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Review

Traceability on Machine Tool Metrology: A Review

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Abstract: Errors during manufacture of high value components are not acceptable nowadays in driving industries such as energy and transportation. Sectors such as aerospace, automotive, shipbuilding, nuclear power, large science facilities or wind power manufacture complex and accurate components that demand close measurements and fast feedback into manufacturing processes. New measuring technologies are already available in machine tools, including integrated touch probes and fast interface capabilities. They shall provide the possibility to measure the workpiece during or after the manufacturing process, maintaining the original setup of the workpiece and avoiding the manufacturing process from being interrupted to transport the workpiece to a measuring position. However, the traceability of the measurement process on a machine tool is not ensured yet and measurement data is still not fully reliable for process control or product validation. Due to the similarity between a coordinate measuring machine and a machine tool, some of the methods applied for a correct assessment of uncertainty in coordinate measuring machines are adapted to the challenges of a machine tool. The scientific objective is to determine the uncertainty on a machine tool measurement and, in this way, convert it into a machine integrated traceable measuring process. This paper reviews the fundamentals of machine tool metrology.

Keywords: machine tool metrology; temperature, uncertainty; traceability, error sources

1. Introduction

Machine tool metrology can be employed at different stages of the manufacturing cycle. It may be applied for machine geometry error monitoring or fast workpiece setup, in-process measurement for flexible manufacturing or post-process measurement for product validation. However, on machine tool measurement is influenced by different error sources that are not fully understood yet, which lead to a lack of metrological traceability chain.

This paper contains a review of the existing technologies and methodologies for traceability assessment on machine tool (MT) measurements. In addition, uncertainty error sources that affect the measurement are analysed in deep and a quantitative approach based error budget is suggested for determining major error sources.

Currently, three different methods are being considered for a correct uncertainty assessment on a machine tool dimensional measurement, approaches based on ISO 15530-3, ISO 15530-4 and VDI 2617-11 standards.

ISO 15530-3 is a method of substitution that simplifies uncertainty evaluation by means of similarity between the dimension and shape of the workpiece achieved on the MT and the calibrated workpiece or standard that is employed for uncertainty characterization [1]. ISO 15530-4 is based on a numerical simulation of the measuring process allowed for uncertainty influences, where important influence quantities are taken into account [2]. VDI 2617-11 of the German Engineering Association (VDI) is the third approach; this method comprises an uncertainty budget where uncertainty sources that affect the measurement process and the correlation between them are considered [3].

For small batch production, mainly in large scale manufacture, substitution method is not an affordable solution because a calibrated workpiece similar to the manufactured part is needed. This

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requirement makes the solution arduous and expensive. Therefore, uncertainty budget based solution is being adopted for the machine measurement of large workpieces [4].

For serial production, usually for small and medium size components, substitution method simplifies uncertainty evaluation. Thus, task specific uncertainty can be assessed.

The method linked to the ISO 15530-4 standard has been already developed and applied for coordinate measuring machine (CMM) uncertainty assessment. However, it has not been developed for traceable machine tool metrology yet.

2. Flexible manufacturing with metrology feedback

In order to achieve self-adapting manufacturing processes, dimensional measurements can be employed at different stages of the manufacturing cycle: from the setup and preparation of the MT to be geometrically fitted to the performance of a final metrology validation of the finished product for final inspection reports and statistical trend analysis. The top four reasons from which in-process measurement would benefit could be listed as follows [5].

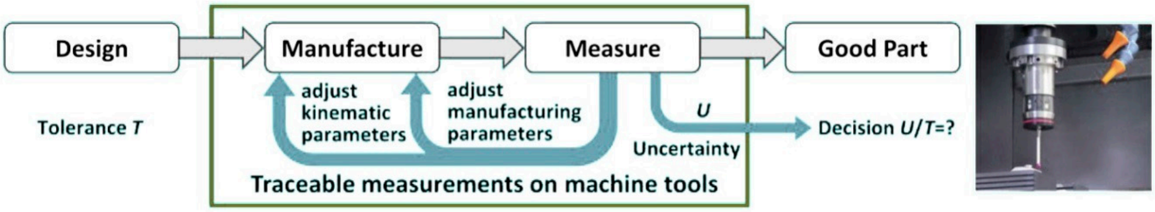

Figure 1. Traceable measurements on machine tools [6].

2.1. Monitoring machine performance

Machine geometry may change during machining operation due to many reasons. By applying an appropriate in-process measurement method with the probe integrated within the machine tool, geometry changes can be measured. These changes can be monitored to avoid making bad parts and to optimally schedule machine maintenance [5].

Figure 2. Monitoring machine tool performance.

2.2 Part setup

Part cutting programs are created based on an assumed workpiece holding coordinate system. Especially for large parts such as the case for aerospace or large die manufacturing for automotive, this process could take a long time. For small part manufacturing and multi-operation processing, precise part locations could be detected automatically. This would reduce both the setup time and the processing time as parts could be cut from optimally sized blocks [5].

2.3 In-process measurement

One of the reasons for performing a metrological measurement of a manufactured part is to provide correction values to manufacturing parameters based on the deviations found from the aimed dimensions. Having this capability directly on the machine tool allows to feedback this metrological data to the machine tool controller allowing an automatic flexible manufacturing process. It could be done several times during the manufacturing process, not just at the end of the manufacturing to optimize the part cutting process [5].

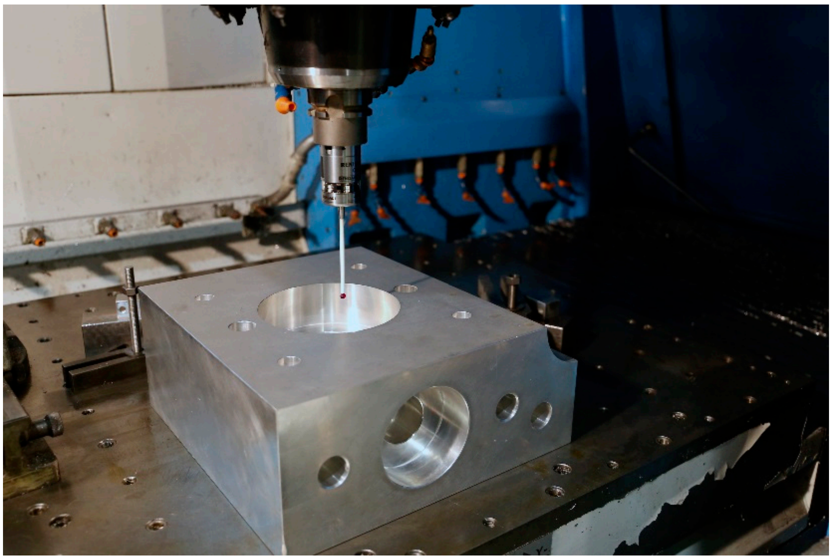

Figure 3. Tactile machine tool probing.

2.4 Post-process control

Programming and running a manufacturing machine as if it were a CMM for in-process measurement generates complete inspection reports without additional effort. For large part manufacturing, there may not even be an option to move the part to an external measuring machine. For mass production, just measuring a few control features would not only generate inspection reports for all the parts but also provide a statistical view of the manufacturing process. In addition, it would help to create historical data monitoring for intelligent process control, which is called industry 4.0.

3. Converting a MT into a CMM

In 2010 Schmitt et al. discussed the possibility of using a large MT as a comparator to measure the geometry of large scale devices during the manufacturing process [7]. Since then, several research works have focused on the idea of converting a MT into a CMM [7–11].

For large scale manufacturing where manufactured parts have to be measured in–situ or in-process, the integration of the measurement process into the MT can avoid time consuming transportation to temperature controlled measuring rooms and improve the process quality. For small and medium size parts, there is a real possibility of achieving finished products on the MT, which offers high product quality, lower manufacturing costs, high productivity and prompt and real-life assessment of product quality [11].

Almost every new machine tool is equipped with a probing system nowadays and offers the possibility to measure product features during or after the manufacturing process. Therefore, machining and measurement processes could take place on the same MT. However, there are some

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key differences between a CMM and a MT, mainly because a CMM is designed for a measurement purpose and a MT is focused on manufacturing production. The biggest challenge for a traceable machine tool measurement is to deal with non-controlled shop floor environment. Time and space dependent thermal effects become the dominant uncertainty source for the measurement of large scale devices [4] [12–26].

Schmitt et al. [4] explain two main approaches to convert a MT into a traceable CMM. The first approach increases process capability by a volumetric calibration and compensation. It means that a calibration process is done previous to manufacturing and measurement processes, but this approach does not ensure that thermal effects do not affect the compensated machine tool. Achievable accuracy can be compared to large CMMs. The second approach applies an external high precision metrological frame to monitor tool center point (TCP) position in real time. This option requires a sign of light between the measuring tracking interferometers and the TCP, which cannot be ensured when the workpiece is on the MT. Moreover, this option is very sensitive against dirt and dust. The current cost of the solution is very high, since 4 tracking interferometers are needed at the same time. However, it offers the possibility of self-calibrating and represents a scalable measuring solution [4].

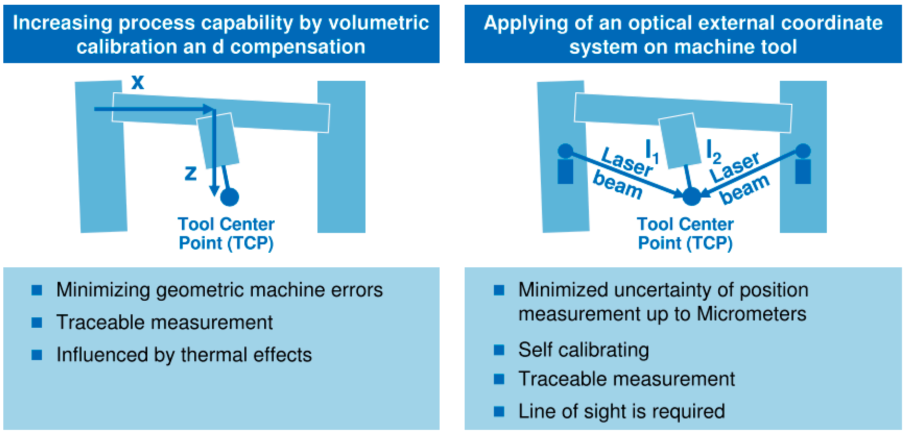

Figure 4. WZL RWTH Aachen approach to convert a MT into a CMM [4].

Currently, the first approach is under research [4], where machine geometric error reduction is of particular importance. Measurement in a shop floor rarely takes place in temperature controlled environment and it means that it is not enough to measure and compensate geometric errors of the MT, it must be accompanied by an understanding of how the MT changes. Time and space dependent dimensional and gravitational drifts on both MT and the measurand shall be compensated dynamically or be considered on the uncertainty budget for traceability assessment on MT measurement.

Although the first approach is being researched in detail, Wendt et al. presented a high accuracy large CMM called M3D3 based on the second approach [27]. In this case, four accurate tracking interferometers are employed for inspection and calibration of large parts directly on-site in production.

4. Approaches to determine measurement uncertainty on a machine tool

Due to the similarity between a CMM and MT, some of the methods for a correct assessment of uncertainty in CMM are adopted for MT. The general guide for a suitable evaluation of measurement data is given in the ISO guide 98-3: 2008 expression of uncertainty in measurement (GUM) [28].

Three different approaches are considered for an uncertainty assessment on a MT dimensional measurement:

4.1 Substitution method based on ISO 15530-3

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The first approach as described in ISO 15530-3 is a method of substitution that simplifies the uncertainty evaluation by means of similarity between the dimension and shape of the workpiece and one calibrated reference part. Moreover, the measurement procedure and environmental conditions shall be similar during evaluation of measurement uncertainty and actual measurement [1]. Due to the similarity requirement between the machined workpiece and the calibrated standard, this approach is very arduous and expensive for large scale metrology. However, it is a suitable approach for small and medium size uncertainty assessment where it is affordable to manufacture and calibrate a reference part for uncertainty assessment purpose.

Across the EURAMET research project Traceable In-process Metrology (TIM), high precision and robust material standards have been developed not just for mapping the geometric errors of machine tools in the harsh environment of the production floor, but for determining the uncertainties associated with task-specific measurements, such as size, form and position measurements for different geometrical shapes such as sphere, cone, cylinder and plane [29–39].

4.2 Numerical simulation based on ISO 15530-4

The second approach is based on ISO 15530-4, a method that is consistent with GUM to determine the task specific uncertainty of coordinate measurements. It is based on a numerical simulation of the measuring process allowed for uncertainty influences, where important influence quantities are taken into account [2]. For that purpose, CMM suppliers, research companies and national metrology institutes (NMI) as PTB and NPL created an uncertainty evaluation software (UES) which is based on Monte-Carlo simulation of the error behaviour of a real CMM [40,41]. In recent years, Virtual gear measuring instrument (VCMM-Gear) and Virtual laser tracker (VLT) have been developed but they have not been integrated into a manufacturer software yet [42]. Nowadays, some research activities are focused on extending the known virtual measuring machines (VMM) concept to virtual measuring processes (VMP) [4] [43].

4.3 Uncertainty budget method based on VDI 2617-11

The third approach is as stated in GUM and VDI 2617-11. In this case, uncertainty evaluation is done based on uncertainty budget where the budget should comprise the uncertainty sources that affect the measurement process and the correlation between them [3]. Thus, a correct assessment of the measurement uncertainty requires contributions from the measurement system, from the object under measurement and from the interaction between them [3,8]. Currently, this approach is being considered for large scale uncertainty assessment. Schmitt et al. are developing a software-based solution for uncertainty evaluation on large MT measurement [4].

5. Uncertainty error sources

The determination of the measurement uncertainty that includes contributions from the complete measurement process in an industrial environment may be separated into contributions from the measurement system, in this case the MT with the touching probe, from the object under measurement and the interaction between both of them [4,44].

5.1 Machine tool as a CMM

International standard ISO 10360-1 defines a CMM as a measuring system with the means to move a probing system and the capability to determine spatial coordinates on a workpiece surface [45]. Due to the similarity between a CMM and MT, some of the methods for a correct assessment of uncertainty in CMM are adopted for MT. However, there are some key differences between a CMM and a MT, mainly because a CMM is designed for measurement purpose and a MT is focused on manufacturing production. For that reason, here an error budget approach will be suggested for machine tool measurement uncertainty assessment.

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As stated by Slocum, MT errors can be divided into systematic errors and random errors. While the former can be measured and compensated, the latter is difficult to predict [46]. Therefore, a machine tool should have three main properties: accuracy, repeatability and resolution [47].

In addition, an error budget is a fast and low cost tool to predict the accuracy and repeatability of a MT [47]. This way, drawing a comparison between design and measurement purposes, an error budget will be established, where each component will be comprised by:

- Accuracy: Systematic geometric errors of the MT (induced by kinematic errors, static loads and control software), touch probe errors and measuring software errors are considered. The accuracy will mean the systematic error of the MT as a CMM, so it can be characterised and compensated.
- Repeatability: Random error sources that affect to the repeatability of the MT: Dynamic loads that affect to the MT (such as backlash, forces and thermo-mechanical loads) and environmental influences that affect either to the MT or to touch probe are considered. The repeatability will mean the random error of the MT as a CMM, so it is difficult to measure and compensate.
- Resolution: Quality of sensors and quality of control system is considered.

