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Machine tool health verification

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Abstract
With stringent safety requirements, tight tolerances, and high-value components, it is imperative that the performance of a machine tool used in the aerospace industry is gauged prior to conducting any machining operations. Routine calibration gives confidence that a machine tool is running within specification, and will therefore be likely to produce good parts. Unfortunately, the full calibration of a machine tool is a lengthy process, making it impractical and costly to a business to run regularly – usually occurring no more than once per year. Instead, there is a necessity for machine tool health verification: a short routine that can be run regularly (i.e. once per shift, day, or week) to ensure a machine tool remains in good working order between calibrations.

This research identified a number of key failure modes that can affect machine tools in aerospace manufacture and proposed solutions that could be utilised in testing for these. To fulfil this, a review of existing commercial systems that could be used for machine health verification, as well as those found in the literature, was conducted. Historical failure mode effect analysis documents from an aerospace manufacturer were examined and compared with current processes to identify faults and down-select those that currently do not have adequate checks in place. From this, a machine health verification suite was proposed which could provide the means to verify if a machine tool is suffering from these particular failure modes.

This paper presents the main findings from the technology and literature scan; outlines the failure mode analysis and down-selection process; and provides the seven proposed solutions to detect the key failure modes identified as: spindle runout, power monitoring, coolant concentration, spindle and work table vibration, coolant contamination, and coolant flow and pressure.

Keywords
Machine tool health verification; spindle runout; power monitoring; coolant concentration; spindle vibration; work table vibration; coolant contamination; coolant flow; coolant pressure; machine tool failure mode effect analysis.

1. Introduction

In any high-precision machining environment, it is important to determine that a machine tool (MT) is in a state that will allow it to produce parts that are within tolerance before any cuts are made. Although exact figures relating to scrapping parts are not widely publicised, in their case study Schmahl et al [1] found approximately 15% of labour time in a machining shop was associated with rework or scrap. Boeing also estimated that they lose around $300 million per year through reworking and scrapping parts [2]. One potential method of reducing scrap is machine health verification (MHV) - a series of regular checks used to determine that the critical characteristics of a MT are running within tolerance.

Currently, there exist a number of systems that are commercially available for MHV; the majority of which focus mainly on kinematic checks through on-machine probing. Whilst kinematic errors do account for a large proportion of the MT's limitation on performance; they are by no means exhaustive when it comes to assessing a MT's overall performance.

To address this issue, the research presented in this paper determined the requirements for a more comprehensive MHV suite for a particular mill-turn MT platform. This included documenting the current state of the art through a general literature and commercial technology review of methods and technologies that could be utilised for MHV. Identification of requirements for MHV was conducted through examination of historical MT failure mode effect analysis (FMEA) documents, and down-selection of failure mode detection methods. Finally, a specific MHV solution is proposed through targeted technology reviews – aimed to address each of the down-selected failure mode detection methods.

2. Literature and technology review

A comprehensive literature and technology review was conducted as part of this research to identify state of the art methods and technologies that could be utilised for MHV of a MT. A selection of the more novel and significant findings are included below.

2.1. Commercially available technology

The use of on-machine probes to carry out kinematic checks through the probing of calibrated artefacts is well established, and many MT builders include such routines as standard. For the most part, these are quasi-static tests and so dynamic performance of the MT is not tested. The advent of contact scanning probes, such as Renishaw SPRINT, has allowed the development of kinematic checks that are: significantly faster; produce more data-rich results; and allow for dynamic checks. SPRINT is able to carry out fully-automated kinematic and rotational error measurements of 5-axis machines through a unique "ball-in-cone" method in less than one minute [3]. Other specialised technologies, such as those produced by IBS (Position Inspector and Rotary Inspector), are able to provide similar testing capabilities. However, the major advantage of SPRINT is that these kinematic checks are in addition to their primary purpose of high-resolution contact-scanning measurement of the workpiece.

Drawbar force is one contributing factor to spindle stiffness [4], which can also help to reduce chatter and excessive wear. The routine for testing drawbar force is relatively simple: a force gauge is loaded into the spindle, the force reading is checked against a minimum value (defined by the MT manufacturer), and the force gauge will then be removed. TAC Rockford manufacture the ForceCheck series of force gauges, which includes a machine-integrated wireless variant. This particular variant is designed to be stored in the magazine of the MT and loaded into the spindle automatically; making it well-suited for MHV.

