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Advances in Large-Scale Metrology – Review and future trends

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ABSTRACT

The field of Large-Scale Metrology has been studied extensively for many decades and represents the combination and competition of topics as diverse as geodesy and laboratory calibration. A primary reason that Large-Scale Metrology continues to represent the research frontier is that technological advances introduced and perfected at a conventional scale face additional challenges which increase non-linearly with size. This necessitates new ways of considering the entire measuring process, resulting in the application of concepts such as virtual measuring processes and cyber-physical systems. This paper reports on the continuing evolution of Large-Scale Metrology.

1. Introduction

In his survey paper "Large-Scale Metrology" in 1978 Puttock defined Large-Scale Metrology as "metrology of large machines and structures" and observed that "the linear dimensions range from tens to hundreds of metres". Puttock pointed out that Large-Scale Metrology means "a significant challenge to the metrologist [. . .] since tolerances become more challenging" [152]. This observation is still the key challenge in this field and will be an underlying theme of this paper. In their paper Estler et al. reinforced the observations of Puttock and focused on the "developments and refinement of versatile instruments," as well as "significant advances across a broad range of technologies" that allow for less customized instrumentation for large scaled measurement tasks in different industries, such as ship and aircraft construction [44]. The further developments of technologies such as laser interferometry, absolute distance measuring systems, high density CCD-cameras, and the evolution of more powerful computers and software solutions allows the realization of measurement systems, that in 1978 "only existed as concept, if they existed at all" [44,152].

This paper will continue and update the review of the current state of Large-Scale Metrology. In addition, it will expand its focus from primarily the instruments to include the complete measurement process. This holistic approach addresses the contributions of the measured object and the effects of environmental conditions on both the measurement system and the object. The extension shall cover the development of an approach for an "uncertainty model" for large-scale measurement processes that will help to ensure traceability and comparability of the measurement results.

The next underlying theme in the field of Large-Scale Metrology was first discussed by Peggs et al., who observed that combinations of different technologies, such as laser trackers and CMM-like probes, or multiscanner measuring systems, can be used to measure large structures. These "bridge designs" provide a range of possible measurement set ups and strategies for Large-Scale Metrology tasks, but also add challenges to ensuring the traceability of the measuring process [147]. The determination of the measurement uncertainty that includes contributions from the complete measurement process in an industrial or terrestrial environment may be separated into contributions from the measurement system and from the object under measurement. This is discussed in international standards that have emerged during recent years. Referring to the "Guide to the expression of uncertainty in measurement", the process oriented estimation of the measurement uncertainty associated with the measured data requires a holistic knowledge of the influences on the measuring process [76]. Large objects are extremely sensitive to environmental influences such as temperature (especially inhomogeneous temperature variation inside the object under measurement) and gravity. Approaches for the separation of the uncertainty contribution of the object under measurement are presented, based on both simulation and experiments. Ultimately, the ability to predict the complex interactions between the measurement

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system and the object under measurement – in the harsh environmental conditions of the industrial shop floor – is required. Model-based performance estimations for the measurement process lead to the optimization of measurement strategies, and therefore allow the evaluation of the test process suitability. European research activities focus on extending the known virtual measuring machines (VMM) concept to virtual measuring processes (VMP). Schmitt, Goch et al. defined the virtual measuring process as a model of the measuring instrument, the object under measurement, and the interaction between them. The objective is to generate simulated measurement results to estimate the measurement uncertainty of the real measurements [119].

1.1. Definition: Large-Scale Metrology

Large-Scale Metrology (LSM), in summary, defines measurement processes that are used in the field of production technology for geometric inspection, in accordance with geometrical product specifications (GPS), for objects in which the linear dimensions vary from one meter to hundreds of meters in linear dimension. Additional attributes of Large-Scale Metrology are:

- The sensor readings (angles and distances) are often related indirectly to the measurands, usually the locations of targets or quantities derived from the measurement systems.
- Challenging tolerances in spite of the large dimensions of the measured part (see Fig. 1), (for example, 4 m diameter bearings with a 20 μm tolerance).
- The non-negligible influence of gravity on the test objects geometry.
- In many cases, the test takes place in the manufacturing environment. Correspondingly, non-ideal environment (air temperature, humidity, vibration) has a large influence on the test object and the measuring system.
- Small batch production and the need for a first-time-right production.
- Classical quality assurance tools (statistics) are difficult to adapt.