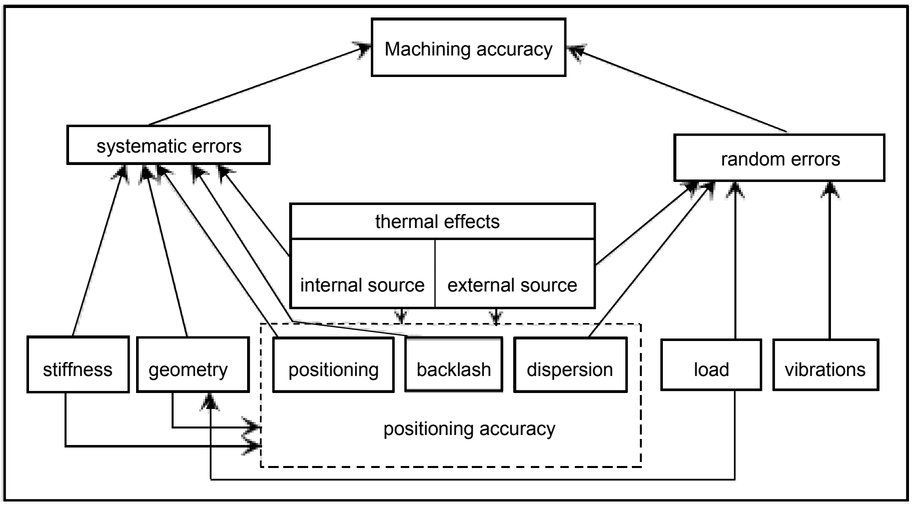

Figure 5. Total error sources of machine tools [48].

5.1.1 Accuracy

5.1.1.1 Systematic geometric error of MT

Either for a CMM or a MT, geometric errors to be considered are relative error motions between the end effector and the object under measurement. Geometric errors can be measured and compensated when MT and measurement procedure have a high repeatability, so that systematic errors can be reduced and not be considered into the uncertainty budget on a potential on-machine measurement [26].

There are several error sources that affect systematically to the accuracy of the relative end-effector position and orientation [26] [49–52]:

- Kinematic errors: Kinematic errors are errors due to imperfect geometry and dimensions of machine components as well as their configuration in the machine's structural loop, axis misalignment and errors of the machine's measuring systems [26] [53–60].
- Static loads: In case of static errors, the non-rigid body behaviour has to be considered. Location errors and component errors change due to internal or external forces. The weight of the

workpiece and the moving carriages can have a significant influence on the machine's accuracy due to the finite stiffness of the structural loop [26,61].

- Control software: Motion control and control software effects on the geometrical error can be significant. In the analysis, they are often distinguishable from the errors caused by other error sources by applying different feed speeds and/or accelerations for the same motion path. However, measuring process is often carried out at small feed speeds, with small acceleration and decelerations as well as small measurement forces. Therefore, error correction and compensation without taking these dynamic forces into account can be successful for measurement purpose [26].

In practice the interaction between these effects plays an important role in the overall system behaviour. Here the research is focused on the overall system behaviour, which means the systematic geometric error of the MT [26].

5.1.1.1.1 Description of geometric errors

Under the assumption of rigid body behaviour, each movement of a machine axis can be described by six components of error, three translations and three rotations. As stated in ISO 230-1, the six component errors of a linear axis are the positioning error, straightness errors, roll error motion and two tilt error motions. For a rotary axis, the six component errors are one axial error motion, two radial error motions, two tilt error motions and the angular positioning error. Moreover, location errors are defined as an error from the nominal position and orientation of an axis in the machine coordinate system. In general, for a linear axis three location errors are considered, while for a rotary axis five location errors are considered [26,62].

5.1.1.1.2 Mapping of geometric errors

Currently, there are different technologies and measurement methods to characterize all the geometrical errors of a serial kinematic configuration machine. As stated by Schwenke et al. [26] "direct" and "indirect" methods can be distinguished. While direct methods allow the measurement of mechanical errors for a single machine axis without the involvement of other axis, indirect measurements require multi-axes motion of the machine under test.

5.1.1.1.2.1 Direct measurement methods

As stated by Uriarte et al. [63], direct measurement of errors analyses all the errors of the axes separately regardless of the kinematic model of the machine and the motion of the other axes. Direct measurement can be classified into three different groups according to their measurement principle:

- Standard based methods, such as straightedges, linear scales, step gauges or orthogonal standards [64,65]. Such artefacts contribute also to the uncertainty of the measuring results. This is why their own calibration uncertainty should be as low as possible but this is not always reachable, mainly when considering the longest ones and the newest highly accurate machines.
- Laser based methods or multidimensional devices, such as interferometers or telescope bars [66–69]. They are usually applied to measure principally the machine positioning properties, because the suitability of the laser wavelength for long length measurements, due to its long-coherence length. The most used is the laser interferometer which, with different optics configurations, allows detecting position, geometrical and form errors.
- Gravity based methods that use the direction of the gravity vector as a metrological reference, such as levels [62,70].

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While direct measurement methods are frequently employed in small and medium size MT, they are rarely employed in large MT where they are very time-consuming and have strong limitations for a volumetric performance characterization [63]. However, there are some measuring scenarios where direct methods offer advantages compared with indirect methods, such as:

- In small and medium size working volumes direct measurement of an error can approximate the geometric behaviour of a machine tool.
- Specific error motion shall be checked in a very specific line or position.
- Specific verification protocol shall be applied for a machine´s acceptance.
- Iterative "measure and adjust" type of work is needed for component assembly operation.
- Results required in real time.
- High accuracy requirement for a specific application.

For direct measurement of positioning errors, calibrated artefacts (step gauges, gauge blocks, line scales and calibrated encoder system) or laser interferometers are applied as a metrological reference aligned to the axis of interest [26,62,71]. The most accurate/ time consuming approach for either short or long machine axis is the use of laser interferometers. Nevertheless, some error sources shall be considered for a correct length measurement [26]:

- Errors in laser wavelength (environmental factors, such as temperature, pressure, humidity and density influence the wavelength compensation).
- Beam deflection shall occur due to temperature changes and gradients.
- Misalignment between interferometer and axis of motion can cause Abbe errors.
- Any movement of the equipment during the measuring process.

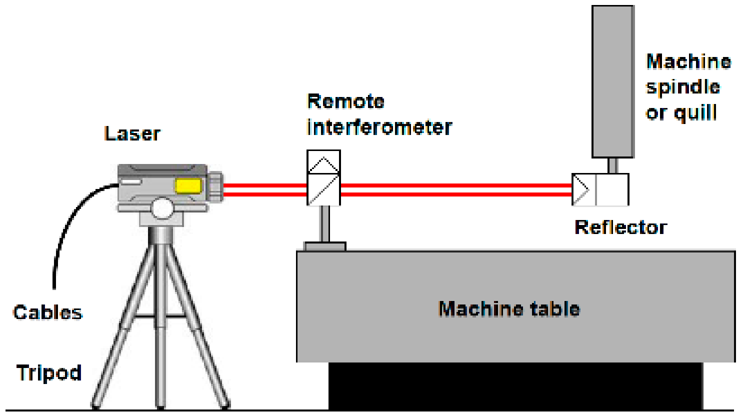

Figure 6. Direct measurement of positioning error through a laser interferometer [72].

Straightness errors of the machine axis can be measured by any of the three measuring principles mentioned before. For large MTs, the most practical way to evaluate straightness is to utilize the direction of the gravity as a reference. Thus, an electronic level is placed on the head of the MT and a reference level is fixed to a non-moving part of the machine to cancel movements of the entire machine [26]. Measured angle over the stepwise displacement is integrated to get the straightness as a result. However, the linear propagation of a laser interferometer is the industry leading method for large MT straightness measurement. In this case a Wollaston prism acts as a beam splitter and the lateral displacement is calculated from two separate beams that exit the prism at an angle [71,72]. For small and medium size MT, standard based method is commonly applied. This way, a displacement indicator (capacitance gauges, electronic gauges or material dial gauges) is fixed to the machine head and it detects lateral displacements along the direction of axis travel [62].

For large MTs and large volume applications, where straightness reference should be long and flat for a long range, a taut wire technique can be used as a straight reference to overcome the limitations of previously mentioned methods [26,73,74]. Even though it has been an extended applied

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method for very large MTs and applications such as CERN components and assemblies [75], main reasons why this method is not widely used at present in accurate large MTs are its low accuracy and inefficient data gathering methods [75]. Another approach under investigation for the straightness measurement on large volume applications is the use of a laser beam as a straight reference and a position sensitive device (PSD) as a pointing sensor unit. Generally, the use of a laser beam as a straightness reference is highly critical in normal shop floor environment, because local and global temperature gradients as well as air turbulence may have a high influence on the straightness of the beam. Therefore, this method is mostly used for axes length below 1.5 meters, where the influence in most cases is sufficiently small. Also the pointing stability (thermal drift) of optical straightness setups can be a major source of uncertainty [26,76,77].

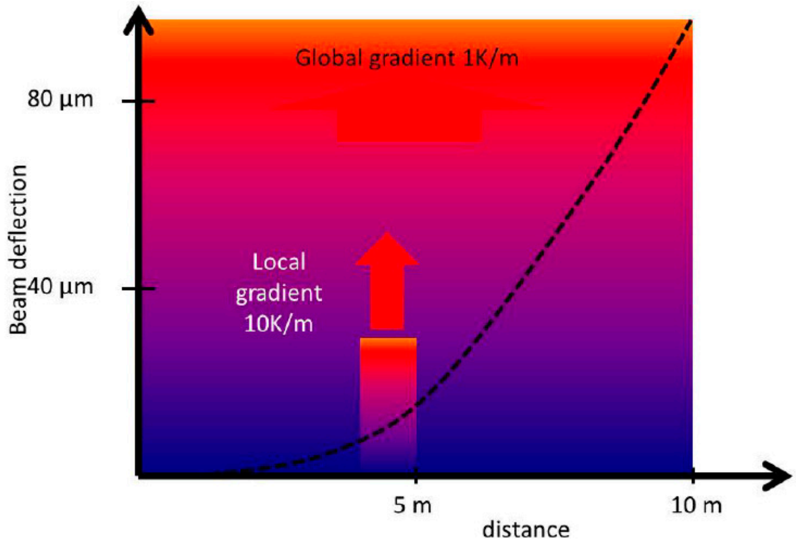

Figure 7. Bending of a straightness reference beam due to local and global gradients [77].

The main approach for squareness measurement in small and medium size MT is to employ granite or ceramic standards with a displacement indicator fixed on the MT head according to the measuring procedure stated in ISO 230-1 [62]. Nevertheless, the main disadvantage of this approach for large MTs is that large and heavy standards are required to verify squareness in large machines. In addition, laser interferometry can also be employed for this purpose but the setup of the laser source and the prism are also very challenging for the squareness error measurement [26].

To measure angular errors in any length machine axis either the use of electronic levels or laser interferometer based techniques are performed. When applying interferometry, two laser beams are generated with a beam splitter so the angular deviation results in a path length difference of the two beams, but the setup of the measuring system can be very challenging for a correct error assessment in a large axis. In case of electronic levels, they do not depend on an optical path, so they are suitable for the measurement of long strokes at unstable temperature environment. A limitation of the electronic level is that they cannot measure rotations around the gravity vector. For this purpose, in small and medium size axes, it is common the use of an autocollimator to measure angular errors. A collimated light beam is aligned to a plane mirror that is fixed to the machine axis. The reflected beam travels back to the measurement system where it is detected either visually or with a PSD. However, the rotation around the axis of motion (roll) cannot be measured with an autocollimator or with a laser interferometer with angular optics. For this, the only known direct method is using electronic levels attached to the axes that measure the rotation directly [26].

A conventional method for the calibration of rotary axis is described in ISO 230-1 [62] which describes the use of a displacement indicators to measure the radial and axial run-out deviation at the centre hole of the rotary axis [26]. For the radial and axial error motions three more sensors are needed to be placed on such a way, that errors are measured with a linear indicator. Of course, all measurements of the five degrees of freedom can be combined in a single measurement, if multiple

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sensors are applied at one gauge [26,78–80]. For the positioning error of the rotation axis, the most practical approach is to use laser interferometry combined with a self-centering device and the proper optical optics for angle measurement [81]. This approach is commonly employed in large MTs with a rotary table, due to the measuring range of the solution is around ± 10º and the resolution is better than 0.01 arcseconds [81].

Recently, multidimensional laser interferometers have been introduced to measure more than one degree of freedom (dof) simultaneously. Thus, several components of error in a machine axis are determined in a unique measurement system setup through direct measurement methods. This multidimensional measuring solutions offer two main possibilities in the near future. Measuring time is reduced to a far extent because different setups and measuring systems are not required anymore. The second advantage is the possibility to be embedded into a MT, where TCP position could be monitored in real time by monitoring 6 dof of each machine movement at the same time with several measuring systems performing all at once.

Three main multidimensional equipments can be found nowadays in the market:

- “XD laser” solution is a combination of different measuring concepts, such as laser interferometry, PSD and level sensors in a unique measuring device [82]. This solution adopts the laser beam as a straight reference to measure straightness. Therefore, it is a suitable solution for small and medium size MT, but not for large MTs.
- “XM-60” multi-axis calibrator also employs the laser beam as a straight reference and PSD sensors to detect the beam and calculate straightness. Therefore, this solution is similar to XD laser solution and cannot be applied for large MTs [83].
- “SP1500C” multi-interferometer solution is a unique interferometer source where beam is divided in order to get a 5 dof measurement laser interferometer. It can be employed for any range MT because laser interferometry is the unique measuring concept employed on the measurement. It is suitable for large MTs because it has a measuring range up to 15 meters. Its main disadvantage is that two straightnesses cannot be measured simultaneously because they are measured by a rotatable optics, so in practice, the equipment is not 5 dof solution, but 4+1 dof for a real time measurement requirement [84].

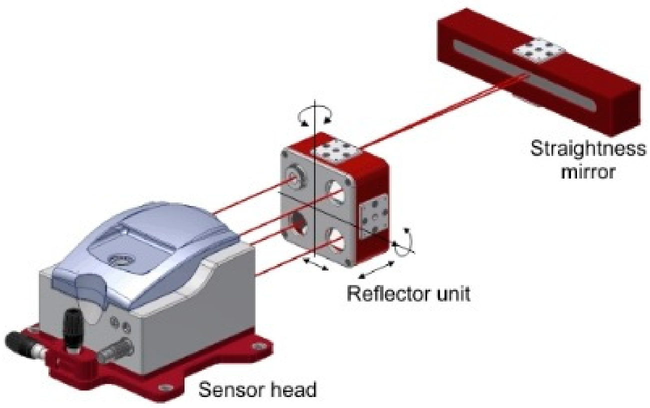

Figure 8. Multidimensional SIOS SPC1500 equipment for 5 dof [84].

A practical approach to test the geometric state of a MT is to apply ISO 230-6 standard that specifies diagonal displacement test [85]. It is suitable for a fast verification of the MT and offers the possibility to monitor some components of error that comprise the diagonal movement, such as positioning and squareness component of error.

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As commented before, direct methods are very time-consuming and have strong limitations for large MTs volumetric performance assessment. In that sense, indirect methods produce a global correction of errors throughout a workspace and require less time than direct measurement.

5.1.1.1.2.2 Indirect measurement methods

Indirect methods are based on the multi-axis movement of a machine during analysis and can be divided into three different measuring methods:

- Based on artefacts that are partially or totally uncalibrated, self-calibration methods with or without scale factor or calibrated artefacts [26,86–90].
- Contour measurements that use simultaneous movements of two or more axes to move on special lines, circular paths produced by two linear axes or circular paths produced by two linear and one rotary axis. Deviations from the nominal lines are measured with special equipment or relative to an artefact [91–97].
- Method that uses simultaneous linear and rotational movements on the MT with nominally no relative movement between the tool/probe side and the workpiece side of the machine, the so-called "chase the ball" measurement [97–99].