Although a wide range of flow meters are available, there is little that is specific to the application of coolant flow checks in MTs. For practical reasons, these are usually intended for permanent installation part way through the system, and not at the critical point where the fluid exits the tool. One exception to this is the TAC Rockford MQL check; a device designed for checking coolant flow in minimum quantity lubrication operations. It is a battery powered device that can be installed into the work volume of the machine, and transmits the flow readings wirelessly to its associated display equipment. The tip of the cutting tool is driven into the aperture in the flow meter which can then measure the flow rate of the coolant exiting the tool-tip. This is obviously a highly-specialised device, as only the measurements of through-tool coolant can be measured, and not that of flood coolant.

Temperature is often used in many sectors of industry as an indicator to process and machine health. To this end, a vast number of industrial temperature sensors, particularly in the guise of thermocouples, are widely available. A more novel approach to temperature measurement is the m&h Temperature Probe. This probe has been designed primarily for the purpose of measuring the temperature of the workpiece before and during machining operations. It can be loaded from the tool magazine and its operation can be fully automated as part of the machining procedure. Although it has been developed for workpiece temperature measurement, there is no reason this device could not also be used on any key part of the MT that the machine head can be driven to, e.g. chuck, steady rests, work bed, etc. This would help determine whether the MT could be subject to any thermal expansion, without the need to take precise, and often timely, volumetric measurements.

2.2. Academic literature

Rahman and Mayer [7] developed a method in which facets in the work bed of the machine tool can be used as an indigenous uncalibrated artefact for a probing routine. This technique uses nothing but the MT's touch probe and un-altered work bed to calculate volumetric errors and backlash (excluding z-axis measurements), with the option of adding a scale bar to calculate absolute scale factors, rather than relative ones. During preliminary testing, the authors investigated the effects of wetting the surface of the work bed with coolant. They found that this only had an effect of ~1 μm on the repeatability of the measurements, meaning that the procedure could be run without the need for an operator to clean the work bed surface of coolant or manually load any artefact or tools. Although the probing test conducted by the authors totalled 2 hours 41 minutes, this was for a detailed calibration routine, so it may be plausible that a far shorter routine may suffice for MHV.

Vogl et al [8] developed a multi-sensor box for the purpose of measuring degradation of linear axes. The device they developed contained one tri-axial rate gyroscope, three accelerometers and two inclinometers, all contained within a metal housing to make it suitable for use in a harsh machining environment. The sensor box was tested on a linear axis testbed, with a commercial laser interferometer system for reference. The testing proved that the device was sensitive to micrometer- and microradian-level degradation, but further testing is required to determine the uncertainty in the device's measurements. If proven to be successful, a number of these devices could be permanently mounted onto components of a MT that utilise linear axes (e.g. tool head, work bed, steady rest, etc) and regular short routines to test each axes could be implemented for MHV.

In previous research conducted at the AMRC, a device for automated tap-testing (Impact Hammer Modal Testing) was developed to allow testing to be undertaken whilst the spindle is run at speed – something not usually possible with manual methods. The device consists mainly of a programmable linear solenoid actuator to act as the hammer, and 2 capacitive displacement sensors to measure the resulting vibrations of the spindle. The device was tested and validated on spindle speeds of up to 30,000 RPM, and was found to have high repeatability. With this system in place, conventional tap-testing could take place automatically at pre-defined intervals to measure the specific response of each machine and cutting tool combination. To gain a picture of the health of the machine tool more generally, it may be possible to use a non-cutting calibrated tool, or even to tap test the spindle directly whilst unloaded, thus removing the variation introduced with varying cutting tools and tool conditions. Although it may be difficult to diagnose any particular issues/faults with the machine tool from this data, if the response was monitored over time, any sudden changes or drift may indicate an issue and further investigation could be carried out.

3. Definition of key failure modes

Considering the complexity of modern day MTs, there is a vast array of failure modes that can occur, each with numerous potential detection methods. Even if it were possible to devise a strategy of MHV that encapsulates all possible failure modes, this would no doubt require an excessive amount of time to run and would therefore be unsuitable for a regular 'quick check'. Instead, the key failure modes needed to be identified and prioritised to allow a suitable MHV routine to be developed.

3.1. FMEAs

It was decided that the best course of action would be to examine existing documentation for issues that are known to affect operations. A process failure mode effect analysis (PFMEA) document for operations run on a modern, 5-axis mill-turn machine and process and equipment FMEA document for an advanced turn-mill MT from Rolls-Royce were examined. The most prominent of these failure modes included items such as: spindle concentricity loss due to bearing wear or crash damage; axis failure due to ballscrew wear; and tool changer crash due to control issue.

321 line items were consolidated into a single document. An initial sweep was then carried out to remove low-risk items and items that already had suitable preventative action(s) in place. This left a total of 74 individual failure modes which could be grouped into the individual failure points and further into the three key sub-systems of the MT: spindle; linear and rotary axes; and tool changer. Through discussions with Manufacturing Engineers from Rolls-Royce, further requirements for verifying coolant delivery and condition; as well as kinematics, were also identified. The failure points grouped into their associated sub-systems are given in Table 1.