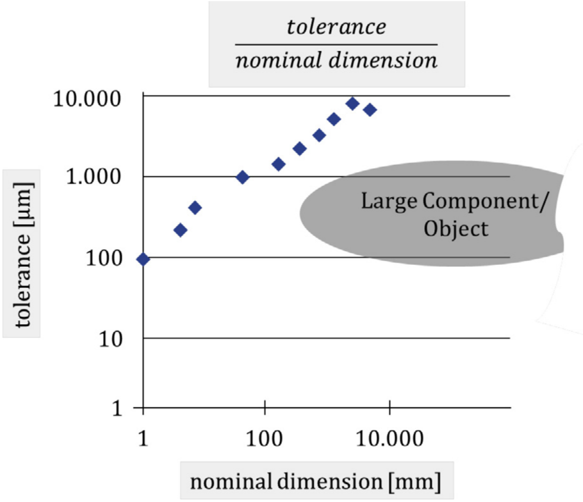


Fig. 1. Approach for a definition of a large object by nominal dimensions and tolerances.

The definition does not cover every application of LSM. Also the attributes listed are not exclusive to LSM, but overlap with tasks in other metrology fields. The objective is to give an understanding of the complexity that will come along with measurements tasks in this special field of metrology. Understanding the complexity of the interaction between a number of the attributes listed above, which at the same time influence both the measurement system and the workpiece being measurand, is the main challenge of LSM. The aspects themselves are well known and are object of research in different scientific fields. However, a holistic approach that will describe the measurement process for large-scale devices, taking into account all possible interactions, is yet to be realized. This complexity motivates the need for virtual processes, which include suitable models of the different influence factors, into one virtual measurement process. The model-based approach is therefore vital to the solution of the main challenges in LSM.

1.2. Examples and motivation

Global megatrends such as the efficient use of natural resources and the continued globalization do not only influence daily life, but also affect complete industrial sectors.

Some of the rapidly growing industries of this millennium can be found in the fields of energy and mobility. Applications in wind energy, aviation and ship construction require an increasing number of sophisticated and individualized large components. Due to close relative tolerances in the large work volumes, the production and quality inspection of these components often encounters the limits of manufacturing and production metrology. The measurement of large-scale devices is absolutely vital for the manufacturing and alignment of many products on which modern life depends.

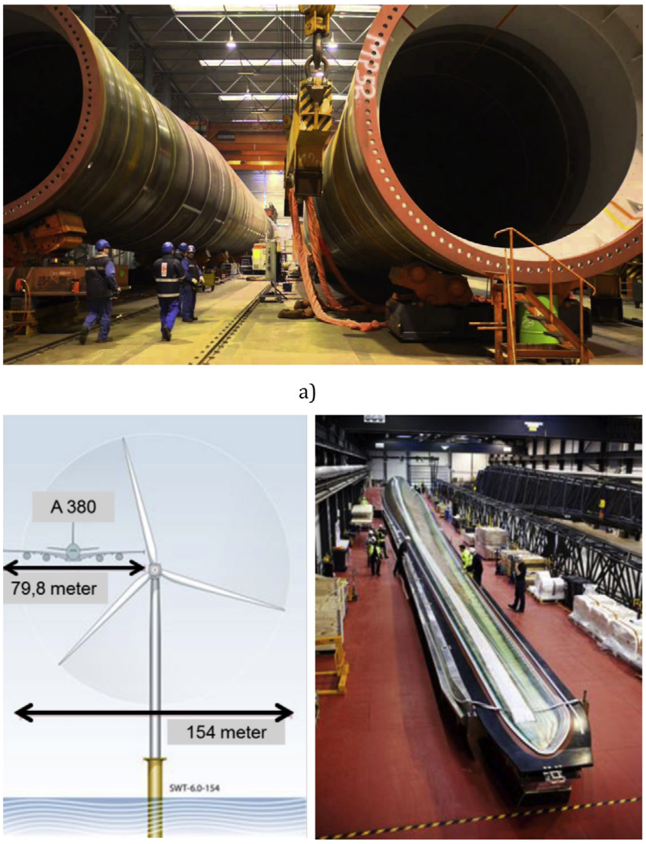
New concepts and innovative technologies are needed to integrate the measurement processes into the manufacturing process. Structures or objects are usually too large to fit into conventional measuring devices or to be transported to a calibration laboratory. They have to be measured in process or in situ. The tradeoff between increasing work piece dimensions and constant or even decreasing tolerances (for example in the field of large gears for wind power industries) and the necessity of making measurements in uncontrolled environments greatly complicate accurate and traceable metrology [119]. The regulation pressures in many industries request a metrology capability that is able to keep pace with these demands.