These indirect methods allow to determine an axis deviation from a combination of measurements and usually analytical or best fit methods are employed for correct determination of geometric errors. Analytical methods are mainly applied when using calibrated artefacts, contour measurements or self-calibration methods [100,101]. However, best fit methods are generally used for geometric error identification if multilateration or ''chase the ball'' measurements are used because a large number of geometric errors influence the result [26].

Currently, three are the main approaches under research: The cheapest approach employs 3D artefacts on the MT working volume measured by a touch probe in order to estimate all the components of error of the MT [102]. The necessary mathematical analysis that calculates the errors of the machine requires from different positions and orientations of the artefact into the measuring volume and different offsets and positions of the touching probe [95]. Since almost every machine tool brings a touch probe nowadays, machine tool builders are looking for fast calibration procedures based on this approach.

Another approach is to employ R-test to measure relative movements between the machine and the workpiece side. A sphere is fixed to the machine table and a measuring sensor, based on three or more length displacement sensors, is coupled to the machine head [98,103,104]. The measurement consists of a sequence of discrete angles of the rotary table. When moving to the next measurement point the linear axes follow the rotation of the rotary table. At each position the probe head measures the relative displacement of the sphere in X, Y and Z direction simultaneously [104]. Compared to the traditional method that employs "Siemens 996" static cycle to locate a rotary axis in the working volume of a MT, R-test offers the possibility to do static and dynamic measurements [103].

Multilateration based approach is by far the most research technique to determine the geometric errors of large manufacturing or measuring systems nowadays [7,26,105–112]. The approach relies on interferometric displacement measurements between reference points that are fixed to the machine base and offset points fixed to the machine spindle, near to the TCP [113]. At least four measuring systems are needed for a complete volumetric verification but usually only one measuring device is available, so in practice, multilateration measurements are usually done in a sequential scheme. Thus, machine movements are repeated several times and measurements are taken from different positions. If four measuring devices are available at the same time, simultaneous multilateration avoids some of the limitations of a sequential multilateration, such as total time consumption, MT repeatability requirement and MT drift due to thermal variation during the measuring process.

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Several uncertainty sources shall be considered for a complete uncertainty assessment in a sequential multilateration process [108]:

- Volume of the MT.
- Spatial displacement measurement uncertainty of the employed tracking interferometer.
- As stated by Aguado et al., the number of measuring systems to be used and the arrangement of them.
- Repeatability of the measured points doesn't just depend on the repeatability of the machine itself. As far as measuring time is extended, environmental influences like machine shop temperature generally lead to slow changes of MT temperatures affecting the whole volumetric performance. Therefore, time is a crucial factor.

Currently, three tracking interferometers are being employed on large scale metrology when applying multilateration with different displacement measurement uncertainty.

- Laser tracer is a high precision length measurement system developed by Etalon AG in collaboration with PTB. It has a spatial displacement measurement uncertainty of U (k = 2) = 0.2 µm + 0.3 µm/m [114]. While laser tracer is a suitable solution for medium and large size MTs, the product "laser tracer MT" is a similar solution to the laser tracer with a telescopic scheme and employed for maximum measuring volumes of 1 m^3 [115].
- Absolute Distance Meter (ADM) based laser tracker has a spatial displacement measurement uncertainty of U (k = 2) = 10 µm + 0.4 µm/m in its whole working range [116].
- Absolute Interferometer (AIFM) based laser tracker has a spatial displacement measurement uncertainty of U (k = 2) = ± 0.4 µm + 0.3 µm/m [116].

The tracking interferometer employed for multilateration shall fit inside the measuring volume in order to execute the measuring procedure. Such a requirement restricts the tracking interferometer to be employed for any size MT. For small size machine tools, the equipment that suitably fits into the measuring volume is the so-called laser tracer MT, it makes use of a metrological beam guiding method of the laser interferometer [115]. For medium size MTs, where the maximum length of the longest axis of the MT is between 1.500 and 12.000 mm, either laser tracer or laser tracker is suitable for the error mapping. However, when applied for very large MTs, longest axis above 12.000 mm, the employment of a laser tracker has two main advantages:

- They are not limited to a measuring range as it is laser tracer. The working range of a laser tracer is up to 15 metres.
- New laser trackers are portable devices that offer the possibility to be embedded into large manufacturing or measuring systems and they transfer data through an integrated wireless LAN communication [116] which allows to a wireless employment of the acquisition technology.

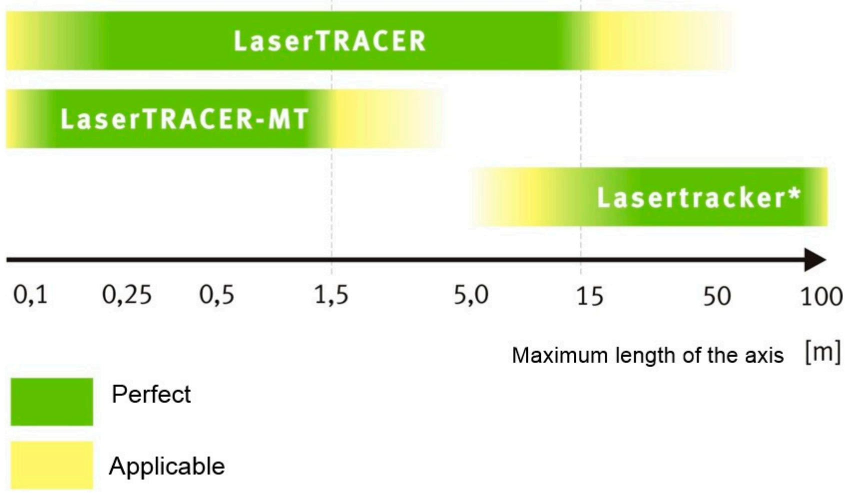

Figure 9. Suitable tracking interferometer according to axial length [77].

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In this context, different solutions have been developed based on a tracking interferometer and multilateration combination mainly for large MT geometric characterisation, where the volumetric performance of the MT is of special interest:

Olarra et al. showed an intermediate approach where linear components of error are measured with a laser tracker based on sequential multilateration and electronic levels are employed for the measurement of the two rotational errors along the two horizontal axis. In this case, multilateration is applied to measure 3D positions with enough accuracy and the approach mimics the idea of using a calibrated artefact in different positions in the volume [117,118]. By comparing measured coordinates to the MT readout and by combining the data from several measurements of the laser tracers or trackers at different positions, an analytical solution is calculated for the geometrical errors of the machine (e.g. for the twenty one geometrical errors of a three axes milling machine). A self-developed software makes it easier to synchronise and achieve the volumetric results [111].

Aguado et al. developed an approach where several commercial laser trackers are employed for sequential multilateration measurement [108]. The adopted technical solution is similar to the solution developed by Olarra et al, where laser trackers are applied to acquire information and multilateration is employed to sort out the mathematical issue. The biggest difference is that Aguado et al. do not use electronic levels for the measurement of the rotational errors of the MT.

Schwenke et al, presented a self-developed hardware and software solution for small to large size MT and CMM volumetric characterisation. The commercial laser tracer [114] is employed for point cloud acquisition and from the error of those points and the kinematic model of the machine it is possible to iterate to minimize the global volumetric error of the machine at considered points. For the measurement of angular errors, different orientation offsets on the spindle side are needed which makes the verification longer.

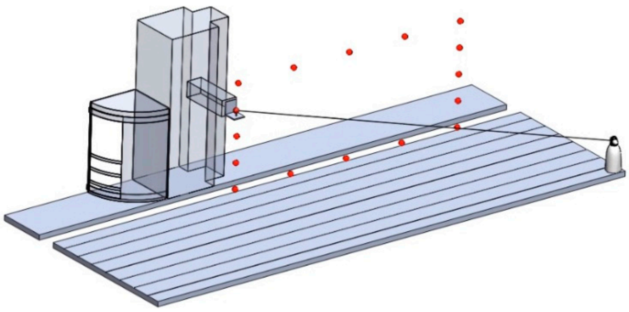

Figure 10. Tracking interferometer and multilateration combination approach.

To sum up, it seems that interferometer based non-contact measuring technology will guide large scale metrology into traceable machine tool metrology in the near future, mainly because the absolute distance measurements allow an easy handling in industry where purely interferometric length measurements depending on fringe counting are quite demanding due to the need of an unbroken line-of-sight between the measuring instrument and the reflector [8].

However, it shall be remarked that the technology has some key limitations nowadays, such as [8]:

- Thermal and refractive index distortions: As the uncertainty of interferometry techniques is significantly influenced by the ambient refractive index of air and industrial environments normally suffer from unstable environmental conditions, the correct determination of the refractive index of air along the beam path is of utmost importance for achieving small measurement uncertainties. Covering the measurement volume with ‘sufficient’ environmental sensors is often not feasible for large measuring volumes and might still miss local temperature sources, such as heating vents.
- Real time: Real-time coordinate metrology is a requirement for a factory of the future where metrology and manufacture are integrated into a single engineering process that enables 'zero defects'.
- Dimensional traceability to the SI metre: It shall be ensured for any metrology based solution in a factory environment.

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- Automation: For a successful integration of the technology into machine and manufacturing processes, wireless and automation capacity shall be improved.

5.1.1.2 Touch probe

Probing has become a vital component of automated production processes on machine tools. The probing system has to ensure reproducibility of the sensing sub-process even in adverse environments and in presence of influences such as workpiece material, surface topography, temperature, vibrations, dynamics and dirt [119,120]. It is necessary to probe the desired point on the real workpiece surface by touching it with a sensing element or by sensing it in a non-contact way [119–122]. Often the application will dictate the choice due to limitations in the speed or accuracy of each solution.

There are two main options when choosing a probing solution, contact or non-contact. There are major differences between both options. The first is that the accuracy of the individual points in contact measurements is higher to that of non-contact measurements. The second is the amount of collected data, non-contact technology can collect millions of sampled points at high speed without touching the workpiece. The third difference is that some surfaces, due to glossiness or transparency, are not suitable for optical measurement and cause special errors [123].

5.1.1.2.1 Contact touch probe

Contact probes can be divided in two general groups, scanning and discrete, based on the type of data being taken. Discrete probes, or touch trigger probes (TTP), are the most prevalent technology available [124,125]. They have the advantage of being less expensive than some of the other options and are good when fewer data points are needed, such as measurements for position or size [126]. Scanning probes, or analog probes, are continuous contact probes that sense the part as the probe is moved along the expected contour, they are useful in the gathering of high-speed data on a part's form characteristics [127,128].

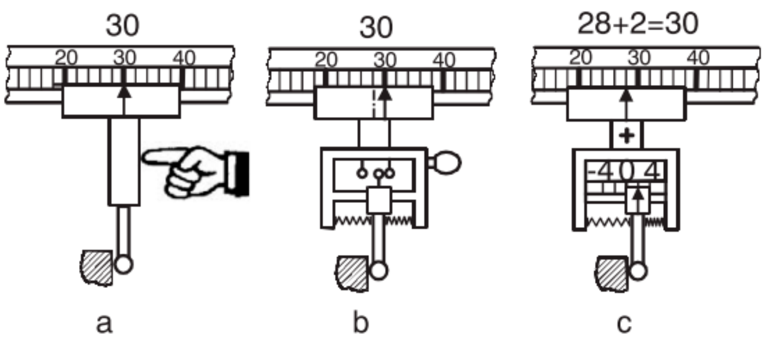

Figure 11. Hard (a), touch-trigger (b) and measuring (c) probe [119].

5.1.1.2.1.1 Touch trigger probe

The two main TTP technologies available for MTs are kinematic resistive probes and strain-gage probes [129,130].

As for kinematic resistive probes, most of the touch trigger probes utilize a kinematic seating arrangement for the stylus. Three equally spaced rods rest on six tungsten carbide balls providing six points of contact in a kinematic location. An electrical circuit is formed through these contacts. The mechanism is spring loaded which allows deflection when the probe stylus makes contact with the part and also allows the probe to reseat in the same position within 1 μm when in free space (not in contact). Under load of the spring, contact patches are created through which the current can flow. Reactive forces in the probe mechanism cause some contact patches to reduce which increases resistance of those elements. On making contact with the workpiece (touch), the variable force on the contact patch is measured as a change in electrical resistance. When a defined threshold is reached, a probe output is triggered.

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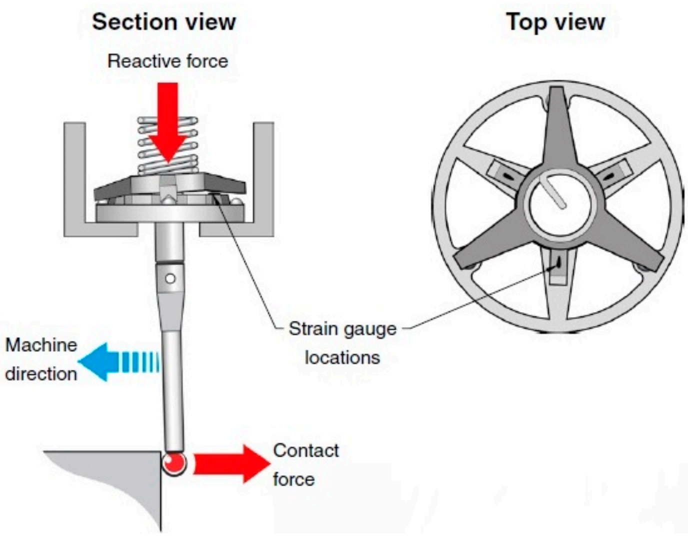

Figure 12. Kinematic resistive probe principle [131].

A number of factors affect kinematic touch probe measuring performance. From the point at which the stylus ball contacts the workpiece there is bending of the stylus prior to electrical triggering of the probe. This is known as pre-travel. Pre-travel will vary dependent on the length and stiffness of the stylus and the contact force. Pre-travel variation (PTV), otherwise commonly known as lobing, probe measuring error or roundness measuring error, can affect measurement performance. Lobing occurs because the pivot distance varies depending on the direction in which the contact force acts in relation to the probe mechanism [131].

On the other hand, technology used in strain gauge probes technology has addressed the performance limitations of the kinematic resistive probe mechanism. This has been made possible by modern compact electronics and solid state sensing. Although strain gauge probes still use a kinematic mechanism to retain the stylus, they do not use the resistance through the contact elements as the means to sense a trigger. Instead, a set of strain gauges is positioned on carefully designed webs in the probe structure above the kinematics. These gauges measure the contact force applied to the stylus and generate a trigger once the strain exceeds a threshold value. This provides a low trigger force, and, since the sensing is not dependent on the kinematics, a consistent trigger characteristic in all directions. As a result, low and almost uniform pre-travel variation is achieved in all directions [131].

Table 1. Comparison table between kinematic and strain gauge probing technology [132].

