the automated method, as we can see in Table 11.

8.1.2 Automated method

Once the axis definition table has been completed the subsequent process only require as long as it takes to write the data to the files. Additionally, the data captured from the basic machine configuration and the subsequent error and test data is all formatted in a standardised way and electronically transmittable and storable with no additional work required.

8.1.3 Comparison

As we can see, the automated method requires slightly more time in the data capture stage, but little additional time beyond this. The traditional method however, required more time to produce the additional documents and would require further time if changes were to be made to the configuration. The manual method does contain the additional tests of the machine's circularity with the ballbar which the automated method does not at present include. This will be added as an optional addition in further development.

	Traditional method	Automated method
Data capture/entry time (mins)	1	2
Data capture errors	0	0
Error list production time (mins)	Not created	≈0
Error list omissions	Not created	0
Test schedule production time (mins)	15	≈0
Test schedule omissions/errors	0	0

Table 11: Cincinnati 500 comparison

8.2 Geiss 5-axis Trimmer

The Geiss plastic trimming machine (Figure 39) is a 5-axis, "fork head" gantry milling machine. The addition of the two rotational axes introduces a number of additional errors that make the manual generation of the metrology index for this machine slightly more complex, however this is still a frequently encountered type of machine tool.

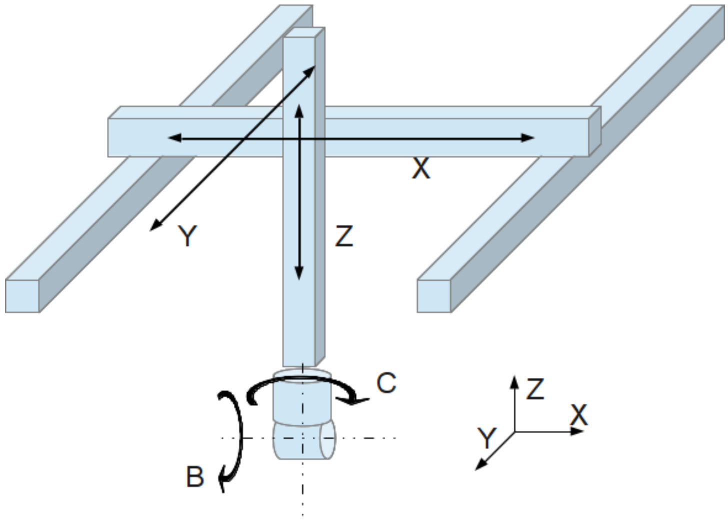

Figure 44: Geiss Axis configuration

8.2.1 Manual method

The traditional manual method of metrology index creation can be created in a relatively short time as this type of machine is encountered on a regular basis and is well understood. Despite this, the fact that it is commonly encountered does not mean it is necessarily mean that it is error free. Additionally the designations of the axes must be manually updated to match the arrangements in the machine. In this case the manual method omits a number of the internal degrees of freedom of the C and B axes.

8.2.2 Automated method

Once the axis definition table has been completed, the error index can be created automatically be and either stored for later use, or directly processed into the test schedule

8.2.3 Comparison

A table comparing the two methods of creating both the error list and test schedule is presented below.

	Manual method	Automatic method
Data capture/entry time (mins)	2	2
Data capture omissions/errors	0	0
Error list production time (mins)	Not created	≈0
Error list omissions/errors	Not created	0
Test schedule production time (mins)	10	≈0
Test schedule omissions/errors	10	0

Table 12: Geiss comparison

8.3 Long bed profiling machine

The long bed profiler is a designed for long, slim parts such as aerospace wing spars. It is a relatively complex machine, as it has three cutting spindles, each with independently adjustable vertical and rotational axes, bringing the total number of axes to 12.

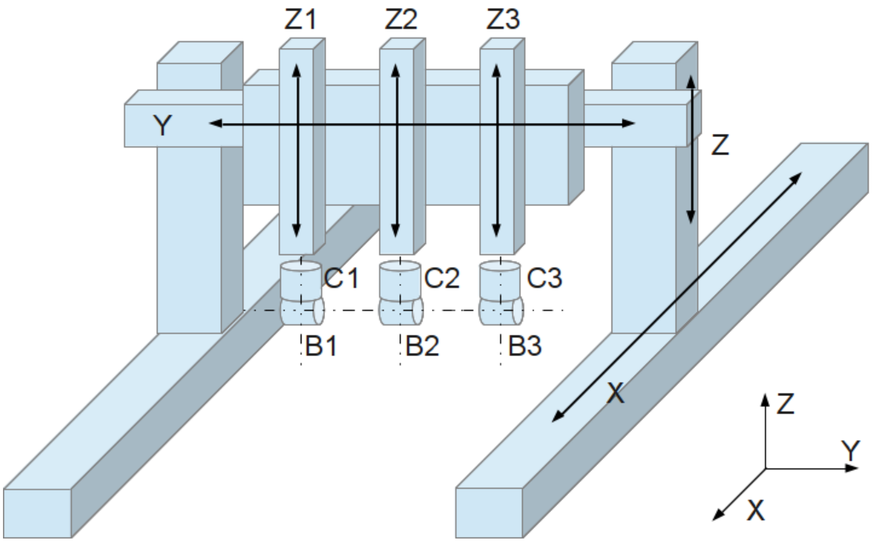

Figure 45: Long bed profiler diagram

8.3.1 Manual method

Due to the large number of axes, the traditional manual method of metrology index creation can take a significant amount of time. Additionally, due to the sheer volume of tests required, numbering errors and simple omissions can easily creep in. The traditional method for recording the configuration is, as before, a simple sketch with additional notations, however this can introduce some confusion due to the complexity of the machine. The missing errors are a number of the internal freedoms of movement of the rotary axes and the vertical roll of the Z-axes.

8.3.2 Automated method

Once the axis definition table has been completed, there is no additional time required than was for the smaller machines. Although the initial time taken to complete the input file is slightly higher than the manual method, it produces a standardised document that is clear, concise, and both easily transmittable and searchable.

8.3.3 Comparison

	Manual method	Automatic method
Data capture/entry time (mins)	5	6
Data capture omissions/errors	0	0
Error list production time (mins)	Not created	≈0
Error list omissions/errors	Not created	0
Test schedule production time (mins)	40	≈0
Test schedule omissions/errors	34	0

Table 13: Long bed profiler comparison

8.4 VTL

The VTL is a good example of a different type of configuration. This configuration of machine highlights the system's ability to adapt correctly to the different measurement base axis in this new configuration. Although there are only four axes in this configuration, the errors must be interpreted differently than when considering a machining centre, as the reference axis is now a linear one.