Energy is the lifeblood of industrial processes. It provides prosperity and quality for life especially in industrialized and emerging countries [72]. Electrical energy is mainly generated from fossil resources such as coal, oil, natural gas, and nuclear fuel. Some of these resources will be exhausted within the next generations. In addition the intensive usage of energy by modern societies leads to environmental pollution, e.g. by carbon dioxide emissions, fracking induced chemical soil contamination, and nuclear waste. To guarantee a sustainable energy supply for the future on the one hand efficiency increases of nonrenewable energy systems are required and on the other hand innovations in the renewable energy sectors are essential.

According to the roadmap and forecast of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany (BMU), the share of wind power in electricity generation has to increase to 25% by 2025, based on today's electricity consumption.

Wind energy systems (WES) are regarded as one of the most promising technologies for renewable energy. Since the beginning in 1980 the market has grown significantly [72]. Goch et al. discussed that only very few WES reach the objective lifetime of 20 years without two or more fatal failures of major components. This is very critical as the failure of mechanical components can lead to downtimes of several days or even weeks. Moreover reliable drivetrain components are mandatory and can only be assured by an enhanced quality of the components. Beneath improved manufacturing technologies, suitable measurement systems and processes are required to assure the quality of bearings, brakes and gears. The growing sizes lead to the fact that only few measuring devices offer sufficient measuring volume and measurement uncertainty. Therefore components of WES are examples of challenges for Large-Scale Metrology (Fig. 2).

The scarcity of fossil fuels requires higher efficiency for gas and coal power plants and engines. Further on a decrease of the pollutant emissions is inevitable to stop the climate change.



a) b) c)

Fig. 2. Manufacturing of off-shore WES (a) manufacturing of piles (Source: SIF Group), (b) dimensions of off-shore 6 MW WES (Source: Siemens), (c) manufacturing of blades (Source: Siemens).

The importance of capable measurement processes can be illustrated by the example of the manufacturing process of turbines generating electricity out of gas or steam. The efficiency of the assembled turbine is significantly influenced by the gap between blade tip and casing. The gap or clearance results in a leakage flow crossing the tip from the pressure side to the suction side of the blade. Slight inaccuracies can lead to significant reduction of turbine work extraction especially seen over the life cycle. The dimensional tolerances of the rotor and casing define the gap of the assembled turbine. The large components of the heavy-duty turbines are produced in different production sites on large machine tools (Fig. 3). Workpiece and machine tool are effected by the normally harsh environmental conditions of the production line. The employed measuring devices need to be portable to facilitate near-process measurements.

Fig. 3. Production of large gas and steam turbines at Alstom Power.
Source: Alstom Power.

Globalization has led to an enormous increase in freight and passenger transportation. During the last decade the strategy to meet the increasing number of flight passengers was the construction of larger airplanes. In addition the resource efficiency will be improved by weight reduction leading to an increasing use of lightweight materials. Size and material bring up new challenges regarding tolerances and quality assurance in manufacturing and assembly.

The fuselage of modern airplanes is constructed with shell elements which have to be assembled to the final airplane structure [163]. To fulfill strict tolerance requirements, the shells have to be positioned and untwisted before they can be assembled (Fig. 4). The untwisting is needed to compensate deformations of the shell (mainly due to gravity). The assembly is done mostly manual and the handling of the components is critical to the reliability and safety of the joints. The main challenge for inline measurement processes for these parts is the gravitational effects on the components structure. A compensation of these effects can improve the measurement process.

The assembly of large scale components (truck cabins, machine tools, turbine house of wind power stations, etc.) changed from manual fixed-site production (stationary assembly) to manual synchronized assembly flow-lines in the recent past (Fig. 5). But, because of the product variety, heavy and awkwardly shaped components and the relative low production volume, the automation of such assemblies is neither economic nor technically feasible. The challenges for an automated assembly of large parts may be solved with metrology systems that were formerly used for classical coordinate metrology tasks.