	Kinematic Resistive Probe	Strain Gauge Probe
Pros	- Simple mechanism, - Low mass (so low inertia at the triggering instant), - Cost – effective, - Easy to retrofit to all types of CMM.	- Improved repeatability, - Low and almost uniform pre-travel variations in all directions, - More accurate measurement, - Low bending deflection (leading low hysteresis), - Low trigger force (few gm.), - Support much longer styli,
Cons	- Directional dependent pre-travel variation, - Micro-degradation of contact surfaces, - Exhibit re-seat failures over time, - Limiting the length of stylus, - Resistance through the contact elements as the means to sense trigger.	- Extra mass - (filtering circuitry), - Expensive,

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5.1.1.2.1.2 Analog scanning probes

Analog scanning probes are a type of contact probe used to measure contoured surfaces such as sheet metal assemblies. The analog scanning probe remains in contact with the workpiece surface as it moves and produces analog readings rather than digital measurements. Continuous analog scanning (CAS) is a relatively new technology. It adds versatility to MTs by offering dramatically increased levels of data acquisition, which speeds and improves the accuracy of measurement and inspection operations. CAS technology is based on continuous rather than point to point acquisition of data with specialized probes and software. It is particularly useful for gauging and surface-mapping complex, contoured shapes, including crankshafts and cams, turbine engine blades and prosthetic devices. It is also suitable for inspecting the form of large sheet metal assemblies, such as automobile bodies. The high density of data provides a full definition of the part's size, position and shape, enabling completely new opportunities for on-machine process control. This is particularly valuable for measuring workpiece features that change continuously, such as the arc on a turbine blade. The ability to acquire data in this manner also allows CAS systems to be used in reverse engineering applications where a new part has to be built to match or fit an existing part. Form and shape measurement require a different approach than prismatic parts measurement [119].

Nowadays, there are several CAS systems commercially available for machine tools [133,134].

5.1.1.2.1.3 Factors affecting probing performance

There are different factors that affect probing performance of touching probe and therefore, their uncertainty must be considered for the MT accuracy assessment when working as a CMM. They are depicted in figure 13.

- Operation principle: As mentioned in previous point, contact probes can be broken into two general groups, scanning and discrete, based on the type of data being taken. Based on uncertainty sources, such as pre-travel variation and repeatability, the uncertainty vary according to the contact touch probe selected for the measuring task on the MT [119].
- Measurement strategy: A disadvantage of discrete-point probing is that it may take a long time for each point as the process of approaching the surface and withdrawing has to be repeated for each point to be probed. In scanning mode the touching element is guided on a line along the surface while a set of coordinates are sampled in a time sequence, the tip ball is all the time in contact with the surface. In scanning mode many more points per unit time can be measured [119].

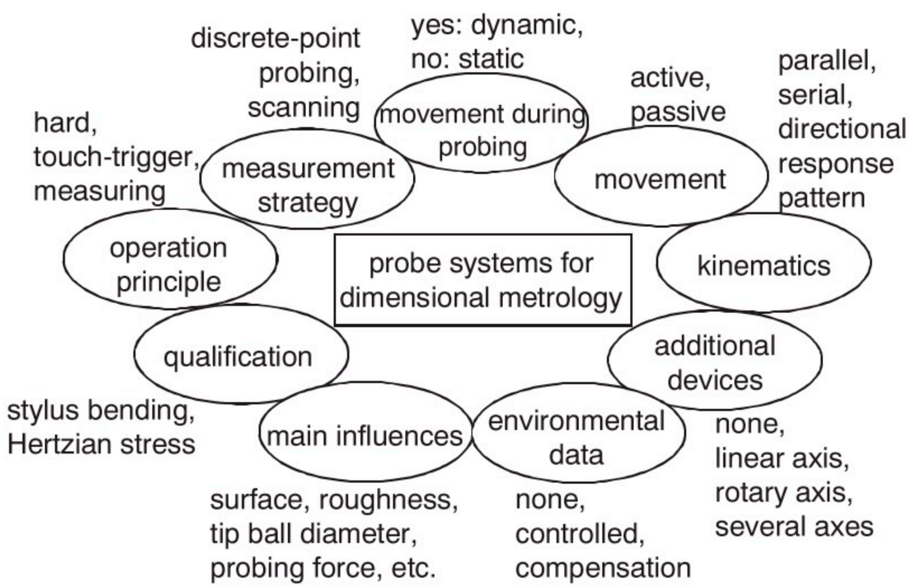

Figure 13. Aspects of probing systems [119].

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- Movement during probing: Static probing is done while each component of the measuring system remains at rest. Dynamic measurement is carried out when at least one component is moving during readout of the measurement systems. With touch-trigger probes there is no possibility for static measurements as the trigger signal can only be generated during movement [119].
- Movement: The suspension can work passively (i.e. without actuation, e.g. spring) or actively (i.e. with actuation, e.g. electro-magnetically). An advantage of the active principle is that a tuneable, direction-independent probing force can be achieved. The advantage of the passive system is the lower mass, providing better dynamic properties and a lower price [119].
- Kinematics: Probing systems must allow movement of the tip ball in each axis. For 2D or 3D probing systems three axes can be arranged in either a parallel or serial manner. The arrangement has a strong influence on the static and dynamic performance, as well as the size and weight of the probing system. Serial kinematics consists of several independent stacked axes, which are usually translational and mutually perpendicular. Movement in one coordinate means movement of one axis. In contrast parallel kinematics is characterized by axes that are connected in such a way that a movement in one coordinate involves at least two axes, like a hexapod structure [135,136]. Serial and parallel kinematics probes are shown in figure 14.
- Directional response pattern: If a probing system is sensitive in more than one direction (2D, 2½D, 3D) the directional response pattern (equivalent to directional pre-travel variation) is of interest [137,138]. The varying directional sensitivity can be caused by the suspension of the stylus, asymmetric moment of inertia of stylus, arrangement of sensors in different directions, direction dependent sensitivity of sensors, set-up of the axes, direction dependent probing force, tip ball form deviation and the direction dependent dynamic behaviour of the probing system including styli combinations [45]. The effect of direction dependent sensitivity has the result that the same displacement of the tip ball leads to different output signals dependent on the direction of the displacement [139]. The evaluation software can compensate this anisotropic effect, if it is reproducible and the probing direction is known [140–144]. If the effect is not compensated, it could result in measurement errors.

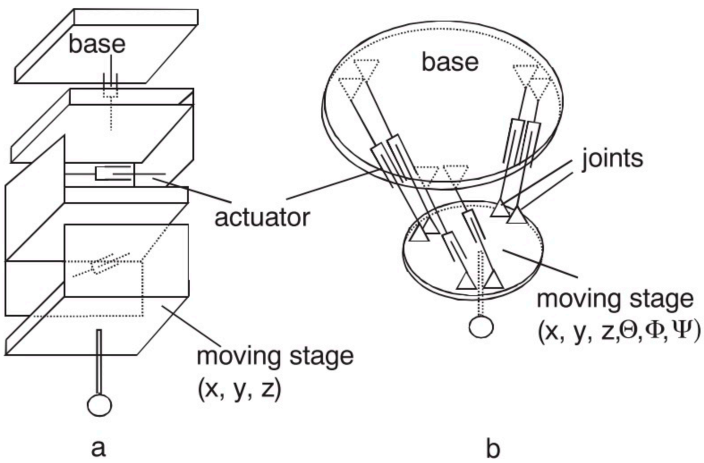

Figure 14. a) serial and b) parallel kinematics probes [119].

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- Environmental influences: Environmental influences affect the result of a measurement dynamically. Consequently, it shall be considered as a part of the repeatability of the MT as a CMM [119].
- Cleanliness of Surface: The cleanliness of surface and tip ball can directly influence the measurement result. Just as in other measurements contaminations can be regarded by the probing system as a part of the workpiece, which leads to a distorted result. In order to avoid probing deviations a cleaned surface and tip ball without dirt, dust or lint must be guaranteed. Swarf will influence the probing result much more seriously than fine cloth or paper lint. The effect depends on the probing force. If the probing force is near zero (e.g. when applying piezo effect) and soft surface contaminations (e.g. oil film) are probed, the signal to noise ratio of the probing system will decrease because of attenuation, which can make a reliable surface detection impossible. In addition to this effect (e.g. oil film), capillary forces can amplify the probing force to an unacceptable [119].
- Tip ball: The output of a probing system is related to the displacement (referred to a defined zero position at the beginning of the measurement) of the contacting element. If that is a tip ball it is usual to characterize its position by the position of the centre point. In order to get the position of the corrected measured point (probed point) the output position of the centre point has to be corrected by adding a tip correction vector of the length of tip ball radius in the direction from the centre point to the probed point [145]. The radius of the tip ball is obtained from a qualification procedure for the probing system [146]. If the direction is needed for the correction process, it can be obtained from the probing system (if the orientation of the vector is measured), by interpolation (from at least three probed points in the neighbourhood of the surface point) or by estimation (from e.g. CAD model). Correct and complete information of a concave surface can only be obtained if the tip ball radius is always smaller than the smallest local radius of curvature of the surface to be probed. Usually real surfaces show, in addition to long-wave form deviations, random short-wave deviations known as roughness [147]. For such a surface the measured geometric properties represent a superposition of measurand and touching element [148] leading to a non- linear mechanical filtering effect. This filtering effect has a characteristic similar to a low pass depending on the tip ball diameter, because a smaller tip ball can penetrate smaller roughness valleys than a bigger ball. Because of this effect one gets for measured features different parameter values (size, position, form deviation) dependent on the diameter of the tip ball. As the measurement result is a superposition of tip ball and surface geometry, also form deviations of the ball directly lead to measurement errors. Thus it is necessary to use a tip ball of negligible form deviation compared to the required measurement uncertainty [119].
- Probing force: The probing force not just causes a bending of the stylus, but also has an effect on the elastic deformation of surface and tip ball due to Hertzian stress. Hertzian stress is the elastic deformation of two bodies touching each other [149]. The extent of deformation is dependent on the materials, micro and macro geometrical forms and the force. The effect of elastic deformations can be compensated to a certain extent by the probing system qualification process.
- Wear of tip ball, plastic deformation and wear of workpiece surface: Due to hardness of the tip ball, probing force and material interaction between tip ball and workpiece, wear and plastic

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deformation may occur during the probing process. There are three main effects causing geometrical changes. 1) Plastic deformation (smearing of roughness peaks [150]) of the workpiece at the probed points or on the scanned lines may be regarded as wear of the workpiece surface [151]. The compressive strength of the workpiece material can be exceeded even by the small probing force because of the very small contact area between tip ball and roughness peak leading to high pressure. It influences the appearance of the surface. 2) Wear of tip ball will mainly be the consequence of the abrasive process during scanning hard rough surfaces. It is vital to ensure that the amounts of wear are negligible compared to the required uncertainty. 3) Materials of tip ball and workpiece interact. It may occur that microscopic small particles break out of the surface due to local welding effects. This may apply e.g. when probing an aluminium surface with a ruby (aluminium oxide) ball, where the tip ball surface could be locally built up and influence the measurement result. However, under normal circumstances, very little pick-up occurs [119].

- Probing system qualification: The position of the tip ball centre point related to the reference point of the probing system, the radius of the tip ball and the lobing error must be known in order to perform correct measurements [152,153]. These parameters are dependent on probing force (magnitude and direction), elastic behaviour of probing system, styli, workpiece and other influences. Their origin can be materials, components, and arrangement of components in the probing system, dimensions like length, diameter of styli, material properties, elastic flexibility of stylus joints including suspension and roundness deviations of the tip ball. Due to the necessary accuracy and the complexity of interactions they cannot be calculated from first principles. They can be determined experimentally for a virtually ideal probing system with a virtually stiff stylus with an effective tip ball diameter using a calibrated artefact under the same conditions as the following measurement is to be performed. This procedure is called probing system qualification.

5.1.1.2.2 Non-contact touch probe

The availability of non-contact 3D data capture systems capable of acquiring dense geometric data from complex surfaces has increased considerably over the past ten years [154]. Optical non-contact inspection techniques have revolutionized CMM inspection applications in the last decade, due to the cost and coverage of the technology. Nevertheless a very small percentage of applications with non-contact measurement are already established, especially in robot and machine tool industry [155].

In this scenario, where a few approaches of non-contact technology integration are known, Dr. Karadayi presented a blue light laser sensor integration within a five axis machine tool, explaining sensor integration and calibration [156]. The laboratory for machine tools and production engineering of the RWTH Aachen University is also exploring the possibility to integrate non-contact sensors into MTs. This way, Mr Paulo de Moraes integrated a 2D laser into a machine tool for an in-process 3D measurement [157].

In manufacturing industry, there is an increasing need to measure accurately 3D shapes. Freeform shaped parts are of great interest in many applications, either for functional or aesthetical reasons. Their relevance for industry is well-known in the design and manufacturing of products having complex functional surfaces [158–165]. These parts are important components in industries such as automotive, aerospace, household appliances and others. Figure 15 shows measuring requirements for most common free form shaped parts.

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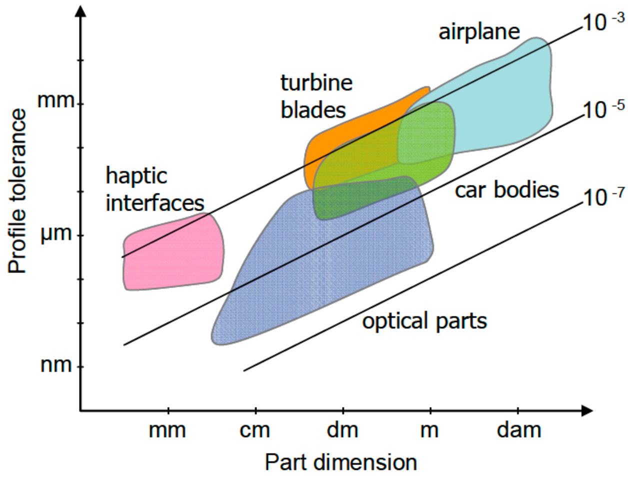

Figure 15. Typical values of tolerances vs. dimensions for most common free form shaped parts [159]

Currently there is a wide variety of 3D optical sensing techniques that can be potentially integrated into machine tools to verify the geometry of a manufactured part on a machine tool measurement. Figure 16 comprises non-contact sensing technology map.

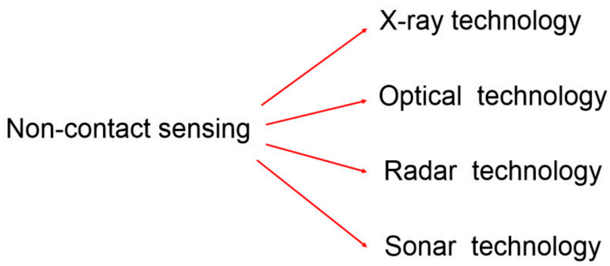

Figure 16. Non-contact sensing technology map.

According to CMM non-contact measurement, optical technology offers the greatest potential for a non-contact measurement on machine tool. Figure 17 shows optical non-contact 3D data capture systems map [165].