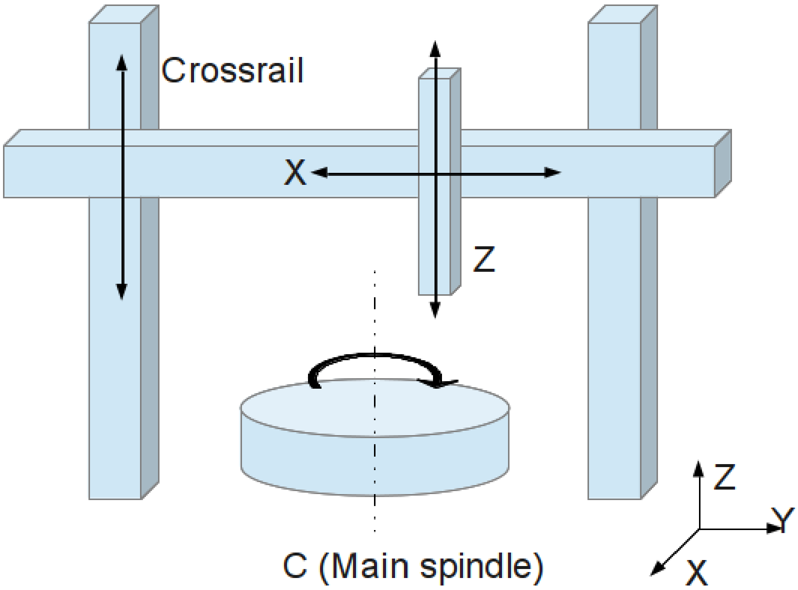

Figure 46: VTL configuration

8.4.1 Manual method

The traditional manual method of metrology index creation can easily accommodate this machine configuration and existing MIs could be adapted to fit the current situations. The traditional method for recording the configuration is, as before, a simple sketch with additional notations. The traditional method omits the internal degrees of freedom for the crossrail, one of the internal freedoms of the main spindle axis and one of each of the linear axes' straightnesses.

8.4.2 Automated method

As before, once the axis definition table has been completed subsequent steps are automatic and the method of recording the configuration unambiguous.

8.4.3 Comparison

	Manual method	Automatic method
Data capture/entry time (mins)	2	3
Data capture omissions/errors	0	0
Error list production time (mins)	Not created	≈0
Error list omissions/errors	Not created	0
Test schedule production time (mins)	6	≈0
Test schedule omissions/errors	9	0

Table 14: VTL Comparison

8.5 WFL Millturn

The WFL Millturn is a complex horizontal lathe with additional milling functions available in all three axes. The number of axes in the machine makes this an interesting test for the system and human operators alike.

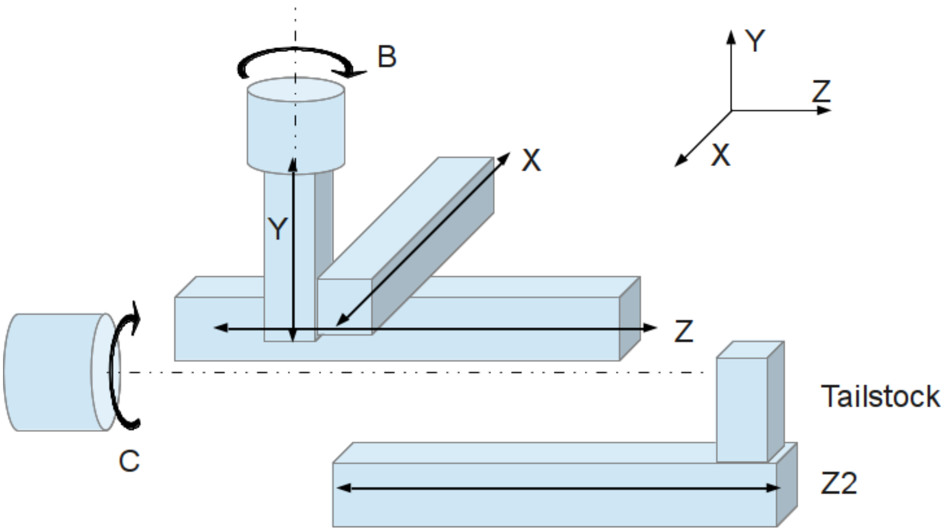

Figure 47: WFL Millturn

8.5.1 Manual method

The traditional manual method of metrology index creation in this case required an on-site visit by the metrology analyst in order to correctly determine the machine's configuration. This highlights the shortcomings in communication between the on-site engineers and the office based analyst. The omitted errors are three of the C axis internal freedoms of movement and five of the B axis internal freedoms.

8.5.2 Automated method

Whilst the correct training to allow the engineers to correctly fill in the data capture sheet may require additional time initially, the automatic system could accomplish the same goals as the traditional one without costly additional site visits.

8.5.3 Comparison

	Manual method	Automatic method
Data capture/entry time (mins)	10	6
Data capture omissions/errors	0	0
Error list production time (mins)	Not created	≈0
Error list omissions/errors	Not created	0
Test schedule production time (mins)	45	≈0
Test schedule omissions/errors	8	0

Table 15: Millturn comparison

9 Conclusions

In the modern machine tool service industry the way data is handled has become extremely important. As with all areas of business, manufacturers will no longer tolerate costly and inefficient processes when there are faster and cheaper alternatives.

To this end, the documentation and reporting system was rationalised and converted to largely automated, template driven process that has removed a large part of the burden of creating calibration reports from office staff. Additionally, the standardised document format has let automated data extraction routines take over many of the previously operator based data manipulation and transcription tasks, further reducing the burden on staff.

A further improvement was the development of the automated machine tool configuration analysis system that can replace still more of the time-intensive analysis processes, previously undertaken by experienced members of staff.

These improvements have had direct financial implications for the organisation in the form of

- Reduced report turnaround time (up to 80% in favourable situations)
- Reduced load on report verification staff (up to 90% in some cases)
- Reduced number of errors in reports delivered to customers
- Increased availability of human resources
    - This has subsequently led to increased development in additional areas as free time has become available
- Introduction of a persistent, reliable tracking system for machine service activities
    - This has allowed the identification of further areas where improvements could be introduced and given further weight to the development of the automated analysis system

These benefits have translated into significant financial savings for the organisation in terms of saved man-hours and increased system efficiently. Specific details of the impacts of each area of the improved reporting system can be found in the appendices.

The system for automatic machine tool error defining, whilst producing promising results, was not implemented in an industrial setting and is at present undergoing further verification checks. This is due to the large number of alterations that would be required for the existing systems to match the rigorous error definitions of the automated system. The potential savings from the implementation of this software in future are greater than the improvements already realised by the report system improvements, as much more of the experienced analyst dependant area of the system could be automated.

9.1 Case study summary

When viewing the case studies as a whole the benefits of the automated system become clear. The time taken to generate the error profiles for the various machines is lower in all cases and there are no omitted freedoms of movement.

Overall, the traditional method omitted a total of 61 freedoms of movement whilst the automated method successfully listed all. Additionally, the automated system produces repeatable results for each set of inputs and requires no additional time after the initial data capture stage. It should be noted that the automated system does not at this time address errors associated with the Tool/Workpiece interfaces.

Machine	Traditional system		Automatic system	
	Omissions	Duplications	Omissions	Duplications
Cincinnati 500	0	0	0	0
Geiss	10	0	0	0
Long bed profiler	34	0	0	0
VTL	9	1	0	0
Millturn	8	0	0	0

Table 16: Comparison Summary

9.2 Objective review

When compared against the initial objectives

1. *Investigate the present methods of data handling and identify areas for potential improvement.*

    - The machine tool measurement and analysis process was thoroughly disassembled and various areas of improvement identified and documented (section 5).

2. *Develop a data extraction and processing system to automate basic transcription tasks*

    - A data extraction system was developed to parse the original metrology documentation and summarise the data. This was further updated when the document structure was rationalised and subject to revision control and was able to save a large number of man-hours (full details in Appendix 1).

3. *Implement a standardised document format and document control system within the machine tool measurement process*

    - A standardised document format and a set of master templates were created and stored in a central location. This vastly reduced variation across the entire reporting system and proved extremely beneficial.