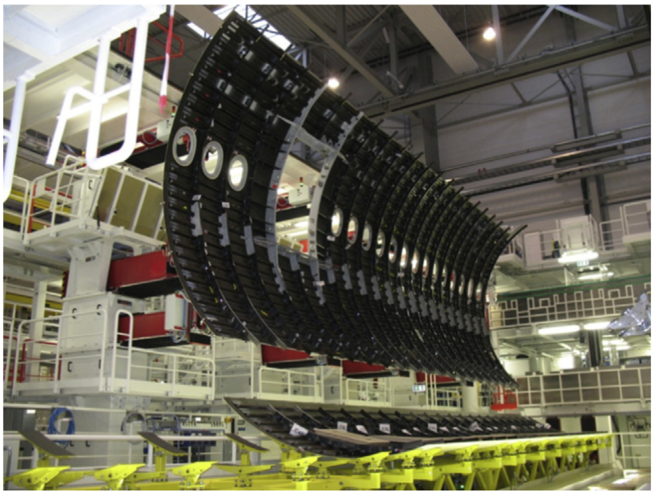


Fig. 4. Fuselage of an airplane body.
Source: PAG.

Fig. 5. Metrology based windshield assembly in motion.
Source: WZL RWTH Aachen Universiy.

2. Measurement systems in Large-Scale Metrology

The state of the art provides a large variety of measurement systems. It has evolved constantly since the last reviews of Puttock in 1978 and Estler et al. in 2002 [44,152]. Schwenke et al. dedicated an article to the state of the art of optical methods in dimensional metrology [170]. In particular, a further development of measurement systems happened in between 2002 and 2009 as Peggs et al. reviewed in 2009 [147]. The latest review of Large-Scale Metrology can be found in [57].

The measurement systems (Fig. 6) for Large-Scale Metrology can be classified by means of their system topology into centralized and distributed systems as suggested by Maisano et al. [115]. A centralized system is a stand-alone unit that can independently measure the coordinates of a point on an object [116]. This may require one or more ancillary devices e.g. a computer or a spherically-mounted reflector (SMR) for the laser tracker [46]. A distributed instrument consists of several, separate and independent units whose separately gathered measurement information needs to be jointly processed in order for the system to determine the coordinates of a point [46]. The individual units of the system typically cannot provide measurements of the coordinates of a point [116]. An example of such system is the Nikon iGPS (indoor GPS) [140]. It is also possible to use centralized systems in combination as a distributed system (e.g. several laser trackers).

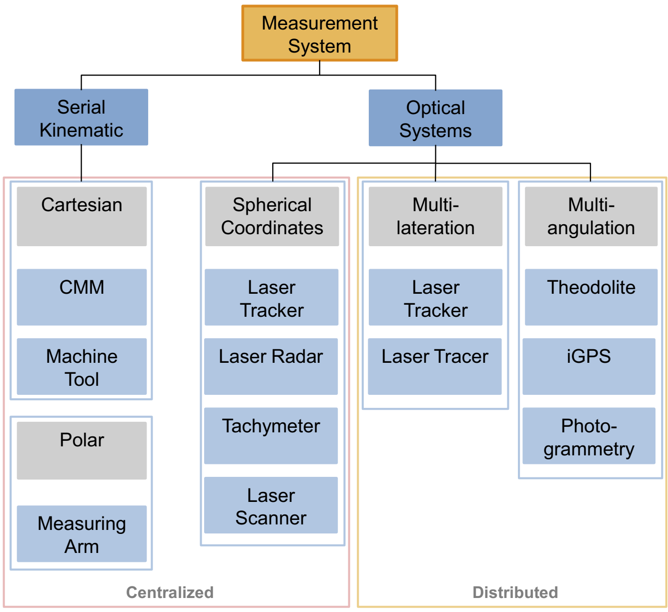


Fig. 6. Classification of Large-Scale Metrology [44,147].

A recent paper by Franceschini et al. presented a general framework for the analysis and classification of LSM systems [54,58].