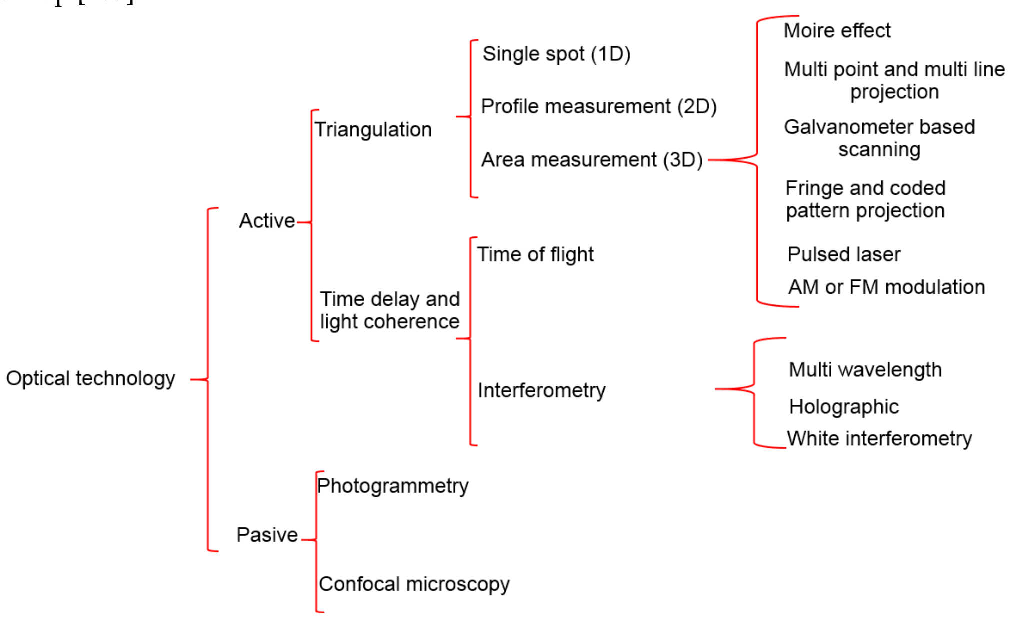

Figure 17. Optical sensing technology map [165].

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Considering the usage of CMM based inspection by tactile probes and the non-contact optical triangulation systems, it seems that machine tool sensing roadmap will follow the CMM current scenario. This way, triangulation based technology is prone to be integrated into MT in the near future complementing the usage of tactile probes in MTs.

5.1.1.2.2.1 Factors affecting non-contact probing performance

Additional error sources may appear when using an optical measuring system on a freeform object. The surface characteristic itself dominates the uncertainty of the acquisition process, therefore its variation in terms e.g. of local curvature may add uncertainty. Other common errors are also induced by: the slope of the surface (which may produce direct reflections to the detector), volume scattering (e.g. for plastic material), or an inhomogeneous surface texture. Secondary reflections, specular reflections, volumetric scattering, colour transitions, or ridges left by machining, may lead to gross systematic measuring errors [166–168].

Post-processing operations of measured data may add further uncertainty. The main difference is the amount and the “destination” of the collected data. For touch probes collected points are controlled directly or indirectly (through a program) by the human operator. The number of points is up to a couple of thousands and they clearly belong to a single feature. For scanning the number of points collected is from several hundred thousand to millions of points and a priori the system has no knowledge on which surface or feature the collected points reside. This circumstance leads to the fundamental issue that distinguishes tactile and non-contact data collection [169,170]. Probably the main barrier in the usage of non-contact methods is the difference in the automatic classification (segmentation) of data. In fact this is very much like the fundamental problem in computer vision [171,172]. The main question is which point of measured data belongs to which feature of the reference model. This is clearly a problem that does not exist in the traditional tactile probe based inspection, since the classification is determined explicitly by the human operator.

5.1.1.3 Measuring software

To perform the complex mathematical calculations required for metrology-based, real-time decision making, a powerful metrology software needs to be integrated within the manufacturing system. Because the system is expected to function by itself without human interaction, it also needs to work autonomously within the manufacturing process. The following characteristics are required from a software program to truly make a machine tool function similar to a CMM [5]:

- Offline programming: A computer-aided manufacturing (CAM)-style programming environment with good machine tool virtual modelling, simulation capabilities, automatic path generation with collision avoidance, and complete geometrical fitting and tolerancing functionality is required. Programming languages such as DMIS also allow to interface and collaborate with CMMs for efficient programming.
- Bi-directional interface: A direct and bi-directional interface is a must to analyse data in real time as soon as the measurement of a feature is completed. The calculated metrology characteristics are used as a part of the on-the-fly decision making and written back to the machine tool controller as a part of the adaptive cycle.
- Ability to handle high-density point cloud data: When interfacing with a laser to measure large parts, very large amounts of data will be gathered. The software, in addition to offering a live interface with the machine tool, must also be able to handle the display and interaction with such data.
- Geometric feature extractions: For on-machine geometrical feature measurements and geometric dimensioning and tolerancing (GD&T) applications, an automatic feature extraction is necessary. Most point cloud systems today are offline and need operator interaction to calculate the required features. An on-machine measurement software that will interface with a laser system should also have a robust automatic feature extraction capability.

- Ease of operation: The measurement program must be integrated into the machining center similar to any other cutting program. This allows the program to be integrated as a part of manufacturing cycles and can be automatically started by itself. A G-Code NC program is created by post-processing the DMIS measurement program and resides in the controller. This program, like any other cutting programs in controller-native language, is used as a part of the manufacturing cycle allowing multiple programs to work along with the cutting programs.

5.1.2 Repeatability

The repeatability of the machine, usually expressed as a standard deviation, is a part of any uncertainty budget. As stated by Slocum, repeatability is difficult to predict and it is often most important to obtain mechanical repeatability, because accuracy can often be obtained by the sensor and control system [47].

There are different error sources that affect the repeatability of the MT working as a CMM: Dynamic loads that affect the MT (such as backlash, dynamic forces and thermo-mechanical loads) and environmental influences that affect either the MT or to touch probe are considered [26,47–52].

Between the dynamic loads that affect the MT can be highlighted backlash, dynamic forces and thermo-mechanical loads:

- Backlash: Backlash error is a position dependent error affecting the contouring accuracy. When the axis changes direction from one side to the other, there is a lag before the table starts moving again, that would cause position error- backlash error [173]. Modelling it is challenging, due to multiple sources and complex behaviour. In general, the backlash vector depends on the history of the motion of all axes. It can result from mechanical play in drives and guideways, cable track forces, and stick/slip effects [77].
- Dynamic forces: The trajectory to be realized by a MT is also affected by the dynamic behaviour of the machine's structural loop. In this case (rapidly) varying forces such as machining forces, measuring forces or forces caused by accelerations or decelerations should be considered instead of quasi-static ones. Vibrations may result in a deformation of the structural loop of the machine under consideration. The deformations due to vibrations in the structural loop are often hard to compensate. This is due to the very often unknown amplitude and in particular the phase angle of the vibration frequencies [26,174–176].
- Thermo-mechanical errors: Due to the presence of, sometimes changing, internal and external heat/cold sources in machine tools and CMMs and the very often significant expansion coefficients and expansion coefficient differences of machine part materials, the resulting thermal distortion of the machine's structural loop often dominate the accuracy of an executed task [11,13,25,26,177–179]. Expansion coefficient differences may lead to thermal stresses if rules of exact constraint design have not been met carefully. Changed thermal conditions may cause location and component errors of machines.

Apart from dynamic loads affecting to the MT, they should be also considered dynamics error sources coming from touch probe. Deviations from the reference temperature of 20°C lead to thermal expansion or shrinkage of the measuring probe. Even worse are temperature gradients inside the workpiece or measuring system including the stylus, because they lead to deformations like bending. Temperature changes can cause temperature gradients and cause an anisotropic expansion effect in the probing system, in styli and styli joints. Another important environmental influence is vibration, as this can cause dynamic effects in the probing system and hence lead to accidental deviations in discrete-point measurements or cause an apparent waviness in the measured surface in scanning mode. Vibrations may result in a deformation in the metrology loop between probe tip and workpiece. The deformations due to vibrations in the metrology loop are hard to compensate for, and therefore contribute to the uncertainty of the measurement if they are not recorded by the probing system [119].

In this scenario, the overall system behaviour is of interest. Some error sources, such as dynamic forces or internal heat sources lead to a fast change of the structural loop that are very hard to measure

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and compensate [26,174–176]. However, there are other error sources such as environmental temperature or simple backlash errors that induce a quasi-static geometric error of the MT that can be monitored and assessed. In fact, quasi-static errors are one of the most important error source for large scale precision manufacturing [8].

5.1.2.1 Quasi-static error assessment and monitoring

The aim of some international research projects, such as "Light controlled factory" or the just finished "Large volume unified metrology for industry novel applications & research (LUMINAR)" and "Traceable in-process dimensional measurements (TIM)", is to tackle several fundamental issues affecting users of large scale metrology (LSM) equipment and techniques in industrial locations [6,180,181] where non controlled environment affects.

In particular, a strong evolution of interferometry-based technology seems to trace the roadmap for the future research of LSM in industrial environment.

Peggs et al. [182] describes that the measurement uncertainty achievable with an ADM (typically 10 mm + 0.4 mm/m) is already approaching what can be achieved with the sort of conventional displacement measuring interferometer fitted to laser trackers (typically ± 0.4 μm + 0.3 μm/m) [116]. Consequently, for the built-in displacement device, increasingly absolute distance meters (ADM) are used beside the relative displacement measuring interferometer (IFM) for radial distance or displacement measurement in commercial laser trackers [8].

Schmitt et al. [109] mentioned the extension of the application of interferometry-based technology which is not only used as dependent measuring unit but also in multilateration applications, for CMM and MT calibration. An external metrological frame is implemented as a virtual reference based on lengths measured with tracking interferometers. The targets positions are calculated using the length measurements with the multilateration principle [27].

Based on ADM technology, multiline technology developed by University of Oxford is a dynamic frequency scanning interferometry (FSI) system scaled up to make many hundreds of measurements for only a small fractional increase in cost compared to laser tracer technology [113], simply by using multiple interferometers whose components are cheap [183]. Despite not having a real time capability (functionality that is under research), this technology allows to monitor large components and structures within an accuracy of 0.5 μm/m. Measurement range is up to 20 metres. It is currently being used in LSM for monitoring of long time stability, deformation by temperature; workpiece weight and foundation drift in many applications [183,184].

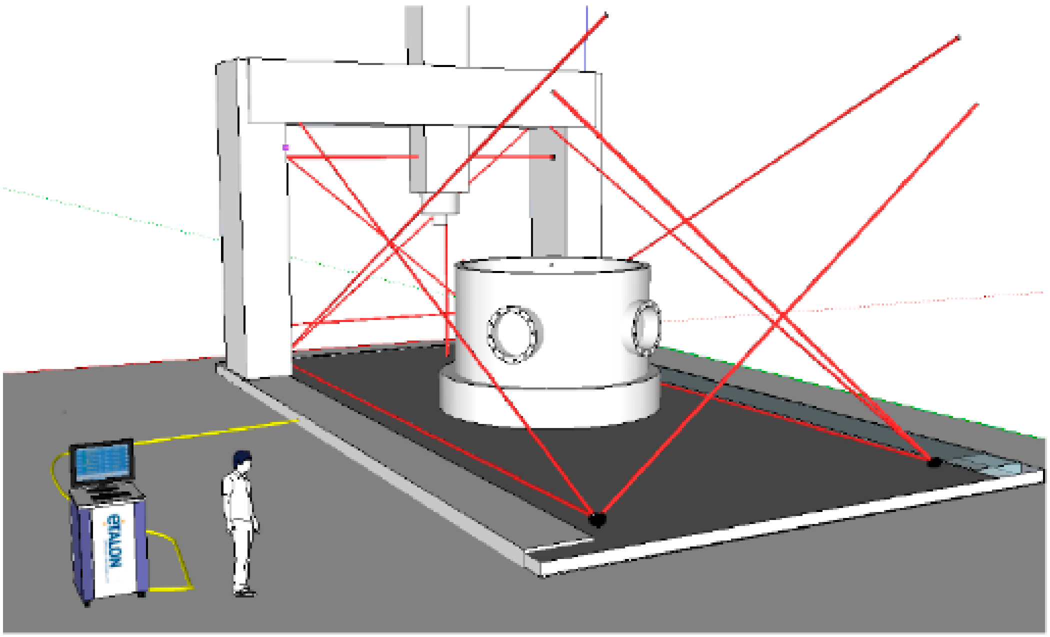

Figure 18. Multiline example on a large MT [184].

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As an evolution of multiline system, a system based on divergent FSI and multilateration is under development at NPL for real-time coordinate metrology for a factory environment [185]. This distributed system comprises multiple sensor heads that surround the measurement volume. Spherical retro reflectors are positioned in the measurement volume to define points of interest e.g. to define the coordinate system, reference points on the part, or to define points on moving parts such as probes or robots. Each sensor is able to measure absolute distance to multiple targets simultaneously using the mentioned frequency scanning Interferometry. A gas absorption cell is incorporated in the system to provide a traceable frequency reference used to determine the scale factor for the FSI based distance measurement.

To overcome thermal and refractive index distortions in large volumes, a tracking refractive index compensated interferometer for absolute length measurements, the '3D- Lasermeter', has been developed by PTB and SIOS within LUMINAR project. The 3D-Lasermeter combines absolute distance measurement by multi-wavelength interferometry, the compensation of the refractive index of air by using the dispersion between two wavelengths, and the tracking capabilities of Laser tracers [8].

More practical approaches are presented nowadays. Schwenke et al. presents a multilateration based continuous data acquisition solution (on the fly) where calibration is speeded up significantly by a continuous measurement at constant speed. This option permits to increase the number of sampling points and reduce drastically the measurement time, allowing the measurement of quasi static errors of MTs [114]. However, the measurement process cannot be automated entirely because multilateration is executed in sequence and the device is located by hand. Gomez-Acedo et al. suggest an automatic approach for a fast measurement of thermal distortion on large MTs based on automatic multilateration measuring procedure [186]. A multilateration scheme is conducted using a single laser tracking device positioned on top of the machine table which movement is automatic. As depicted in Figure 19, YZ plane is measured with a sampling period of 20 minutes during a thermal cycle of 5 hours.

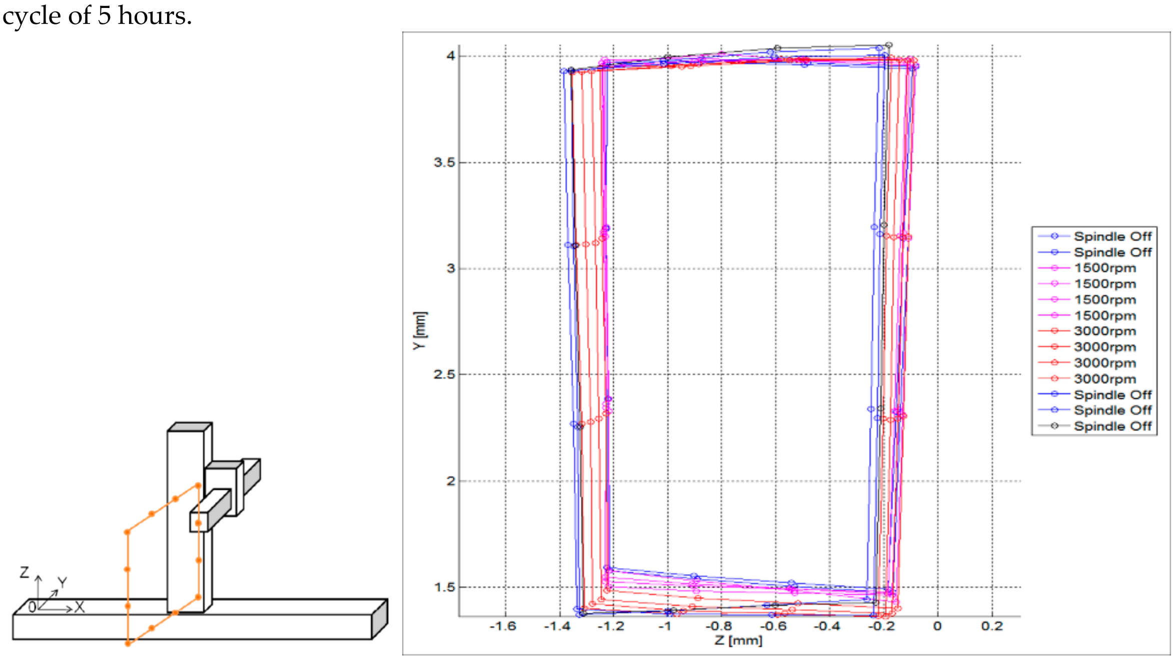

Figure 19. YZ plane measurement and thermal drift assessment on the YZ plane [186].