4. *Create a standardised and flexible classification system for the identification of machine tool configuration*

- A generalised method of describing machine tool axes and components was developed and tested against a large number of existing configurations (see section 8). As stated in the objectives, this does not at present extend to the classification of the cutting or grinding tools as these will most likely have to be treated on a case by case basis.

5. *Develop an automated system for calculating all the possible freedoms of moment within a machine tool configuration*

    - A novel system of computing the freedoms of movement within a machine tools geometry was developed to cope with both simple and extremely complex machine configurations (see sections 7, 8). This has the potential to save large amounts of time by assisting or replacing expert analysis.

10 Further work

There is great scope to expand the software into a fully functional machine tool measurement and condition tracking system. Now that a means of identifying and classifying a machine is available, a database to store each individual instance could be constructed relatively simply. Various asset tracking and management database products already provide this type of service, with the associated machine axes for each asset being a relatively simple addition.

10.1 Measurement Procedures

The creation of the catalogue of measurement methods would be a slightly more demanding task and would be heavily situation dependant; depending on which organisation is hosting the system, there may be significant differences in equipment, training levels or procedural detail. However, as this type of system would present the greatest benefits to organisations working in areas that demanded high levels of efficiency and traceability, a large amount of common "best practice" would probably be found. If the system proved successful enough, it may even be possible to provide a centralised database of methods that have provided the greatest levels of efficiency, or proved to be the most reliable or flexible in the field. This would require access to a centralised web-accessible database however, and may introduce safety or security concerns for sensitive applications.

A suitable format for storing methods of test would have to include information on the following information:

1. Measurement equipment to be used
    a. Weight of machine supported measurement equipment
    b. Total weight of specified equipment
    c. Any health and safety restrictions
2. Measurement procedure
3. Measurement procedure diagram
    a. One or more steps, if required
4. Required number of operators
5. Expected or average measurement time
6. What situation (axis combination) the method was applicable to
    a. Any upper limits on measurement range
    b. And lower limits on machine size (600mm granite square will not fit into a 400mm working volume)
7. Expected levels of uncertainty associated with the measurement
8. Format of recorded measurements

Including all of the above information would allow each measurement procedure to be a self-contained unit containing all of the information required to perform the specified measurement. Additionally, it would also allow for multiple measurements, selected with input from the earlier metrology index creation procedure, to be combined into an accurate work plan.

This format also creates the requirement for at least a basic equipment register in which to store the relevant details relating to the measurement equipment (weight, H&S etc.).

10.2 Scheduling and estimation

If the metrology index provides the data relating to the degrees of freedom within the machine, given adequate measurement methods or techniques to measure all of the presenting errors, a further simple scheduling algorithm would be able to combine all the time, equipment and human resources required to produce a simple but reliable plan for the measurement of whatever machine is presented.

The situation is made more complex when activities such as removal of guarding, covers, or creation of measurement movement programs are taken into consideration, but this simply provides another area for continued improvement. A suitable artificial intelligence planning system (as discussed by Parkinson (13)) could produce from this data not only an overall time estimate for the measurements, but the most efficient order in which to perform them, saving further valuable machine downtime.

10.3 Monitoring

Whilst single visit measurements and calibration certificates may provide evidence that a machine is has performed to a given level of accuracy at a specific time and date, much like a vehicles MOT, it is only valid for that specific point in time. Far more valuable to modern production facilities is the ability to accurately assess the rate of degradation of a machine.

10.4 Results

With these goals in mind the format in which captured data is stored present a number of problems. The format must be flexible enough to enable all meaningful measurement data to not only be stored, but also analysed for any trends that may be present. The time, date, and environmental situation surrounding the machine are of almost as much importance as the measurements themselves. Additionally, the format must be able to accommodate single and multiple point readings taken from both manual and digital sources.

1. Environmental
    a. Time and date

    b. Temperature readings
    c. Any further environmental details relevant to the result (pressure, humidity etc)
2. Machine setup
    a. Axis Positions
    b. Any offsets active in the controller
3. Measurement Result
    a. Measured value
    b. Axis location

…

Recording of results in a standard common format would allow tolerances and measurement to be compared automatically and instantly presented in other formats using standardised conversion methods and constants. This would also remove the possibility for human error to be introduced at either the copying, conversion, or comparison stages and greatly increase the overall system efficiency.

10.5 Visual Illustrations

A further beneficial addition to the communication and verification aspect of the program would be a simple visual interpretation of the machine being described. As all the information required to assemble a virtual model of the machine tool in question is recorded to allow the generation of the degrees of freedom and the measurement test list, there is also enough to enable a simple line drawing to be constructed. This should provide a quick and reliable method of visual verification of the captured data to the engineers on-site and further improve the reliability of the system.

10.6 Targeted error selection

Where time is critical and there is pre-existing knowledge regarding the possible location or cause of an error it may be possible to produce a targeted test list to measure. The error list can be filtered so that only the freedoms of movement that can directly produce an error in the suspect direction are measured. This has the potential to reduce the number of measurements and time required if there is access to the data on what the machine’s symptoms are is available.

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12 Appendices

12.1 Appendix 1: Report Compilation Improvements

12.1.1 First Issue Report

Report Section	**Old System**		**New System (mins)**	
	Best case	**Worst Case**	**Best case**	**Worst Case**
Capture the machine configuration	10 mins (Based on good diagrams available)	1 day (Limited data available, no photos, no site visit etc.)	Unchanged	Unchanged
Deliver machine configuration to RV for generation of Metrology Index	N/A	N/A	5 mins (email)	1 day (Email not possible)
Generate Metrology Index	– 2 hrs (all info available and reliable)	2-3 days (Sketchy info received has to be changed on feedback)	Unchanged	Unchanged
Create report reference in Report Tracker database (first instance)	5 mins	1 hr (chasing job info – may not be available)	1	20 (chasing job info – may not be available)
Generate Folder structure for data storage	10 mins (Creating and naming files)	10 mins (Creating and naming files)	1	2
Generate test documents as specified by the Metrology Index	Variable – Based on machine config and number of axes			
• Geometry	1 – 2 days	3-4 days (You know reasons why)	2hrs	2-3 days
• Laser	1 hour	0.5 days	1	4
• Ballbar	30 mins	1 hr	1	4
• Machine services	Completed by engineers	Completed by engineers	Completed by engineers	Completed by engineers
• Front Pages	20 mins	2-3 hours (Can be more if waiting for engineer info)	Unchanged	Unchanged

Report Section	Old System		New System (mins)	
	Best case	Worst Case	Best case	Worst Case
• Ballscrew Checks	30 mins	1 hour	2	10
• Spindle Draw Tension	10 mins	10 mins	Unchanged	Unchanged
• Pre-Assessment Review form	10 mins	10 mins	5	5
• Deliver the generated documents to the engineers on site	10 mins	10 mins	Unchanged	Unchanged
Update the entry in the Report Tracking database to record when the templates were delivered	1 mins	5 mins	1 mins	5 mins