Table 1 – Sub-systems and associated failure points of a MT.

Linear and rotary axes	Spindle	Kinematics	Coolant	Tool Changer
Ball screw	Motor	Linear and rotary axis positioning	Coolant pumps	Limit switches
Ball screw bearings	Encoder	Drive parameters	Feed pipes	Controller/ Software
Motor	Bearings		Coolant condition	Carousel/ Magazine
Encoder	Coolant pipe			Changing arm
Taper lock coupling	Crash damage			Tool reader
Slideway	Collet/ drawbar			
Slideway wipers				
Control				
Oil cooling seals				

Potential symptoms for each failure mode were then identified and added to the consolidated FMEA. By doing this, it was found that certain symptoms are shared by failure modes; and so multiple failure modes could potentially be detected by a single monitoring method. By indexing the failure modes by symptom, identification of which failure modes could be measured by employing the same measurement methods was simplified.

To maximise efficiency, and therefore provide a more appealing solution for industry, measurement methods that detected the most potential failure modes for each area of the MT were prioritised. This gave a shortlist of 14 measurement methods:

- **artefact probing routine** – kinematics;
- **runout monitoring** – spindle damage and failures;
- **servo power monitoring** – axis and spindle motor performance;
- **coolant refractometry** – coolant concentration;
- **spindle-mounted accelerometer** – spindle performance and machine head motion;
- **work-table mounted accelerometer** – work-table motion (and balancing for mill-turns)
- **coolant particulate monitoring** – coolant contamination;
- **all-in-one coolant monitoring system** – coolant concentration, temperature, level and usage.
- **oil/lubricant particulate monitoring** – degradation of axes;
- **coolant flow and pressure monitoring** – delivery of coolant;
- **limit switch routine** – limit switch performance;
- **spindle tachometer** – drive parameters and spindle performance; and
- **tool holder-integrated accelerometer** – tool changer performance.

Commercially available technology for each of these methods was then briefly investigated in five mini-studies (one for each sub-system) to gain an understanding of the range of equipment that was available and its suitability for application in this research. The details of these 14 measurement methods from the mini-studies were then compiled into a single down-selection matrix.

3.2. Down-selection

The down-selection matrix was devised amongst the research team in an attempt to consider all aspects of implementing a new system within a production facility. The factors included in the decision making were: **cost** (of equipment); **implementation** (time required for implementation, including development and testing); **installation** (downtime for installation); **duration** (downtime for each check); **technical risk** (risk of failure based on maturity of technology and experience of method within AMRC); **industrial partner interest** (expressed interest from the Rolls-Royce stakeholders).

Due to the limited time available during the mini-study phase, it was not possible to carry out full supplier engagement to gain all details required. Instead, information freely available in online marketing material, and prior experience of similar technologies, was used to provide estimates of cost, implementation, installation and duration for each system. These estimates comprised of a minimum and maximum value to account for the best and worst case scenarios, respectively. From these, a mean value was also calculated. To make each of these values comparable, they were quantised into a scoring of one to five; one being shortest/cheapest/most desirable; five being the longest/most expensive/undesirable.

Overall scores were calculated for each measurement method by multiplying all factors together. This produced an upper, lower and average score from the minimum, maximum and mean estimates, respectively. All factors were equally weighted with the exception of industrial partner interest. This was double-weighted as it represented first-hand experience of the risk associated with each failure mode, and support/interest for each technology from the stakeholders. Ranking of the methods was then possible by sorting by the overall average score and is shown in Table 2. Please note – the lower the score, the better.

Table 2 – Ranking of the proposed measurement methods, including lower, upper, and average estimated scorings.

Measurement Method	Min Score	Max score	Average Score
Artefact probing routine	64	288	128
Runout monitoring	4	750	180
Servo power monitoring	48	600	192
Coolant refractometry	72	600	288
Spindle-mounted accelerometer	144	800	384
Work-table mounted accelerometer	192	800	384
Coolant particulate monitoring	128	1280	432
Coolant flow monitoring	96	1280	432
Oil/lubricant particulate monitoring	256	2048	576
All-in-one coolant monitor	800	1600	800
Coolant pressure gauge	384	5120	1728
Limit switch routine	750	12000	2250
Spindle tachometer	900	6750	2400
Tool holder integrated accelerometer	4500	10000	6000

Key: Best (4) Worst (12000)

4. Proposed design of solution

Although an ideal solution would include all of the technologies in Table 2, restrictions on budget and resources meant that only some of these could be selected for further investigation. In conjunction with the Rolls-Royce stakeholders, it was decided that sufficient coverage for their operations would be provided by the top eight of these methods, and therefore future research and testing could focus on these. This section provides an overview of the technology proposed for each method that were deemed suitable for the target machine (a mill-turn MT). It should be noted that the industrial partner developed their own solution for artefact probing, the details of which are not included in this paper.