5.1.3 Resolution

Resolution is the distance separating two adjacent points in the axis movement (the smallest change in the position). The electromechanical components of the positioning system that affect the resolution are the lead screw pitch, the gear ratio, and the step angle in the stepping motor (open loop) or the angle between the slots in the encoder (closed-loop). Features smaller than the control resolution could not be produced. The programming resolution cannot exceed the control resolution

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[187]. The resolution of a small and medium size MT is usually between 0.1 ÷ 1 µm and for large MT, it is usually 1 µm [188,189].

5.2 Measured object

Measurement processes are strongly influenced by the measurement systems and especially for large-scale components, by the object under measurement. Temperature changes, either in the environment or during the machining process lead to temperature changes that influence the geometry of the part significantly, making a significant contribution to the uncertainty of measurements. At the same time, gravitational forces affect the geometry even of heavy and apparently stable objects. These influences are evident during handling or clamping for machining, but mainly when doing an on-machine measurement [8].

The variation of workpiece temperature represents a significant uncertainty source for measurand related to quality inspection. The influence increases proportionally with temperature differences and component size. Therefore, particularly for large components tested in a thermally unstable production environment, thermal effects can represent a high percentage of the total measurement uncertainty [8,12,13,190–192].

As stated by Schmitt et al., the time-dependent ambient temperature of the production site (whether daily, weekly, or longer cycles) and heat conduction via the contact between the clamping surface and the workpiece at different temperatures have a net effect on the component temperature. Another heat source is the manufacturing process, which leads to a transient, non-homogeneous temperature distribution inside the component. Complex or asymmetric workpieces with different wall thicknesses or materials enhance this thermal inhomogeneity. The process heat stored inside the workpiece leads to unsteady shape, position, and size of the measured characteristics when compared to their thermal reference state [8].

In the other side, all the geometric measurements done on earth suffer from gravitational deformations. These elastic deformations depend on the positioning and orientation, the material characteristics, the geometry, and the mounting conditions of the component. Moreover, due to changing orientation and mounting conditions during the machining process, object suffers from varying gravity deformations that affect to a potential on-machine measurement during the machining process.

When it comes to the object under measurement, quasi static errors are not as important as they are for large measuring systems, but it is crucial to determine the behaviour of the component according to a specific temperature and gravitational influences on the moment when measurement is executed [8].

To undertake the necessary modelling to understand and predict how large measurand behave under specific thermal and gravitational conditions, FEM software is widely used. It should be noted that any computational method that can accept temperatures and gravitational forces as a load condition to calculate localized displacements could be applied for such an application [193].

The first step is to define with high accuracy the boundary and initial conditions of the simulation. In the one hand, temperature related information should be characterized, such as, environment temperature information and initial temperature distribution. If the temperature of the part is homogeneous and it is known, the systematic geometry deviations can be compensated numerically. However, inhomogeneous temperature distributions are difficult to compensate and it should be assigned to the measurement uncertainty [194]. In the other hand, gravity related influences shall be added to the simulation. Information about fixtures that locate and clamp the component on the machine table, clamping orientation related to the gravity vector and a detailed information about the component (mass and geometry) are achieved generally from the computer aided design (CAD).

The second step is to run the simulation. All commercial software has user interfaces for programming individual data exchange possibilities or modified computation methods. The generated simulation results are not uncertainties, as from a Monte-carlo simulation, but positive or negative compensation values that can be applied as input to the measurement software for

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compensating thermal geometry and gravitational effects to a certain homogeneous reference temperature and position [8].

Finally, post processing is done to achieve results that can be viewed and analysed depending upon the requirements of the on-machine measurement to be done. Commercially available FEM software for the compensation of thermal and gravitational effects are listed next: Abaqus, Ansys, Comsol and Nastran [195–197].

6. Quantitative approach

The aim at this point is to develop a quantitative approach of a simple error budget [47] on the machine tool side where the weighting factor of each uncertainty source can be distinguished. This way, main error contributors are detected and future research activities are suggested.

Small and medium size machine tools, from 0.5 m^3 to 2 m^3, offer a positioning accuracy better than 5 µm and a repeatability around 2 ÷ 3 µm [198]. However, as stated by Keller at TIM final workshop [10], the geometry variation of a 630 mm x 730 mm x 860 mm MT between 15 ÷ 30 ºC could be higher. On this experimental study, the positioning error variation is around 20 µm and the perpendicularity error variation is around 8 µm. While position and squareness errors are dominant and strong contributors to the varying total geometric error due to temperature effects, straightness and rotational errors are less prone to temperature effects. Table 2 depicts a simple error budget where major error uncertainties are described. Temperature effect is the most important error source, unless it is measured and compensated. As demonstrated by Schmitt et al. the uncertainty of a dimensional measurement done on a MT can be around 20 ÷ 30 µm for a small MT [4].

Table 2. Error budget for small and medium size MTs.

Error source	Significance		
	0 ÷ 10 µm	10 ÷ 100 µm	100 ÷ 100 µm
Accuracy			
Machine tool geometry			
Touch probe			
Repeteability			
MT repeteability			
Temperature effect			
Other effects			
Resolution			

The most frequent configurations of large machines are based in serial kinematics and 3, 4 or 5 motions are located at the machine head. This way, part is fixed to the table and it is not required a heavy slide to move the part. The dominant serial kinematics configurations for large machines are: movable column, gantry and elevated gantry [63]. The positioning accuracy of a high-tech large machine tool is around 10 ÷ 15 µm and repeatability is better than 10 µm [188]. As stated by Kortaberria at TIM final workshop [199], while the positioning error variation of a large MT (6000 mm x 3000 mm x 1500 mm) is around 80 µm, the squareness and straightness error maintain stable. In addition, as stated by Wennemer [200] a very large MT geometry is extremely sensitive to the temperature influence, a length deviation of 300 µm is shown under temperature variation without any length compensation in beam direction and it is reduced to the half with length deviation. Table 3 depicts a simple error budget for a large MT.

One of the most employed tactile probes nowadays is OMP400 from Renishaw. It offers a repeatability better than 0.5 µm and the 3D lobing error is around ± 2 µm for a 100 mm stylus length [120].

Table 3. Error budget for large size MTs.

Error source	Significance		
	0 ÷ 10 µm	10 ÷ 100 µm	100 ÷ 1000 µm
Accuracy			
Machine tool geometry			
Touch probe			
Repeteability			
MT repeteability			
Temperature effect			
Other effects			
Resolution			

7. Outlook and conclusions

If machine tools are considered to be used as the new concept of CMM for a factory environment, all the error sources and their contribution to the uncertainty budget should be known. Machine tool metrology has the potential to test product characteristics during or right after the manufacturing process, resulting in improved part quality and reduction of waste material. Other major advantage is the reduction of the production time by prevention of transporting the workpiece to a measuring position.

For serial production, usually for small and medium size components, substitution method based on ISO 15530-3 simplifies the uncertainty assessment of machine tool metrology by means of similarity between the workpiece and the employed standard. However, for small batch production, mainly in large scale manufacture, substitution method is not an affordable solution because of the size and cost of the standards. In this case, uncertainty budget solution based on VDI 2617-11 is being adopted for large workpiece machine tool metrology.

There are two main error sources to be considered on an error budget. Errors coming from the measuring machine, in this case the MT, and errors coming from the measurand. As stated by Slocum, the machine tool has three main properties: Accuracy, repeatability and resolution. Quantitative approach shows that lack of repeatability of the MT becomes the major error source on a potential machine tool metrology. The accuracy and repeatability of the machine tool, both within 10 µm for a small machine tool and within 30 µm for a large machine tool, get worse when temperature affects to the process. In addition, position and squareness errors are the dominant contributors to the varying total geometric error due to temperature effects, mainly influenced by thermal expansion of linear scales. Errors coming from the touch probe should be seriously considered for small machine tool error budget, although for large machine tool it represents a minor error source.

It seems that machine tool sensing roadmap will follow the CMM current scenario. This way, triangulation based sensing technology has already been successfully integrated into MTs for complementing the usage of tactile probes in the near future.

As a result of the state of the art study, a strong evolution of interferometry based technology seems to trace the roadmap for the future research of error mapping and monitoring in industrial environment. ADM technology is getting affordable and it is already being used in commercial devices, such as laser trackers, beside IFM for displacement measurement. However, there are some key points to tackle by the technology in order to achieve traceable machine tool metrology based on interferometry assessment:

- Thermal and refractive index distortions
- Real time capability.
- Dimensional traceability to the SI metre.

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When it comes to the object under measurement, in time and space varying quasi static errors are not as important as they are for large measuring systems, but it is crucial to determine the behaviour of the component according to a specific temperature and gravitational influences on the moment when measurement is executed.

Many challenges remain; these range from the need for complete knowledge of the error sources that affect to the measuring process to the weighting factor of each contribution to the uncertainty budget. In addition, a complete system of standards supporting machine integrated traceable measuring process is needed.

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References

1. *ISO 10360-3: 2004. Geometrical Product Specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement — Part 3: Use of calibrated workpieces or standards*; 2004.
2. ISO *ISO 10360-4:2008. Geometrical Product Specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement — Part 4: Evaluating task-specific measurement uncertainty using simulation*; 2008.
3. Verein Deutscher Ingenieure (VDI) *VDI/VDE 2617-11-Accuracy of Coordinate Measuring Machines - Characteristics and Their Checking - Determination of the Uncertainty of Measurement for Coordinate Measuring Machines Using Uncertainty Budgets.*; 2011.
4. Schmitt, R.; Peterek, M. Traceable measurements on machine tools-Thermal influences on machine tool structure and measurement Uncertainty. *Procedia CIRP* **2015**, *33*, 576–580.
5. Karadayi, R. *Adaptive manufacturing with metrology feedback*; 2012.
6. Physikalisch-Technische Bundesanstalt (PTB). Traceable in-process dimensional measurements (TIM) EMRP project IND 62 https://www.ptb.de/emrp/ind62-home.html.
7. Nisch, S.; Schmitt, R. *Production integrated 3D measurements on large machine tools*; 2010.
8. Schmitt, R.; Peterek, M.; Morse, E.; Knapp, W.; Galetto, M.; Härtig, F.; Goch, G.; Hughes, B.; Forbes, A.; Estler, W. Advances in Large-Scale Metrology – Review and future trends. *CIRP Ann. - Manuf. Technol.* **2016**.
9. Brecher, C.; Klocke, F.; Schmitt, R. Industrie 4.0: Aachener Perspektiven: Aachener Werkzeugmaschinenkolloquium 2014.
10. Keller, F. Traceability of on-machine measurements under a wide range of working conditions, Traceable in-process dimensional measurement Final Workshop. **2016**.
11. Schmitt, R.; Jatzkowski, P.; Peterek, M. Traceable Measurements using Machine Tools. In *Laser metrology and machine performance X : 10th International Conference and Exhibition on Laser Metrology, Machine Tool, CMM and Robotic Performance, Lamdamap*; 2013.
12. Bryan, J. International Status of Thermal Error Research (1990). *CIRP Ann. - Manuf. Technol.* **1990**, *39*, 645–656.
13. Bryan, J. International Status of Thermal Error Research. **1967**.
14. Bryan, J.; Pearson, J.; Brewer, W.; McClure, E. Thermal effects in dimensional metrology. *Mech. Eng.* **1965**, *87*, 70.
15. Ross-pinnock, D.; Mullineux, G. *Compensating for thermal and gravitational effects in structures and assemblies*;

2016.

16. Puttock, M. *Large Scale metrology*; 1978.
17. Blazejewski, A.; Kwasny, W.; Gim, T. Modelling thermal deformation of tilting rotary table with direct drive system. *J. Mach. Eng.* **2010**, *10*.
18. Kim, S. M.; Lee, S. K. Prediction of thermo-elastic behavior in a spindle-bearing system considering bearing surroundings. *Int. J. Mach. Tools Manuf.* **2001**, *41*, 809–831.
19. Kim, S.; Lee, S.; Lee, K. Effect of Bearing Surroundings on the High-Speed Spindle- Bearing Compliance. *Int. J. Adv. Manuf. Technol.* **2002**, *19*, 551–557.
20. Li, H.; Shin, Y. C. Analysis of bearing configuration effects on high speed spindles using an integrated dynamic thermo-mechanical spindle model. *Int. J. Mach. Tools Manuf.* **2004**, *44*, 347–364.
21. Li, H.; Shin, Y. C. Integrated Dynamic Thermo-Mechanical Modeling of High Speed Spindles, Part 2: Solution Procedure and Validations. *J. Manuf. Sci. Eng.* **2004**, *126*, 159–168.
22. Li, H.; Shin, Y. C. Integrated Dynamic Thermo-Mechanical Modeling of High Speed Spindles, Part 1: Model development. *J. Manuf. Sci. Eng.* **2004**, *126*, 148–158.
23. Postlethwaite, S. R.; Allen, J. P.; Ford, D. G. Machine tool thermal error reduction - An appraisal. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **1999**, *213*, 1–9.
24. Mayr, J.; Jedrzejewski, J.; Uhlmann, E.; Alkan Donmez, M.; Knapp, W.; Härtig, F.; Wendt, K.; Moriwaki, T.; Shore, P.; Schmitt, R.; Brecher, C.; Würz, T.; Wegener, K. Thermal issues in machine tools. *CIRP Ann. Manuf. Technol.* **2012**, *61*, 771791.
25. van den Bergh, C. Reducing thermal errors of CMM located on the shop- floor, Katholieke Umniversiteit Leuven, Belgium, 2001.
26. Schwenke, H.; Knapp, W.; Haitjema, H.; Weckenmann, A.; Schmitt, R.; Delbressine, F. Geometric error measurement and compensation of machines—An update. *CIRP Ann. - Manuf. Technol.* **2008**, *57*, 660–675.
27. Wendt, K.; Franke, M.; Härtig, F. Mobile Multilateration Measuring System for High Accurate and Traceable 3D Measurements of Large Objects. In *Proceedings of the 10th ISMQC, the 10th International Symposium on Measurement and Quality Control Tokyo: JSPE Techn. Committee for Intelligent Nanomeasure (Paper No. 25): E3-025-1–E3-025-4*; 2010.
28. ISO *ISO/IEC Guide 98-3:2008: Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement.*; 2008.
29. Widmaier, T.; Kuosmanen, P.; Hemming, B.; Esala, V.; Brabandt, D. New material standards for traceability of roundness measurements of large-scale rotors. In *58th IWK, Ilmenau Scientific Colloquium Technische Universität*; 2014.
30. Acko, B.; Milfelener, M. Temperature-invariant material Standard for monitoring performance of machine tools. In *Proc. 18th International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology"*; 2014; pp. 297–300.
31. Hemming, B.; Widmaier, T.; Palosuo, I.; Esala, V.; Laukkanen, P. Traceability for roundness measurements of rolls - European Metrology Research Programme, project No. IND62. In *Proc. 9th International DAAAM Baltic Conference industrial engineering*; 2014.
32. Acko, B.; Klobucar, R.; Acko, M. Traceability of in-process measurement of workpiece geometry. *Procedia Eng.* **2015**, *100*, 376–383.
33. Zeleny, J.; Linkeova, I.; Skalnik, P. Calibrated CAD model of freeform standard. In *Proc. XXI IMEKO World Congress*; 2015.
34. Forbes, A.; McCarthy, M. Calibration of grid plates bearing a high density of targets. In *Proc. 15th Euspen*;

2015; pp. 129–130.