12.1.2 Processing

Report Section	Old System		New System (mins)	
	Best case	Worst Case	Best case	Worst Case
Verify that all the data has been returned from the engineers. If there are omissions, they must be accompanied by a sufficient reason; otherwise all omissions should be referred back to the engineers.	1 day	2 days	Unchanged	Unchanged
Once all data has been returned, update the Report Tracker entry for the report to record the date this happened. Then begin the verification processes	1 mins	5 mins	0.5	0.5
• Check the details in the Front Pages, then save this document over the placeholder (save as new report file in old system)	10 mins	30 mins	1	30
• Complete the Equipment details page with the calibration dates	10 mins	2-3 hours (or more)	5	30
• Insert the Mechanical Service document.	10 mins	10 mins	1	1
• Check that the highlighting/formatting on the service document is correct and then list any items that are highlighted in the RAG List	10 mins	2-3 hours (if template has been corrupted by engineers)	5	120
• Insert the Electrical Service document.	10 mins	10 mins	1	1
• Check that the highlighting on the service document is correct and then list any items that are highlighted in the RAG List	10 mins	2-3 hours (can be worse template has been corrupted by engineers)	5	120

Report Section	Old System		New System (mins)	
	Best case	Worst Case	Best case	Worst Case
• Insert the Ballscrew Checks document. Add to RAG list if required.	10 mins	2-3 hours (can be worse template has been corrupted by engineers)	2	10
• Insert the Spindle Draw Tension document. Add to RAG list if required.	5 mins	5 mins	2	5
• Insert the Geometry document and check formatting	1 hour	1-2 days (can be worse if template has been corrupted)	5	30
• Examine Geometry section for mistakes/errors	2 hours	1-2 days (can be worse if waiting for engineer response)	60	300
• Insert the Laser document and check formatting	1 hour	1-2 days (can be worse if template has been corrupted)	5	10
• Examine Laser section for mistakes/errors	2 hours	1-2 days (can be worse if waiting for engineer response)	10	60
• Insert the Ballbar document and check formatting	1 hour	1-2 days (can be worse if template has been corrupted)	5	10
• Examine Ballbar section for mistakes/errors	2 hours	1-2 days (can be worse if waiting for engineer response)	10	60

Report Section	Old System		New System (mins)	
	Best case	Worst Case	Best case	Worst Case
• Insert the "Appendix" section	10 mins	10	1	1
• Create the Metrology Summary	2 -3 hours	2-3 days (on discovering erroneous result and then chasing for solution/answer , also document has error where report has to be amended)	2	180
• Verify Metrology Summary	1-2 hours	2-3 days (on discovering erroneous result and then chasing for solution/answer , also document has error where report has to be amended)	30	120
• Update the contents page at the start of the document	1 – 2 hours (average size report)	0.5 – 1 day (Typing content list and updating page numbers accurately)	10	60
• Send the report, metrology summary and RAG list to analyst for verification	N/A	N/A	5	10
• Update the Report tracker database to record this date	N/A	N/A	5	10

Report Section	Old System		New System (mins)	
	Best case	Worst Case	Best case	Worst Case
Once the report has been initially approved (returned from analyst) the report must be finalised before it is sent for Final analysis and approval. This was completed by the main analyst under the old system.				
• Update the report tracker database	N/A	N/A	1	5
• Implement the report changes	N/A	N/A	0	120
• Add the items from the Metrology Summary to the RAG	0	2-3hrs	1	1
• Insert the completed Metrology summary document into Appendix of the main report	5 mins	10 mins	2	2
• Insert the completed RAG list into the Appendix of the main report	5 mins	10 mins	2	2
• Update the Appendix contents page	1 mins	1 mins	1	1
• Update the main contents page	1 mins	1 mins	1	1
• Update the empty Optimisation Plan	3 mins	5 mins	1	1
• Update the RAG Actions List document	10 mins	30 mins	2	2
• Update the Optimisations Recommendations	10 mins	30 mins	2	2
• Update the RFQ document	5 mins	15 mins	5	5
• Update the Amended Actions document with the machine and report details	N/A	N/A	5	5

12.1.3 Uploading

Once the documents have been finalised, they must be uploaded to the "Report system" area of Groove.

Report Section	Old System	New System (mins)
Create a new folder in the "Pre-Approval" folder on Groove with the standard naming convention.	1	Unchanged
Upload the Report documents	5	Unchanged
Send a message using the Chat function on the right of the Groove window alerting him to the new report	1	Unchanged
Update the entry in the Report Tracker database to record the date	1	Unchanged

12.2 Appendix 2: Comparison Metrology Indexes – Traditional format

12.2.1 Cincinnati 500

Test 1 – X bed levels (X about X)
Test 2 - X bed levels (X about Y)
Test 3 - X rotation about Z
Test 4 - Y bed levels (Y about X)
Test 5 - Y bed levels (Y about Y)
Test 6 - Y rotation about Z
Test 7 - Z rotation about X
Test 8 - Z rotation about Y
Test 9 - Z rotation about Z
Test 10 - X Vertical Straightness
Test 12 - X Horizontal Straightness
Test 13 - Y Horizontal Straightness
Test 13 - Y Vertical Straightness in Z
Test 14 - Z Horizontal Straightness (in X)
Test 15 - Z Horizontal Straightness (in Y)
Test 16 - X squareness to Y
Test 17 - Z squareness to X
Test 18 - Z squareness to Y
Test 19 - Spindle Axial Runout
Test 20 - Spindle Radial Runout
Test 21 - Spindle Internal Taper Runout
Test 22 - Spindle Parallelism to Z axis in X
Test 23 - Spindle Parallelism to Z axis in Y
Test 24 - X positional accuracy (1 run bi-directional)
Test 25 - X accuracy and repeatability (5 runs bi-directional)
Test 26 - Y positional accuracy (1 run bi-directional)
Test 27 - Y accuracy and repeatability (5 runs bi-directional)
Test 28 - Z positional accuracy (1 run bi-directional)
Test 29 - Z accuracy and repeatability (5 runs bi-directional)
Test 30 - XY Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 31 - XY Plane Circularity - 360 Bi-Directional (1000mm/Min)
Test 32 - YZ Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 33 - YZ Plane Circularity - 360 Bi-Directional (1000mm/Min)
Test 34 - ZX Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 35 - ZX Plane Circularity - 360 Bi-Directional (1000mm/Min)

12.2.3 Geiss 5-axis trimmer

Test 1 - Y bed levels (Y about X)
Test 2 - Y bed levels (Y about Y)
Test 3 - Y rotation about Z
Test 4 – X bed levels (X about X)
Test 5 - X bed levels (X about Y)
Test 6 - X rotation about Z
Test 7 - Z Levels in the horizontal (Z about X)
Test 8 - Z Levels in the horizontal (Z about Y)
Test 9 - X Vertical Straightness
Test 10 - X Horizontal Straightness
Test 11 - Y Horizontal Straightness
Test 12 - Y Vertical Straightness
Test 13 - Z Horizontal Straightness (in X)
Test 14 - Z Horizontal Straightness (in Y)
Test 15 - X squareness to Y
Test 16 - Z squareness to X
Test 17 - Z squareness to Y
Test 18 - C Parallelism to XY Plane
Test 19 - B Parallelism to XZ Plane
Test 20 - B to C offset
Test 21 - Spindle to C axis concentricity
Test 22 - Spindle Axial Runout
Test 23 - Spindle Radial Runout
Test 24 - Spindle Internal Taper Runout
Test 25 - Spindle Parallelism to Z axis in X
Test 26 - X positional accuracy (1 run bi-directional)
Test 27 - X accuracy and repeatability (5 runs bi-directional)
Test 28 - Y positional accuracy (1 run bi-directional)
Test 29 - Y accuracy and repeatability (5 runs bi-directional)
Test 30 - Z positional accuracy (1 run bi-directional)
Test 31 - Z accuracy and repeatability (5 runs bi-directional)
Test 32 - XY Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 33 - XY Plane Circularity - 360 Bi-Directional (1000mm/Min)
Test 34 - YZ Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 35 - YZ Plane Circularity - 360 Bi-Directional (1000mm/Min)
Test 36 - ZX Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 37 - ZX Plane Circularity - 360 Bi-Directional (1000mm/Min)