The work was based on a deep bibliometric analysis of the scientific literature and on the study of the patents issued in the last decades. This produced a scheme for a taxonomy based on the introduction of five perspectives of analysis, which permits a rigorous classification of LSM systems considering the working principles, the field of application and the constraints of use. This framework can be helpful for both the analysis and classification of existing systems, with the aim of giving a tool for choosing the most appropriate ones in conformity with the measurement needs, and for the study of new ones according to emerging technologies.

In particular, referring to the dominant technologies, the study showed a strong evolution of optical systems especially in the last ten years, with prevalent involvement of laser-interferometry, photogrammetry and structured-light scanning.

It must be highlighted that this explosion of interest around the optical systems must be carefully considered because, despite the great level of performance and ease the use that these systems can currently offer, they still suffer from significant technical problems related to the surface characteristics and to the environmental conditions [170]. For that reason, much research must still be done in order to overcome these problems and make it possible to integrate these systems in a real production environment.

In general, as main outcome of the review presented in the present paper, and considering the trend of patents observed in [54] and [58], the new solutions proposed in the scientific literature and the technological state of the art, three main elements seem to trace the roadmap for the future research:

- development of multi-sensor architectures
- introduction of “intelligent” technologies
- integration in “smart manufacturing systems”.

2.1. Serial kinematics for maximum precision

Conventional large scale Coordinate Measuring Machines (CMM) are used when a small measurement uncertainty is required or when the features to be measured are difficult to access e.g. bore holes or recesses [147]. Large CMMs can reach working spaces up to $5\,\mathrm{m} \times 11\,\mathrm{m} \times 3.5\,\mathrm{m}$ with a maximum permissible error (MPE) of $7\,\mu\mathrm{m} + L/250\,\mu\mathrm{m}$ [26]. CMMs can be equipped with non-contact probes like laser scanners to measure with high point densities [159]. Different probing systems in dimensional metrology were reviewed by Weckenmann et al. [187]. An overview of data fusion for multi-sensor systems was given by Weckenmann et al. in 2009 [188]. Advances have been made in measurement arms which are less accurate, but portable and can cover working areas of a few meters [36,147,159].

Schmitt et al. discussed the possibility of using a large machine tool as a comparator to measure the geometry of large-scale devices during the manufacturing process. The main objective is the traceability of the measurements. Known methods for the traceability of CMMs are adapted to the challenges of a machine tool [164].

2.2. Optical measurement systems

Laser Trackers are Large-Scale Metrology systems which consist of an interferometric distance measurement device, angular sensors of the beam guiding system and a tracking capability. They measure in spherical polar coordinates. Recent developments in the functionality of Laser Trackers were described in Peggs et al. [147]: 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. ADMs additionally to the interferometer offer the convenience of resetting the measuring system without having to return the retro-reflector to the datum position. Bridges et al. introduced the Faro Xtreme, an ADM that also can be used alone and does not necessary require stationary targets. For complex measurement such as small holes Parker introduces advanced mirror retroreflector arrangements [20,144]. To enable the measurement of complex parts, features are attached to the probe to realize measurements of six degrees of freedom (6DOF). The features enable capturing parts of the workpiece surface that otherwise would be out of sight. The Leica T-probe, the API IntelliProbes and the TrackArm by Faro are three demonstrators available on the market [45,109,147]. Flynn uses Laser Trackers with active targets in combination with other metrology systems to reduce engineering time for large CNC Machine compensation [47]. Active targets are self-positioning a spherically mounted retroreflector (SMR) that automatically maintains its reflection axis oriented toward the Laser Tracker. It is especially useful for measurements related to compensation of very large machine tools when the measuring point is out of reach of the operator. Specialized active targets like API Smart Track Sensor measure the angle when ensuring the line of sight. Peggs et al. [147] mentioned the extension of application of laser trackers which are not only used as dependent measuring unit but also in multilateration applications, for CMM and machine tool calibration.

In order to extend the range of laser trackers, a new method of frog-jumping was developed and presented by Liu et al. [111].

At the PTB in Braunschweig a new reference wall for testing and calibrating mobile 3D measuring systems for large measuring ranges (up to 10 m) was built.