35. Zeleny, J.; Linkeova, I. Design and calibration of free-form standard. In *Laser Metrology and Machine Performance XI*; 2015; pp. 147–148.
36. Viprey, F.; Nouira, H.; Lavernhe, S.; Tournier, C. Novel multi-feature bar design for machine tools geometric errors identification. *Precis. Eng.* **2016**, *46*, 323–338.
37. Acko, M.; Klobucar, R.; Milfelener, M. Design of a Measurement Standard for Monitoring Metrological Performance of Machine Tools. In *Proc. In-Tech*; 2015; pp. 104–107.
38. Woodward, S.; Brown, S.; Dury, M.; McCarthy, M. Producing dimensional transfer material standards for the assessment of workshop machine tool performance. In *Euspen's 16th International Conference & Exhibition*; 2016.
39. Klobucar, R.; Acko, B. Experimental Evaluation of Ball Bar Standard Thermal Properties by Simulating Real Shop Floor Conditions. *Int. J. Simul. Model.* **2016**, *15*, 511–521.
40. Trapet, E.; Wäldele, F. Trapet, Waldele - 1991 - A reference object based method to determine the parametric error components of coordinate measuring machines and machine tools.pdf. *Measurement* **1991**, *9*, 17–22.
41. Trapet, E. *Traceability of Coordinate Measurements According to the Method of the Virtual Measuring Machine*; 1999; Vol. PTB-report.
42. Härtig, F.; Kniel, K.; Schulze, K. *Messunsicherheitsermittlung: Ermittlung einer aufgabenspezifischen Messunsicherheit von 3D-Verzahnungsmessungen*; 2008.
43. Maropoulos, P. G.; Guo, Y.; Jamshidi, J.; Cai, B. Large volume metrology process models: A framework for integrating measurement with assembly planning. *CIRP Ann. - Manuf. Technol.* **2008**, *57*, 477–480.
44. García, M. In-Process Inspection of Large High Value Components on a Machine Tool Platform. 2016.
45. Flack, D. *Measurement Good Practice Guide No. 42: CMM verification*; 2001.
46. Slocum, A. Precision Machine-Design - Macromachine Design Philosophy and Its Applicability to the Design of Micromachines. In *Micro Electro Mechanical Systems, MEMS '92, Proceedings. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robot. IEEEMEMS '92, Proceedings. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robot. IEEE*; 1992.
47. Slocum, A. *Fundamentals of Design: Error budgets*; 2012.
48. Ispas, C.; Anania, D.; Mohora, C. Contribution concerning machine tool acuracy using software methods for geometrical errors compensation. **2006**, 26–27.
49. Hocken, R. J. Technology of machine tools. Volume 5. Machine tool accuracy. **1980**.
50. Knapp, W.; Matthias, E. Test of the Three-Dimensional Uncertainty of Machine Tools and Measuring Machines and its Relation to the Machine Errors. *CIRP Ann. - Manuf. Technol.* **1983**, *32*, 459–464.
51. Soons, J. A. Accuracy Analysis of Multi-Axis Machines. **1993**.
52. Weekers, W. Compensation for Dynamic Errrors of Coordinate Measuring Machines, Eindhoven University of Technology, 1996.
53. Abbe, E. Meßapparate für Physiker. *J. Instrum. Inf.* **1890**, *10*, 446 – 448.
54. Ibaraki, S.; Sawada, M.; Matsubara, A.; Matsushita, T. Machining tests to identify kinematic errors on five-axis machine tools. *Precis. Eng.* **2010**, *34*, 387–398.
55. Dassanayake, K. M. M.; Tsutsumi, M.; Saito, A. A strategy for identifying static deviations in universal spindle head type multi-axis machining centers. *Int. J. Mach. Tools Manuf.* **2006**, *46*, 1097–1106.
56. Donmez, M. A.; Blomquist, D. S.; Hocken, R. J.; Liu, C. R.; Barash, M. M. A general methodology for machine tool accuracy enhancement by error compensation. *Precis. Eng.* **1986**, *8*, 187–196.
57. Huang, T.; Whitehouse, D. A simple yet effective approach for error compensation of a tripod-based

parallel kinematic machine. *CIRP Ann. Technol.* **2000**, *49*, 285–288.

58. Hocken, R. J. Three dimensional Metrology. In *Annals of the CIRP*; 1977; pp. 403–408.
59. Zhang, G.; Veale, R.; Charlton, T.; Borchardt, B.; Hocken, R. Error Compensation of Coordinate Measuring Machines. *CIRP Ann. - Manuf. Technol.* **1985**, *34*, 445–448.
60. Soons, J. A.; Theuws, F. C.; Schellekens, P. H. Modeling the errors of multi-axis machines: a general methodology. *Precis. Eng.* **1992**, *14*, 5–19.
61. Schellekens, P.; Rosielle, N.; Vermeulen, H.; Vermeulen, M.; Wetzels, S.; Pril, W. Design for Precision: Current Status and Trends. *CIRP Ann. - Manuf. Technol.* **1998**, *47*, 557–586.
62. ISO (Technical comitee ISO/TC 39/SC 2). *ISO 230-1:2012, Test code for machine tools -- Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*; 2012.
63. Uriarte, L.; Zatarain, M.; Axinte, D.; Yag??e-Fabra, J.; Ihlenfeldt, S.; Eguia, J.; Olarra, A. Machine tools for large parts. *CIRP Ann. - Manuf. Technol.* **2013**, *62*, 731–750.
64. Knapp, W.; Tschudi, U.; Bucher, A. *Vergleich von Prufkorpern zur Abnahme von Koordinatenmessgeräten*; 1990.
65. Weckenmann, A. Comparison of CMM length measurement tests conducted with different 1D, 2D and 3D standards. In *proceedings of the 11th National, 2nd International Scientific Conference Metrology in Production Engineering, At Lublin, Poland*; 2005.
66. Kunzmann, H.; Trapet, E.; Wäldele, F. A Uniform Concept for Calibration, Acceptance Test, and Periodic Inspection of Coordinate Measuring Machines Using Reference Objects. *CIRP Ann. - Manuf. Technol.* **1990**, *39*, 561–564.
67. Pahk, H. J. A. E.; Kimt, Y. S. A. M.; Moon, J. H. E. E. A New Technique for Volumetric Error Assessment of CNC MTs Incorporating Ball Bar Measurement and 3D Volumetric Error Model. *Int. J. Mach. Tools Manuf.* **1997**, *37*, 1583 – 1596.
68. Zargarbashi, S. H. H.; Mayer, J. R. R. Assessment of machine tool trunnion axis motion error, using magnetic double ball bar. *Int. J. Mach. Tools Manuf.* **2006**, *46*, 1823–1834.
69. Knapp, W. Machine Tool Testing Methods: Overview over ISO Standards and other Special Tests for Machine Tool Performance Evaluation and Interim Checking. In *Proceedings of METROMEET 2005, Bilbao, Spain*; 2005.
70. Belforte, G.; Bona, B.; Canuto, E.; Donati, F.; Ferraris, F.; Gorini, I.; Morei, S.; Peisino, M.; Sartori, S.; Levi, R. Coordinate Measuring Machines and Machine Tools Selfcalibration and Error Correction. *CIRP Ann. - Manuf. Technol.* **1987**, *36*, 359–364.
71. Knapp, W. *Comparison of National and International Standards for Evaluation of Positioning Accuracy and Repeatability of NC Axes*; 1992.
72. Renishaw *The benefits of remote interferometry for linear, angular and straightness measurements. Technical white paper: TE335*.
73. Hickman, P. A. Optical tilting viewed in a new light. *Laser Focus* **1968**, *4*, 22.
74. Salsbury, J. G.; Hocken, R. J. Taut Wire Straightedge Reversal Artifact. In *Initiatives of Precision Engineering at the Beginning of a Millennium*; 2002; pp. 644–648.
75. Quesnel, J.; Durand, H. M.; Touzé, T. Stretched Wire Offset Measurements: 40 Years of Practice of This Technique At Cern. *Int. Work. Accel. Alignment* **2008**, 1–6.
76. American National Standards Institute (ANSI) *ANSI/ASME B89.4.19-Performance evaluation of laser-based spherical coordinate measuring systems*; 2006.
77. Schwenke, H. The latest trends and future possibilities of volumetric error compensation for machine tools. In *The 15th International Machine Tool Engineers' Conference, IMEC, Tokyo, Japan, 2-3 November*; 2012; p. 57–71.

78. CIRP Unification document Axes of Rotation. In *Annals of the CIRP*; 1976; pp. 545–564.
79. Renishaw *Interferometric calibration of rotary axes-Technical white paper: TE327*.
80. Estler, W. T. Uncertainty Analysis for Angle Calibrations Using Circle Closure. *J. Res. Natl. Inst. Stand. Technol.* **1998**, *103*, 11.
81. Chapman, M. A. V.; Fergusson-Kelly, R.; Holloway, A.; Lock, D.; Lee, W. *Interferometric angle measurement and the hardware options available from Renishaw-Technical white paper: TE326*.
82. Automated Precision Inc. (API) XD laser measuring solution.
83. Renishaw *XM-60 multi-axis calibrator*; 2016.
84. SIOS Calibration Interferometer: SP 15000 C Series.
85. ISO (Technical comitee ISO/TC 39/SC 2). *ISO 230-6:2002, Test Code for Machine tools. Part 6. Determination of Positioning Accuracy on Body and Face Diagonals (Diagonal Displacement Tests)*; 2002.
86. Rahman, M.; Mayer, R. Calibration performance investigation of an uncalibrated indigenous artefact probing for five-axis machine tool. *J. Mach. Eng.* **2016**, *16*.
87. Erkan, T.; Mayer, J. R. R.; Dupont, Y. Volumetric distortion assessment of a five-axis machine by probing a 3D reconfigurable uncalibrated master ball artefact. *Precis. Eng.* **2011**, *35*, 116–125.
88. Guenther, A.; Stöbener, D.; Goch, G. Self-Calibration Method for a Ball Plate Artefact on a CMM. *CIRP Ann. - Manuf. Technol.* **2016**, *65*, 503–506.
89. Honegger, A. E.; Kapoor, S. G.; Devor, R. E. A Hybrid Methodology for Kinematic Calibration of Micro/Meso-Scale Machine Tools (mMTs). *J. Manuf. Sci. Eng.* **2006**, *128*, 513.
90. Schellekens, P. H. J.; Spaan, H. A. M.; Soons, J. A.; Trapet, E.; Loock, V.; Dooms, J. Development of Methods for Numerical Correction of Machine Tools. In *Proceedings of the 7th International Precision Engineering Seminar, Springer Verlag, Kobe (Japan)*; 1993; pp. 213–223.
91. Bringmann, B.; Küng, A.; Knapp, W. A Measuring Artefact for true 3D Machine Testing and Calibration. *CIRP Ann. - Manuf. Technol.* **2005**, *54*, 471–474.
92. Knapp, W.; Weikert, S. Testing the Contouring Performance in 6 Degrees of Freedom. *CIRP Ann. - Manuf. Technol.* **1999**, *48*, 433–436.
93. Bryan, J. B. A simple method for testing measuring machines and machine tools. Part 2: Construction details. *Precis. Eng.* **1982**, *4*, 125–138.
94. Bryan, J. B. A simple method for testing measuring machines and machine tools. Part 1: Principles and applications. *Precis. Eng.* **1982**, *4(2)*, pp. 61–69.
95. Burdekin, M.; Park, J. . A Computer Aided System for Assessing the Contouring Accuracy on NC Machine Tools. In *Proceedings of the Twenty-Seventh International Matador Conference*; 1988.
96. Knapp, W. Machine Tool Acceptance by Circular Measurements. In *Proceedings of Lamdamap 93, Southhampton, England*; 1993; pp. 11–27.
97. Yagüe, J. a; Velázquez, J.; Albajez, J. a; Aguilar, J. J.; Lope, M. a; Santolaria, J. Development and calibration of self-centring probes for assessing geometrical errors of machines. *Meas. Sci. Technol.* **2009**, *20*, 115103.
98. Florussen, G. H. J.; Spaan, H. A. M. Static R-Test: Allocating the Centreline of Rotary Axes of Machine Tools. In *Laser Metrology and Machine Performance VIII, Lamdamap, Euspen, Bedford*; 2007.
99. Morfino, G. System and process for measuring, compensating and testing numerically controlled machine tool heads and/or tables 2004.
100. ISO (Technical comitee ISO/TC 39/SC 2). *ISO 230-4:2005, Test Code for MTs. Part 4. Circular Tests for Numerically Controlled machine tools*; 2005.
101. Sartori, S.; Zhang, G. X. Geometric Error Measurement and Compensation of Machines. *CIRP Ann. - Manuf.*

Peer-reviewed version available at *Sensors* **2017**, *17*, 1605; doi:10.3390/s17071605

Technol. **1995**, *44*, 599–609.
102. Mayer, J. R. R. Five-axis machine tool calibration by probing a scale enriched reconfigurable uncalibrated master balls artefact. *CIRP Ann. - Manuf. Technol.* **2012**, *61*, 515–518.
103. Florussen, G. H. J.; Spaan, H. A. M. Determining the machine tool contouring performance with dynamic R-test measurements 3D probe head Masterball C-axis. In *Proceedings of the 12th euspen International Conference, Stockholm.*; 2012; pp. 1–5.
104. Florussen, G. H. J.; Spaan, H. A. M. Dynamic R-test for rotary tables on 5-axes machine tools. **2012**, *1*, 536–539.
105. Hughes, E. B.; Wilson, A.; Peggs, G. N. Design of a High-Accuracy CMM Based on Multilateration Techniques. *CIRP Ann. - Manuf. Technol.* **2000**, *49*, 391–394.
106. Schwenke, H.; Franke, M.; Hannaford, J.; Kunzmann, H. Error mapping of CMMs and machine tools by a single tracking interferometer. *CIRP Ann. - Manuf. Technol.* **2005**, *54*, 475–478.
107. Weckenmann, A.; Jiang, X.; Sommer, K. D.; Neuschaefer-Rube, U.; Seewig, J.; Shaw, L.; Estler, T. Multisensor data fusion in dimensional metrology. *CIRP Ann. - Manuf. Technol.* **2009**, *58*, 701–721.
108. Aguado, S.; Santolaria, J.; Samper, D.; Aguilar, J. J. Influence of measurement noise and laser arrangement on measurement uncertainty of laser tracker multilateration in machine tool volumetric verification. *Precis. Eng.* **2013**, *37*, 929–943.
109. Schmitt, R.; Peterek, M.; Quinders, S. Concept of a Virtual Metrology Frame Based on Absolute Interferometry for Multi Robotic Assembly. **2014**, *m*, 79–86.
110. Kenta, U.; Ryosyu, F.; Sonko, O.; Toshiyuki, T.; Tomizo, K. Geometric calibration of a coordinate measuring machine using a laser tracking system. *Meas. Sci. Technol.* **2005**, *16*, 2466.
111. Olarra, A.; Zubeldia, M.; Gomez-acedo, E.; Kortaberria, G. *Measuring positioning accuracy of large machine tools*; 2012.
112. Brecher, C.; Flore, J.; Haag, S.; Wenzel, C. High precision, fast and flexible calibration of robots and larde multi-axis machine tools. *MM Sci. J.* **2012**.
113. Schwenke, H. *Accuracy Improvement of Machine Tool via New Laser Measurement Methods*; 2015.
114. Schwenke, H.; Schmitt, R.; Jatzkowski, P.; Warmann, C. On-the-fly calibration of linear and rotary axes of machine tools and CMMs using a tracking interferometer. *CIRP Ann. - Manuf. Technol.* **2009**, *58*, 477–480.
115. Etalon AG. Laser tracer MT http://www.etalon-ag.com/en/products/lasertracer-mt/.
116. Metrology, H. Leica absolute tracker at930 http://www.hexagonmi.com/products/laser-tracker-systems/leica-absolute-tracker-at930.
117. ISO *ISO 10360-2:2009. Geometrical product specifications (GPS) -- Acceptance and reverification tests for coordinate measuring machines (CMM) -- Part 2: CMMs used for measuring linear dimensions*; 2009.
118. Trapet, E.; Aguilar Martín, J. J.; Yagüe, J. A.; Spaan, H.; Zelený, V. Self-centering probes with parallel kinematics to verify machine-tools. *Precis. Eng.* **2006**, *30*, 165–179.
119. Weckenmann, A.; Estler, T.; Peggs, G.; McMurtry, D. Probing systems in dimensional metrology. *CIRP Ann. - Manuf. Technol.* **2004**, *53*, 657–684.
120. Renishaw *OMP400 optical machine probe systems. Technical paper: H-5069-8504-05-A*; 2008.
121. Weckenmann, A. Comparability of tactile and optical form measuring techniques with resolution in the nanometre range. In *Proceedings of X. International Colloquium on Surfaces*; 2000; pp. 50–62.
122. Yang, Q.; Butler, C. A 3-D noncontact trigger probe for coordinate measuring machines. *Meas. J. Int. Meas. Confed.* **1996**, *17*, 39–44.
123. Lukacs, G.; Lockhart, J.; Facello, M. *Non-contact whole-part inspection*; 2013.