12.2.5 Long bed profiling machine

Test 1 - X in Y
Test 2 – X in Z
Test 3 – Y in X
Test 4 – Y in Z
Test 5 – Z in X
Test 6 – Z in Y
Test 7 - X Axis Bed Levels X Ab X
Test 8 - X Axis Bed Levels X Ab Y
Test 9 - Angular Deviation Of The X-Axis About The Z-Axis X About Z (Master)
Test 10 - Angular Deviation Of The Y-Axis About The X-Axis Y About X
Test 11 - Angular Deviation Of The Y-Axis About The Y-Axis Y About Y
Test 12 - Angular Deviation Of The Y-Axis About The Z-Axis Y About Z
Test 13 - Angular Deviation Of The Z-Axis About The X-Axis Z About X
Test 14 - Angular Deviation Of The Z-Axis About The Y-Axis Z About Y
Test 15 - Angular Deviation Of The Z-Axis About The Y-Axis Z About Z
Test 16 - Positional Deviation Along The X-Axis X Positional (Middle)
Test 17 - Positional Accuracy & Repeatability Of X-Axis X Acc Rep (Middle)
Test 18 - Positional Deviation Along The Y-Axis Y Positional
Test 19 - Positional Accuracy & Repeatability Of Y-Axis Y Acc Rep
Test 20 - Positional Deviation Along The Z-Axis Z Positional
Test 21 - Positional Accuracy & Repeatability Of Z-Axis Z Acc Rep
Test 22 - Perpendicularity Of Y-Axis To X-Axis (Y To X)
Test 23 - Perpendicularity Of Z-Axis To X-Axis (Z To X)
Test 24 - Perpendicularity Of Y-Axis To Z-Axis (Y To Z)
Test 25 - Table Surface Parallelism To X Axis
Test 26 - Table Surface Parallelism To Y Axis
Test 27 - Spindle1 Axial Runout
Test 28 - Spindle1 Radial Runout
Test 29 - Spindle1 Internal Taper Runout
Test 30 - Parallelism of Spindle1 Centreline to Z-Axis (in X)
Test 31 - Parallelism of Spindle1 Centreline to Z-Axis (in Y)
Test 32 - Spindle1 Trammel To X Axis
Test 33 - Spindle1 Trammel To Y Axis
Test 34 - Spindle2 Axial Runout
Test 35 - Spindle2 Radial Runout
Test 36 - Spindle2 Internal Taper Runout
Test 37 - Parallelism2 of Spindle Centreline to Z-Axis (in X)
Test 38 - Parallelism2 of Spindle Centreline to Z-Axis (in Y)
Test 39 - Spindle2 Trammel To X Axis
Test 40 - Spindle2 Trammel To Y Axis
Test 41 - Spindle3 Axial Runout
Test 42 - Spindle3 Radial Runout
Test 43 - Spindle3 Internal Taper Runout
Test 44 - Parallelism of Spindle3 Centreline to Z-Axis (in X)
Test 45 - Parallelism of Spindle3 Centreline to Z-Axis (in Y)
Test 46 - Spindle3 Trammel To X Axis
Test 47 - Spindle3 Trammel To Y Axis

Test 48 - Spindle Parallelism To Y Axis In X Plane
Test 49 - Spindle Parallelism To Y Axis In Z Plane
Test 50 - Distance Between Spindle Centrelines
Test 51 - X Axis Reference Position (X Datum)
Test 52 - Y Axis Reference Position (Y Datum)
Test 53 - Z Axis Reference Position (Z Datum)
Test 54 - Height Of X Axis Beds To Each Other
Test 55 - ZX Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 56 - ZX Plane Circularity - 360 Bi-Directional (1000mm/Min)
Test 57 - XY Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 58 - XY Plane Circularity - 360 Bi-Directional (1000mm/Min)
Test 59 - YZ Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 60 - YZ Plane Circularity - 360 Bi-Directional (1000mm/Min)

12.2.6 VTL

Test 1 - Rotary Table Levels
Test 2 - Rotary Table Planarity
Test 3 - Axial Runout Of Spindle Bearing
Test 4 - Radial Runout Of Spindle Bearing
Test 5 - Squareness Of Cross Rail To Table Rotation
Test 6 - Parallelism Of Cross Rail To Table Rotation
Test 7 - Squareness Of Ram To Table Rotation
Test 8 – Parallelism of Ram to Table Rotation
Test 9 - Spindle Axial Runout
Test 10 - Spindle Radial Runout
Test 11 - Spindle Internal Taper Runout
Test 12 - Parallelism Of Spindle Centreline To Z-Axis
Test 13 - Straightness of X axis in Vertical plane
Test 14 - Straightness of Z in horizontal plane
Test 15 - Spindle Concentricity To C-Axis Rotation
Test 16 - Angular Deviation Of The X-Axis About The Y-Axis X About Y
Test 17 - Angular Deviation Of The X-Axis About The Z-Axis X About Z
Test 18 - Positional Deviation Along The X-Axis X Positional
Test 19 - Positional Accuracy & Repeatability Of X-Axis X Accrep
Test 20 - Angular Deviation Of The Z-Axis About The X-Axis Z About X
Test 21 - Angular Deviation Of The Z-Axis About The Y-Axis Z About Y
Test 22 - Positional Deviation Along The Z-Axis Z Positional
Test 23 - Positional Accuracy & Repeatability Of Z-Axis Z Accrep
Test 24 - Positional Deviation Around The C-Axis C Positional
Test 25 - Positional Accuracy & Repeatability Of C-Axis C Accrep
Test 26 - XZ Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 27 - XZ Plane Circularity - 360 Bi-Directional (1000mm/Min)