4.1. Spindle runout

It was known that the target MT is supplied with a factory-fitted Blum Micro Compact NT laser tool setter. Upon investigation, it was found that this model features the 'RunoutControl' routine. This allows the runout of the spindle to be determined automatically in less than one minute, making it ideal for MHV. 'RunoutControl' could be used to trend spindle performance over time and highlight degradation.

4.2. Servo power monitoring

The target machine tool supplier have developed a wear diagnosis system (WDS) which utilises a combination of servo signals, accelerometer readings and thermocouple data available to the controller to analyse the condition of the MT during a short routine. The data collected is sent to the OEM for analysis and a full report is produced for a fee. Potentially the data produced during this routine could be analysed locally. Unfortunately, the complexity of the work required for developing an analysis method for this data is unknown, and could require many months of work. Alternatively, retro-fitted sensors could be utilised, for which there would be additional cost and installation time required.

4.3. Coolant concentration

In-line devices, such as the K-Patents process refractometer, make it possible to monitor the concentration of a liquid continuously, with sampling times ranging from as little as 1 s to a number of minutes. This means coolant concentration can be monitored with no downtime required. Data can be logged and an alarm set up within the PLC (using a 4-20 mA connection) that is triggered when the coolant strays from the desired concentration level.

4.4. Spindle and work table vibration

It was discovered that the target MT has factory-fitted accelerometers on the spindle-casing and embedded in the work-table. Due to the MT configuration, the spindle-mounted accelerometer could monitor vibrations introduced by X-, Y- and Z-axis linear motions and spindle rotation. The work table accelerometer would be able to capture those introduced by A- and C-axis rotary movements. Therefore, if testing proved these sensors suitable, the only additional equipment required would be a data acquisition unit to collect these signals. To conduct MHV with these signals, a 'fingerprint' routine is proposed, in which each of the MTs axes and spindle are run in isolation. The vibrational fingerprint produced during this repeatable routine could then be monitored and trended over time to detect any degradation in each of the MT components' motions. This solution may require significant implementation effort to develop the analysis software, and if the existing sensors are not suitable, additional accelerometers may be required.

4.5. Coolant contamination

Filtertechnik's Particle Pal and PC9001 particle counters are devices that use a laser light blockade principle to measure the size and number of particles in a fluid; primarily pure oil, water or fuel. The Particle Pal is a battery-powered, portable unit; whilst the PC9001 is a static in-line device. The Particle Pal would cost around double that of the PC9001 – though it should be noted that the Particle Pal can be used to measure multiple MTs, thus reducing the cost per machine. Installation and implementation should be fairly straightforward with these technologies. However, the effectiveness of the laser blockade method on an emulsion such as coolant is an unknown. The droplets of oil in the coolant may trigger counts erroneously, making it difficult to distinguish between the metal fines/contaminants and oil.

4.6. Coolant flow

A device similar to IFM's mechatronic flow meter would be ideally suited for coolant flow monitoring. A short routine in which flood coolant and through-tool coolant are cycled would be required. This would also require the loading of a standard non-operational tool to provide a comparable result for through-tool coolant. This would reduce variability that could be introduced by tool damage or blockages. This check should take no longer than one minute to complete.

5. Conclusions and recommendations

This research has investigated the requirements for MT health verification and provided a proposal for a MHV suite suitable for an advanced mill-turn MT. This suite, outlined in Table 2, has been selected to minimise cost and downtime for the MT, whilst maximising the failure mode detection capability. With the exception of the WDS, this suite may be suitable for use on any MT platform.

It is hoped that future research could develop and test each of these technologies for the application of MHV on a MT.

Table 3 – Comparison table of proposed solutions for the target MT.

	Cost of equipment	**Time for implementation** (months)	**Time for installation** (days)	**Duration of check** (mins)
RunoutControl	Installed	0.5-0.75	0	<1
Wear diagnosis system	Installed	3-12	0.1	2-3
Refractometer	Medium	1-3	0.25-1	Continuous
Accelerometers	Medium	6-12	0.25-0.5	1-2
Particulates (in-line)	Low	1-3	0.5-1	Continuous
Particulates (portable)	Medium*	1-3	0	5**
Flow meter	Very low	1-2	0.25-0.5	<1

**One device can serve multiple machines so the cost per machine would be 'low'.*

***This could occur whilst machine is running so may not add to down-time.*

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