124. Marsh, B. An Investigation of Diameter Measurement Repeatability Using A Coordinate Measuring Machine And A Multi-Baseline Repeatability Assessment Methodology. In *2nd Annual Quality & Metrology Symposium Proceedings, Center for Quality, Measurement, and Automation, Bowling Green State University*; 1996.
125. Dove, J. *Probe qualification and precision coordinate metrology*; 2000.
126. Renishaw *Measurement on CMMs. White paper H-1000-3218-01*.
127. Imkamp, D.; Schepperle, K. *The Application Determines the Sensor: VAST Scanning Probe Systems*; 2006.
128. Knebel, R. *Gage RR for CMMs*; 1998.
129. Ali, S. H. R. Probing System Characteristics in Coordinate Metrology. *Meas. Sci. Rev.* **2010**, *10*, 120–129.
130. Berisso, K.; Ollison, T. Coordinate Measuring Machine Variations for Selected Probe Head Configurations. *J. Ind. Technol.* **2010**, *26*.
131. Renishaw *Probing systems for CNC machine tools*.
132. Karuc, E. Design of a touch triger probe for a coordinate measuring machine, The graduate school of natural sciences of middle east technical university, 2007.
133. Renishaw *SPRINT high-speed scanning system. H-5465-8399-03 white paper*.
134. Novotest, B. Digilog touch probes http://www.blum-novotest.com/en/products/measuring-components/digilog-touch-probes/tc63-tc64-digilog.html.
135. Weckenmann, A.; Kampa, H. *Koordinaten messgeraete, VDI-Z*; 1983.
136. Weckenmann, A.; Kampa, H.; Georgi, B.; Goch, G.; Hesper, H. . *Koordinatenmessgeraete*; 1984.
137. Aston, R.; Davis, J.; Stout, K. A probing question: A customer´s investigation into the directional variability of a coordinate measuring machine touch trigger probe. **1998**, *38*, 15–27.
138. Chan, F. M. M.; Davis, E. J.; King, T. G.; Stout, K. J. Some performance characteristics of a multi-axis touch trigger probe. *Meas. Sci. Technol.* **1997**, *8*, 837.
139. Dobosz, M.; Woźniak, A. Metrological feasibilities of CMM touch trigger probes. *Measurement* **2003**, *34*, 287–299.
140. Shen, Y.-L.; Zhang, X. Pretravel compensation for vertically oriented touch-trigger probes with straight styli. *Int. J. Mach. Tools Manuf.* **1997**, *37*, 249–262.
141. Kishinami, T.; Nakamura, H.; Saito, K. Three Dimensional Curved Surfaces measurement using Newly Developed Three Dimensional Tactile Sensing Probe. In *Proceedings of the International Symposium on Metrology for Quality Control in Production Tokyo*; 1984; pp. 288–293.
142. Moons, S.; Shen, Y.-L. Errors in probe offset Vectors of multiple orientations in CMM measurements. In *ASPE proceedings*; 1998; pp. 512–515.
143. Ogura, I.; Okazaki, Y. A Study for Development of Small-CMM Probe detecting Contact Angle. In *Proceedings ASPE Summer Topical Meeting on Coordinate Measuring Machines*; 2003; pp. 74–77.
144. Yang, Q.; Butler, C.; Baird, P. Error compensation of touch trigger probes. *Meas. J. Int. Meas. Confed.* **1996**, *18*, 47–57.
145. Li, Y. F.; Liu, Z. G. Method for determining the probing points for efficient measurement and reconstruction of freeform surfaces. *Meas. Sci. Technol.* **2003**, *14*, 1280–1288.
146. Weckenmann, A. *Koordinatenmesstechnik*; 1998.
147. Uhlmann, E.; Förster, R.; Laufer, J.; Sroka, F. Three-dimensional roughness values for the functional characterization of ceramic surfaces. In *Proceedings 10th International Colloquium on Surfaces : Chemnitz (Germany)*; 2000; pp. 265–276.
148. Lonardo, P. M.; Lucca, D. a.; De Chiffre, L. Emerging Trends in Surface Metrology. *CIRP Ann. - Manuf. Technol.* **2002**, *51*, 701–723.

149. Puttock, M. J.; Thwaite, E. G. Elastic Compression of Spheres and Cylinders at Point and Line Contact. *Natl. Stand. Lab. Tech. Pap.* **1969**, *25*, 64.
150. Uhlmann, E.; Oberschmidt, D.; Kunath-fandrei, G. 3D-Analysis of Microstructures with Confocal Laser Scanning Microscopy. In *ASPE Winter Topical Meeting 1*; 2003; pp. 93–97.
151. Zahwi, S.; Mekawi, A. M. Some effects of stylus force on scratching surfaces. *Int. J. Mach. Tools Manuf.* **2001**, *41*, 2011–2015.
152. Edgeworth, R.; R.G., W. Uncertainty Management for CMM Probe Sampling of Complex Surfaces. In *ASME Manufacturing Science and Engineerin*; 1996; pp. 511–518.
153. Aoyama, H.; Kawai, M.; Kishinami, T. A New Method for Detecting the Contact Point between a Touch Probe and a Surface. **1989**, *38*, 7–10.
154. Marshall, S.; Gilby, J. *New Opportunities in Non-Contact 3D Measurement*; 2002.
155. Keferstein, C.; Züst, R. *Minimizing technical and financial risk when integrating and applying optical sensors for in- process measurement*.
156. Karadayi, R. Blue Light Laser Sensor Integration and Point Cloud Metrology. In *CMSC conference*; 2016.
157. Paulo de Moraes, J.; Peterek, M. *Integration of a laser scanner into a machine tool for an in-process 3D measurement*; 2012.
158. Streppel, A. H.; Lutters, D.; Brinke, E. ten; Pijlman, H.; Kals, H. J. Selective measuring of freeform surfaces for quality control and selective maintenance of bending tools. *J. Mater. Process. Technol.* **2001**, *115*, 147–152.
159. Savio, E.; Chiffre, L. De; Schmitt, R. Metrology of freeform shaped parts. **2007**, *56*, 810–835.
160. Brinksmeier, E.; Preuss, W. Diamond machining of the 3 m reflector of the KOSMA submillimeter telescope by a single-point fly-cutting process. In *Proceedings of the annual meeting - American Society for Precision Engineering*; 1996; pp. 56–61.
161. Brinksmeier, E.; Riemer, E.; Glabe, O. *Process Chains for the Replication of Complex Optical Elements*; 2004.
162. Katahira, K.; Ohmori, H.; Yoshida, K.; Kasuga, H.; Hirai, S. Elid grinding effects on fabrication of advanced ceramics components riken. In *Proceedings of of euspen Int. Top.Conf., Aachen, Germany,*; 2003; pp. 317–320.
163. Klocke, F.; Dambon, O. Precision Machining of Glass for Optical Applications. In *Proceedings of Int. Workshop on Extreme Optics and Sensors, Tokyo, Japan*; 2003; pp. 185–193.
164. Savio, E.; De Chiffre, L. Inspection of free form functional surfaces on fan blades. In *Proceedings of PRIME 2001 Int. Conf., Sestri Levante, Italy, 20-22 June*; 2001.
165. Beraldin, J.-A.; Gaiani, M. Evaluating the Performance of Close-Range 3D Active Vision Systems for Industrial Design Applications. *Videometrics VIII - SPIE Electron. Imaging* **2005**, *5665*, 67–77.
166. Carmignato, S. Traceability of coordinate measurements on complex surfaces, Università di Padova, DIMEG, Italy, 2005.
167. Carmignato, S., Neuschaefer-Rube, U., Schwenke, H.; Wendt, K. Tests and artefacts for determining the structural resolution of optical distance sensors for coordinate measurement. In *Proceedings of the 6th International Conference European Society for Precision Engineering and Nanotechnology*; 2006.
168. Sansoni, G.; Carmignato, S.; Savio, E. Validation of the measurement performance of a three-dimensional vision sensor by means of a coordinate measuring machine. *Conf. Rec. - IEEE Instrum. Meas. Technol. Conf.* **2004**, *1*, 773–778.
169. Bartscher, M.; Hilpert, U.; Neuschaefer-Rube, U. *Industrielle Computertomographie auf dem Weg zur Koordinatenmesstechnik*; 2007.
170. Bartscher, M.; Neukamm, M.; Hilpert, U.; Neuschaefer-Rube, U.; Härtig, F.; Kniel, K.; Ehrig, K.; Staude, A.; Goebbels, J. Achieving Traceability of Industrial Computed Tomography. *Key Eng. Mater.* **2010**, *437*, 79–83.

171. Sonka, M.; Hlavac, V.; Boyle, R. *Image Processing, Analysis, and Machine Vision*; 1999.
172. Chen, X.; Golovinskiy, A.; Funkhouser, T. Benchmark for 3D Mesh Segmentation. In *Proceedings of SIGGRAPH*; 2009.
173. Liu, H.; Xue, X.; Tan, G. Backlash Error Measurement and Compensation on the Vertical Machining Center. **2010**, *2010*, 403–407.
174. Rehsteiner, F.; Weikert, S.; Rak, Z. Accuracy Optimization of Machine Tools under Acceleration Loads for The Demands of High-Speed-Machining. In *Proceedings of the annual meeting - American Society for Precision Engineering*; 1998; pp. 602–605.
175. Weikert, S. When five axes have to be synchronized. In *Proceedings of the 7th Lamdamap Conference*; 2005; pp. 87–96.
176. Weekers, W. G.; Schellekens, P. H. J. Compensation for dynamic errors of coordinate measuring machines. *Precis. Eng.* **1997**, *20*, 197–209.
177. Delbressine, F. L. M.; Florussen, G. H. J.; Schijvenaars, L. A.; Schellekens, P. H. J. Modelling thermomechanical behaviour of multi-axis machine tools. *Precis. Eng.* **2006**, *30*, 47–53.
178. Florussen, G. H. J. Accuracy Analysis of Multi-axis Machines by 3D Length Measurements, University of Technology, Eindhoven, 2002.
179. Gruber, R.; Knapp, W. *Temperatureinflüsse auf die Werkzeugmaschi- nengenauigkeit*; 1998.
180. Muelaner, J. E.; Maropoulos, P. G. Large volume metrology technologies for the light controlled factory. *Procedia CIRP* **2014**, *25*, 169–176.
181. National physical laboratory (NPL) LUMINAR EMRP project http://projects.npl.co.uk/luminar/.
182. Peggs, G. N.; Maropoulos, P. G.; Hughes, E. B.; Forbes, A. B.; Robson, S.; Ziebart, M.; Muralikrishnan, B. Recent developments in large-scale dimensional metrology. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2009**, *223*, 571–595.
183. Warden, M. S. Absolute distance metrology using frequency swept lasers, University of Oxford, 2011.
184. Etalon AG Absolute multiline technology http://www.etalon-ag.com/produkte/absolute-multiline-technologie/.
185. Hughes, B.; Warden, M. S. Novel Coordinate Measurement System Based on Frequency Scanning Interferometry. In *Proceedings of CSMC*; 2013; pp. 19–24.
186. Gomez-Acedo, E.; Olarra, A.; Zubieta, M.; Kortaberria, G.; Ariznabarreta, E.; de Lacalle, L. N. Method for measuring thermal distortion in large machine tools by means of laser multilateration. *Int. J. Adv. Manuf. Technol.* **2015**, *80*, 523–534.
187. Buffalo, U. of *Computer numerical control (CNC)*.
188. Zayer KAIROS machine tool http://www.zayer.com/en/product/movingcolumn/kairos/25.
189. DMG Mori Vertical machining center-cmx 600 v http://en.dmgmori.com/products/milling-machines/vertical-machining-centres/cmx-v/cmx-600-v#Intro.
190. Mian, N. S.; Fletcher, S.; Longstaff, A. P.; Myers, A. Efficient estimation by FEA of machine tool distortion due to environmental temperature perturbations. *Precis. Eng.* **2013**, *37*, 372–379.
191. Maier, T.; Zaeh, M. F. Modeling of the thermomechanical process effects on machine tool structures. *Procedia CIRP* **2012**, *4*, 73–78.
192. Ross-Pinnock, D.; Maropoulos, P. G. Identification of key temperature measurement technologies for the enhancement of product and equipment integrity in the light controlled factory. *Procedia CIRP* **2014**, *25*, 114–121.
193. Klocke, F.; Lung, D.; Puls, H. FEM-Modelling of the thermal workpiece deformation in dry turning. *Procedia*

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Peer-reviewed version available at *Sensors* **2017**, *17*, 1605; doi:10.3390/s17071605

CIRP **2013**, *8*, 240–245.

194. Bath, U. of *Coping with Thermal Expansion in Large Volume Metrology - Good practise guide - LUMINAR EMRP project*.
195. Adams, V. *Building Better Products with Finite Element Analysis*; 1999.
196. Moaveni, S. *Finite element analysis: theory and application with ANSYS*; 2003.
197. Nakasone, Y. *Engineering Analysis with ANSYS Software*; 2006.
198. Makino Vertical machining center - ps-series-vmc https://www.makino.com/vertical-machining-centers/ps-series-vmc/ps-brochure-(electronic).pdf.
199. Kortaberria, G. *Characterization of large machine tool volumetric behaviour in workshop conditions - (TIM) EMRP project IND 62*; 2015.
200. Wennemer, M. *A case study on a very large machine tool: systematic deviations and thermo-elastic deformations - Etalon Forum*; 2016.