12.2.7 Millturn

Test 1 - Z-Axis Straightness (Z In Y)
Test 2 - Z-Axis Straightness (Z In X)
Test 3 - X-Axis Straightness (X In Y)
Test 4 - X-Axis Straightness (X In Z)
Test 5 - Y-Axis Straightness (Y In X)
Test 6 - Y-Axis Straightness (Y In Z)
Test 7 - Z2-Axis Straightness (Z2 In X)
Test 8 - Z2-Axis Straightness (Z2 In Y)
Test 9 - Angular Deviation Of The Z-Axis About The X-Axis Z About X
Test 10 - Angular Deviation Of The Z-Axis About The Y-Axis Z About Y
Test 11 - Angular Deviation Of The Z-Axis About The Z-Axis Z About Z
Test 12 - Angular Deviation Of The X-Axis About The X-Axis X About X
Test 13 - Angular Deviation Of The X-Axis About The Y-Axis X About Y
Test 14 - Angular Deviation Of The X-Axis About The Z-Axis X About Z
Test 15 - Angular Deviation Of The Y-Axis About The X-Axis Y About X
Test 16 – Angular Deviation of the Y-Axis about the Y-axis Y About Y
Test 17 - Angular Deviation Of The Y-Axis About The Z-Axis Y About Z
Test 18 - Angular Deviation Of The Z2-Axis About The X-Axis Z2 About X
Test 19 - Angular Deviation Of The Z2-Axis About The Y-Axis Z2 About Y
Test 20 - Angular Deviation Of The Z2-Axis About The Z-Axis Z2 About Z
Test 21 - Positional Deviation Along The Z-Axis Z Positional
Test 22 - Positional Accuracy & Repeatability Of Z-Axis Z Accrep
Test 23 - Positional Deviation Along The X-Axis X Positional
Test 24 - Positional Accuracy & Repeatability Of X-Axis X Accrep
Test 25 - Positional Deviation Along The Y-Axis Y Positional
Test 26 - Positional Accuracy & Repeatability Of Y-Axis Y Accrep
Test 27 - Positional Deviation Along The Z2-Axis Z Positional
Test 28 - Positional Accuracy & Repeatability Of Z2-Axis Z Accrep
Test 29,30 Parallelism Of Z Axis To Headstock Centreline
Test 31 - Perpendicularity Of X-Axis To C-Axis Centreline (X To C)
Test 32 - Perpendicularity Of Y-Axis To C-Axis Centreline (Y To C)
Test 33 - Perpendicularity Of Y-Axis To X-Axis (Y To X)
Test 34,35 Headstock Axial And Radial Runout
Test 36 - Radial Runout Of Spindle Flange
Test 37 - Positional Deviation Around The C-Axis C Positional
Test 38 - Positional Accuracy And Repeatability Of C-Axis C Accrep
Test 39 - Milling Spindle Axial Runout
Test 40 - Milling Spindle Radial Runout
Test 41 - Spindle Internal Taper Runout
Test 42,43 - Spindle Parallelism To Z Axis @B=+/-90
Test 44,45 - Spindle Parallelism To X Axis
Test 46 - Perpendicularity Of The B Axis To The XZ Plane
Test 47 - Pivot Length Check
Test 48 - Repeatability Of Bore Bar Indexing
Test 49 - Positional Deviation Around The B-Axis B Positional
Test 50 - Positional Accuracy And Repeatability Of B-Axis B Accrep
Test 51 - Tailstock Spindle Centre Axial Runout

Test 52 - Tailstock Spindle Centre Radial Runout
Test 53,54 - Tailstock Spindle Parallelism To Z Axis
Test 55,56 - Tailstock Quill Parallelism To Z1 Axis In Two Planes
Test 57 - Difference In Height Between Headstock And Tailstock Centres
Test 58 - Perpendicularity Of X Axis To Z Axis
Test 59 - Perpendicularity Of Y-Axis To Z-Axis (Y To Z)
Test 60 – C datum
Test 61 – X datum
Test 62 – Y datum
Test 63 – Z datum
Test 64 – B datum
Test 65 – Z2 datum
Test 66 - ZX Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 67 - ZX Plane Circularity - 360 Bi-Directional (1000mm/Min)
Test 68 - XY Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 69 - XY Plane Circularity - 360 Bi-Directional (1000mm/Min)
Test 70 - YZ Plane Circularity - 360 Bi-Directional (270mm/Min)
Test 71 - YZ Plane Circularity - 360 Bi-Directional (1000mm/Min)

12.3 Appendix 3: Comparison Metrology/Error Indexes – Automated format

12.3.1 Cincinnati 500

#	Error		Test for error
1	XTX	=>	Positional Accuracy of X-Axis
2	XTX	=>	Accuracy and Repeatability of X-Axis
3	XRX	=>	Angular deviation of X-Axis about X
4	XTZ	=>	Straightness of X-Axis in Z direction
5	XRZ	=>	Angular deviation of X-Axis about Z
6	XTY	=>	Straightness of X-Axis in Y direction
7	XRY	=>	Angular deviation of X-Axis about Y
8	ZTX	=>	Straightness of Z-Axis in X direction
9	ZRX	=>	Angular deviation of Z-Axis about X
10	ZTZ	=>	Positional Accuracy of Z-Axis
11	ZTZ	=>	Accuracy and Repeatability of Z-Axis
12	ZRZ	=>	Angular deviation of Z-Axis about Z
13	ZTY	=>	Straightness of Z-Axis in Y direction
14	ZRY	=>	Angular deviation of Z-Axis about Y
15	YTX	=>	Straightness of Y-Axis in X direction
16	YRX	=>	Angular deviation of Y-Axis about X
17	YTZ	=>	Straightness of Y-Axis in Z direction
18	YRZ	=>	Angular deviation of Y-Axis about Z
19	YTY	=>	Positional Accuracy of Y-Axis
20	YTY	=>	Accuracy and Repeatability of Y-Axis
21	YRY	=>	Angular deviation of Y-Axis about Y
22	ZWX	=>	Squareness between Z-Axis and X-Axis
23	YWX	=>	Squareness between Y-Axis and X-Axis
24	YWZ	=>	Squareness between Y-Axis and Z-Axis

12.3.2 Geiss 5-axis trimmer

#	Error		Test for error
1	XTX	=>	Positional Accuracy of X-Axis
2	XTX	=>	Accuracy and Repeatability of X-Axis
3	XRX	=>	Angular deviation of X-Axis about X
4	XTZ	=>	Straightness of X-Axis in Z direction
5	XRZ	=>	Angular deviation of X-Axis about Z
6	XTY	=>	Straightness of X-Axis in Y direction
7	XRY	=>	Angular deviation of X-Axis about Y
8	ZTX	=>	Straightness of Z-Axis in X direction
9	ZRX	=>	Angular deviation of Z-Axis about X
10	ZTZ	=>	Positional Accuracy of Z-Axis
11	ZTZ	=>	Accuracy and Repeatability of Z-Axis
12	ZRZ	=>	Angular deviation of Z-Axis about Z
13	ZTY	=>	Straightness of Z-Axis in Y direction
14	ZRY	=>	Angular deviation of Z-Axis about Y
15	YTX	=>	Straightness of Y-Axis in X direction
16	YRX	=>	Angular deviation of Y-Axis about X
17	YTZ	=>	Straightness of Y-Axis in Z direction
18	YRZ	=>	Angular deviation of Y-Axis about Z
19	YTY	=>	Positional Accuracy of Y-Axis
20	YTY	=>	Accuracy and Repeatability of Y-Axis
21	YRY	=>	Angular deviation of Y-Axis about Y
22	BTX	=>	Radial runout of B-Axis in X direction
23	BRX	=>	Angular deviation of B-Axis about X
24	BTZ	=>	Radial runout of B-Axis in Z direction
25	BRZ	=>	Angular deviation of B-Axis about Z
26	BTY	=>	Axial runout of B-Axis
27	BRY	=>	Positional Accuracy of B-Axis
28	BRY	=>	Accuracy and Repeatability of B-Axis
29	BOC	=>	Offset between B-Axis and C-Axis
30	CTX	=>	Radial runout of C-Axis in X direction
31	CRX	=>	Angular deviation of C-Axis about X
32	CTZ	=>	Axial runout of C-Axis
33	CRZ	=>	Positional Accuracy of C-Axis
34	CRZ	=>	Accuracy and Repeatability of C-Axis
35	CTY	=>	Radial runout of C-Axis in Y direction
36	CRY	=>	Angular deviation of C-Axis about Y
37	XWY	=>	Squareness between X-Axis and Y-Axis
38	ZWX	=>	Squareness between Z-Axis and X-Axis
39	ZWY	=>	Squareness between Z-Axis and Y-Axis
40	BWX	=>	Parallelism of B-Axis Plane of rotation to X-Axis
41	BWZ	=>	Parallelism of B-Axis Plane of rotation to Z-Axis
42	CWX	=>	Parallelism of C-Axis to Z-Axis in X direction
43	CWY	=>	Parallelism of C-Axis to Z-Axis in Y direction

12.3.3 Long bed profiling machine

#	Error		Test for error
1	XTZ	=>	Straightness of X-Axis in Z direction
2	XRZ	=>	Angular deviation of X-Axis about Z
3	XTY	=>	Straightness of X-Axis in Y direction
4	XRY	=>	Angular deviation of X-Axis about Y
5	ZTX	=>	Straightness of Z-Axis in X direction
6	ZRX	=>	Angular deviation of Z-Axis about X
7	ZTZ	=>	Positional Accuracy of Z-Axis
8	ZTZ	=>	Accuracy and Repeatability of Z-Axis
9	ZRZ	=>	Angular deviation of Z-Axis about Z
10	ZTY	=>	Straightness of Z-Axis in Y direction
11	ZRY	=>	Angular deviation of Z-Axis about Y
12	YTX	=>	Straightness of Y-Axis in X direction
13	YRX	=>	Angular deviation of Y-Axis about X
14	YTZ	=>	Straightness of Y-Axis in Z direction
15	YRZ	=>	Angular deviation of Y-Axis about Z
16	YTY	=>	Positional Accuracy of Y-Axis
17	YTY	=>	Accuracy and Repeatability of Y-Axis
18	YRY	=>	Angular deviation of Y-Axis about Y
19	Z1TX	=>	Straightness of Z1-Axis in X direction
20	Z1RX	=>	Angular deviation of Z1-Axis about X
21	Z1TZ	=>	Positional Accuracy of Z1-Axis
22	Z1TZ	=>	Accuracy and Repeatability of Z1-Axis
23	Z1RZ	=>	Angular deviation of Z1-Axis about Z
24	Z1TY	=>	Straightness of Z1-Axis in Y direction
25	Z1RY	=>	Angular deviation of Z1-Axis about Y
26	B1TX	=>	Radial runout of B1-Axis in X direction
27	B1RX	=>	Angular deviation of B1-Axis about X
28	B1TZ	=>	Radial runout of B1-Axis in Z direction
29	B1RZ	=>	Angular deviation of B1-Axis about Z
30	B1TY	=>	Axial runout of B1-Axis
31	B1RY	=>	Positional Accuracy of B1-Axis
32	B1RY	=>	Accuracy and Repeatability of B1-Axis
33	B1OC1	=>	Offset between B1-Axis and C1-Axis
34	C1TX	=>	Radial runout of C1-Axis in X direction
35	C1RX	=>	Angular deviation of C1-Axis about X
36	C1TZ	=>	Axial runout of C1-Axis
37	C1RZ	=>	Positional Accuracy of C1-Axis
38	C1RZ	=>	Accuracy and Repeatability of C1-Axis
39	C1TY	=>	Radial runout of C1-Axis in Y direction
40	C1RY	=>	Angular deviation of C1-Axis about Y
41	Z2TX	=>	Straightness of Z2-Axis in X direction
42	Z2RX	=>	Angular deviation of Z2-Axis about X
43	Z2TZ	=>	Positional Accuracy of Z2-Axis
44	Z2TZ	=>	Accuracy and Repeatability of Z2-Axis
45	Z2RZ	=>	Angular deviation of Z2-Axis about Z
46	Z2TY	=>	Straightness of Z2-Axis in Y direction

#	Error		Test for error
47	Z2RY	=>	Angular deviation of Z2-Axis about Y
48	B2TX	=>	Radial runout of B2-Axis in X direction
49	B2RX	=>	Angular deviation of B2-Axis about X
50	B2TZ	=>	Radial runout of B2-Axis in Z direction
51	B2RZ	=>	Angular deviation of B2-Axis about Z
52	B2TY	=>	Axial runout of B2-Axis
53	B2RY	=>	Positional Accuracy of B2-Axis
54	B2RY	=>	Accuracy and Repeatability of B2-Axis
55	B2OC2	=>	Offset between B2-Axis and C2-Axis
56	C2TX	=>	Radial runout of C2-Axis in X direction
57	C2RX	=>	Angular deviation of C2-Axis about X
58	C2TZ	=>	Axial runout of C2-Axis
59	C2RZ	=>	Positional Accuracy of C2-Axis
60	C2RZ	=>	Accuracy and Repeatability of C2-Axis
61	C2TY	=>	Radial runout of C2-Axis in Y direction
62	C2RY	=>	Angular deviation of C2-Axis about Y
63	Z3TX	=>	Straightness of Z3-Axis in X direction
64	Z3RX	=>	Angular deviation of Z3-Axis about X
65	Z3TZ	=>	Positional Accuracy of Z3-Axis
66	Z3TZ	=>	Accuracy and Repeatability of Z3-Axis
67	Z3RZ	=>	Angular deviation of Z3-Axis about Z
68	Z3TY	=>	Straightness of Z3-Axis in Y direction
69	Z3RY	=>	Angular deviation of Z3-Axis about Y
70	B3TX	=>	Radial runout of B3-Axis in X direction
71	B3RX	=>	Angular deviation of B3-Axis about X
72	B3TZ	=>	Radial runout of B3-Axis in Z direction
73	B3RZ	=>	Angular deviation of B3-Axis about Z
74	B3TY	=>	Axial runout of B3-Axis
75	B3RY	=>	Positional Accuracy of B3-Axis
76	B3RY	=>	Accuracy and Repeatability of B3-Axis
77	B3OC3	=>	Offset between B3-Axis and C3-Axis
78	C3TX	=>	Radial runout of C3-Axis in X direction
79	C3RX	=>	Angular deviation of C3-Axis about X
80	C3TZ	=>	Axial runout of C3-Axis
81	C3RZ	=>	Positional Accuracy of C3-Axis
82	C3RZ	=>	Accuracy and Repeatability of C3-Axis
83	C3TY	=>	Radial runout of C3-Axis in Y direction
84	C3RY	=>	Angular deviation of C3-Axis about Y
85	ZWX	=>	Squareness between Z-Axis and X-Axis
86	ZWY	=>	Squareness between Z-Axis and Y-Axis
87	YWX	=>	Squareness between Y-Axis and X-Axis
88	Z1WX	=>	Squareness between Z1-Axis and X-Axis
89	Z1WY	=>	Squareness between Z1-Axis and Y-Axis
90	B1WX	=>	Parallelism of B1-Axis Plane of rotation to X-Axis
91	B1WZ	=>	Parallelism of B1-Axis Plane of rotation to Z-Axis
92	C1WX	=>	Parallelism of C1-Axis to Z-Axis in X direction
93	C1WY	=>	Parallelism of C1-Axis to Z-Axis in Y direction
94	Z2WX	=>	Squareness between Z2-Axis and X-Axis
95	Z2WY	=>	Squareness between Z2-Axis and Y-Axis

#	Error		Test for error
96	B2WX	=>	Parallelism of B2-Axis Plane of rotation to X-Axis
97	B2WZ	=>	Parallelism of B2-Axis Plane of rotation to Z-Axis
98	C2WX	=>	Parallelism of C2-Axis to Z-Axis in X direction
99	C2WY	=>	Parallelism of C2-Axis to Z-Axis in Y direction
100	Z3WX	=>	Squareness between Z3-Axis and X-Axis
101	Z3WY	=>	Squareness between Z3-Axis and Y-Axis
102	B3WX	=>	Parallelism of B3-Axis Plane of rotation to X-Axis
103	B3WZ	=>	Parallelism of B3-Axis Plane of rotation to Z-Axis
104	C3WX	=>	Parallelism of C3-Axis to Z-Axis in X direction
105	C3WY	=>	Parallelism of C3-Axis to Z-Axis in Y direction

12.3.4 VTL

#	Error		Test for error
1	XTX	=>	Positional Accuracy of X-Axis
2	XTX	=>	Accuracy and Repeatability of X-Axis
3	XRX	=>	Angular deviation of X-Axis about X
4	XTZ	=>	Straightness of X-Axis in Z direction
5	XRZ	=>	Angular deviation of X-Axis about Z
6	XTY	=>	Straightness of X-Axis in Y direction
7	XRY	=>	Angular deviation of X-Axis about Y
8	ZTX	=>	Straightness of Z-Axis in X direction
9	ZRX	=>	Angular deviation of Z-Axis about X
10	ZTZ	=>	Positional Accuracy of Z-Axis
11	ZTZ	=>	Accuracy and Repeatability of Z-Axis
12	ZRZ	=>	Angular deviation of Z-Axis about Z
13	ZTY	=>	Straightness of Z-Axis in Y direction
14	ZRY	=>	Angular deviation of Z-Axis about Y
15	CTX	=>	Radial runout of C-Axis in X direction
16	CRX	=>	Angular deviation of C-Axis about X
17	CTZ	=>	Axial runout of C-Axis
18	CRZ	=>	Positional Accuracy of C-Axis
19	CRZ	=>	Accuracy and Repeatability of C-Axis
20	CTY	=>	Radial runout of C-Axis in Y direction
21	CRY	=>	Angular deviation of C-Axis about Y
22	CRTX	=>	Straightness of CR-Axis in X direction
23	CRRX	=>	Angular deviation of CR-Axis about X
24	CRTZ	=>	Positional Accuracy of CR-Axis
25	CRTZ	=>	Accuracy and Repeatability of CR-Axis
26	CRRZ	=>	Angular deviation of CR-Axis about Z
27	CRTY	=>	Straightness of CR-Axis in Y direction
28	CRRY	=>	Angular deviation of CR-Axis about Y
29	X2TX	=>	Positional Accuracy of X2-Axis
30	X2TX	=>	Accuracy and Repeatability of X2-Axis
31	X2RX	=>	Angular deviation of X2-Axis about X
32	X2TZ	=>	Straightness of X2-Axis in Z direction
33	X2RZ	=>	Angular deviation of X2-Axis about Z
34	X2TY	=>	Straightness of X2-Axis in Y direction
35	X2RY	=>	Angular deviation of X2-Axis about Y
36	Z2TX	=>	Straightness of Z2-Axis in X direction
37	Z2RX	=>	Angular deviation of Z2-Axis about X
38	Z2TZ	=>	Positional Accuracy of Z2-Axis
39	Z2TZ	=>	Accuracy and Repeatability of Z2-Axis
40	Z2RZ	=>	Angular deviation of Z2-Axis about Z
41	Z2TY	=>	Straightness of Z2-Axis in Y direction
42	Z2RY	=>	Angular deviation of Z2-Axis about Y
43	XWZ	=>	Parallelism of X-Axis to C-Axis plane of rotation
44	ZWX	=>	Parallelism of Z-Axis to C-Axis centreline in X direction
45	ZWY	=>	Parallelism of Z-Axis to C-Axis centreline in Y direction
46	CRWX	=>	Parallelism of CR-Axis to C-Axis centreline in X direction

#	Error		Test for error
47	CRWY	=>	Parallelism of CR-Axis to C-Axis centreline in Y direction
48	X2WZ	=>	Parallelism of X2-Axis to C-Axis plane of rotation
49	X2WY	=>	Squareness between X2-Axis and Y-Axis
50	Z2WX	=>	Parallelism of Z2-Axis to C-Axis centreline in X direction
51	Z2WY	=>	Parallelism of Z2-Axis to C-Axis centreline in Y direction

12.3.5 Millturn

#	Error		Test for error
1	XTX	=>	Positional Accuracy of X-Axis
2	XTX	=>	Accuracy and Repeatability of X-Axis
3	XRX	=>	Angular deviation of X-Axis about X
4	XTY	=>	Straightness of X-Axis in Y direction
5	XRY	=>	Angular deviation of X-Axis about Y
6	XTZ	=>	Straightness of X-Axis in Z direction
7	XRZ	=>	Angular deviation of X-Axis about Z
8	ZTX	=>	Straightness of Z-Axis in X direction
9	ZRX	=>	Angular deviation of Z-Axis about X
10	ZTY	=>	Straightness of Z-Axis in Y direction
11	ZRY	=>	Angular deviation of Z-Axis about Y
12	ZTZ	=>	Positional Accuracy of Z-Axis
13	ZTZ	=>	Accuracy and Repeatability of Z-Axis
14	ZRZ	=>	Angular deviation of Z-Axis about Z
15	YTX	=>	Straightness of Y-Axis in X direction
16	YRX	=>	Angular deviation of Y-Axis about X
17	YTY	=>	Positional Accuracy of Y-Axis
18	YTY	=>	Accuracy and Repeatability of Y-Axis
19	YRY	=>	Angular deviation of Y-Axis about Y
20	YTZ	=>	Straightness of Y-Axis in Z direction
21	YRZ	=>	Angular deviation of Y-Axis about Z
22	Z1TX	=>	Straightness of Z1-Axis in X direction
23	Z1RX	=>	Angular deviation of Z1-Axis about X
24	Z1TY	=>	Straightness of Z1-Axis in Y direction
25	Z1RY	=>	Angular deviation of Z1-Axis about Y
26	Z1TZ	=>	Positional Accuracy of Z1-Axis
27	Z1TZ	=>	Accuracy and Repeatability of Z1-Axis
28	Z1RZ	=>	Angular deviation of Z1-Axis about Z
29	BTX	=>	Radial runout of B-Axis in X direction
30	BRX	=>	Angular deviation of B-Axis about X
31	BTY	=>	Axial runout of B-Axis
32	BRY	=>	Positional Accuracy of B-Axis
33	BRY	=>	Accuracy and Repeatability of B-Axis
34	BTZ	=>	Radial runout of B-Axis in Z direction
35	BRZ	=>	Angular deviation of B-Axis about Z
36	CTX	=>	Radial runout of C-Axis in X direction
37	CRX	=>	Angular deviation of C-Axis about X
38	CTY	=>	Radial runout of C-Axis in Y direction
39	CRY	=>	Angular deviation of C-Axis about Y
40	CTZ	=>	Axial runout of C-Axis
41	CRZ	=>	Positional Accuracy of C-Axis
42	CRZ	=>	Accuracy and Repeatability of C-Axis
43	XWZ	=>	Parallelism of X-Axis to C-Axis plane of rotation
44	ZWX	=>	Parallelism of Z-Axis to C-Axis centreline in X direction
45	ZWY	=>	Parallelism of Z-Axis to C-Axis centreline in Y direction
46	YWX	=>	Squareness between Y-Axis and X-Axis

#	Error		Test for error
47	YWZ	=>	Parallelism of Y-Axis to C-Axis plane of rotation
48	Z1WX	=>	Parallelism of Z1-Axis to C-Axis centreline in X direction
49	Z1WY	=>	Parallelism of Z1-Axis to C-Axis centreline in Y direction
50	BWX	=>	Squareness between B-Axis and X-Axis
51	BWZ	=>	Parallelism of B-Axis to C-Axis plane of rotation