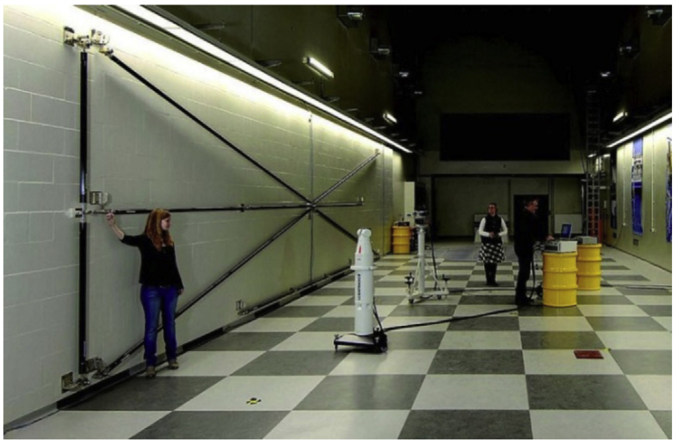


Fig. 7. PTB's new reference wall for testing and calibrating mobile 3D measuring systems for large measuring ranges (up to 10 m).

Laser scanner and laser radar are laser based range finders which enable a measurement of non-cooperative targets and featureless surfaces. For some laser scanners, the 3D coordinate measurement is based on triangulation. The type of distance measurement can differ between the specific devices and is either based on time-of-flight measurement, phase-shift technology or triangulation methods. The systems can perform one, two or three dimensionally. An overview of the different technologies and working principles were given by Peggs et al. 2009 [147]. Modern, imaging laser scanners are able to stitch multiple scans together and locate themselves via GPS data. Although laser scanners are less accurate than laser trackers, they have the advantage of not requiring ancillary devices. An interesting approach for dimensional geometry with these systems is the digitization of the Parthenon west frieze carved blocks exhibited in the Acropolis Museum of Athens in Bouzakis [15].

The theodolite is a widely used instrument for angular measurements, in particular in geodetic applications [152]. Total stations are theodolites with an added distance measurement capability [147]. An example for the advancement is the Leica Multistation. It is a total station with additional laser scanning, digital imaging and GNSS (global navigation satellite system) capabilities [108].

The Nikon iGPS (indoor global positioning system) is a distributed measurement system based on automatic theodolites [140]. The measurement principle of the laser-based iGPS is multiangulation. It consists of transmitters (automatic theodolites) that emit two rotating laser planes and a vertical strobe pulse. The sensors consist of photodiodes. The angular measurement is based on the evaluation of the signal sequence. The system is capable to measure 6DOF (position and orientation) in any scalable coordinate system by evaluating the information of several receivers with known relative positions. Detailed descriptions of the working principle and evaluations can be found in [46,115,136,141,147]. A similar approach is described in [106,112,194–196].

Photogrammetry is a measurement technique based on the evaluation of two dimensionals. The basic principle can be found in [44]. Peggs et al. gave a detailed overview of different techniques [147]. Photogrammetry can be categorized into multi camera methods, target based methods and structured light methods. The main difference between these methods is the method of evaluation. In the first case features are used for the coordinate calculation. To avoid ambiguity either markers can be placed on the object or, if this is not possible, structured light patterns can be projected.

Estler et al. described Absolute Distance Meters (ADMs) as an extension of conventional Laser Trackers which operates either in parallel with the interferometer using a retro reflector target or is used alone when interferometry resolution is not required [44].

The Faro tracker illustrated in Bridges et al. is a commercial application that realizes almost real-time distance measurement. In practice, a Kalman filter is used to optimize the distance performance based on noise in the system and the speed of the target [20]. Peggs describes that the measurement uncertainty achievable with an ADM (typically 10 μm + 0.4 μm/m) is already approaching what can be achieved with the sort of conventional displacement-measuring interferometer fitted to laser trackers (typically – 0.5 μm/m) [147].

Dale et al. developed a multi-channel absolute interferometer to measure numerous lengths between 0.2 m and 20 m [37]. The so called "Snapshot Phase Shifting Interferometry" realizes a precision of the length measurement of 0.5 μm + 0.5 μm/m. In every measurement, the molecular absorption spectrum of a gas cell is scanned and the system is recalibrated. Advantages of this metrology are the measurement of multiple distances at the same time.

The LaserTracer is an interferometry device similar to the laser tracker technology that allows tracking the reflector movements. The LaserTracer has no angular measurement systems. The interferometer integrated in the laser tracer moves on a gimbal mount around a fixed precision sphere. The uncertainty of the displacement measurement is $U(95\%) = 0.2$ μm + l*0.3 μm/m (l = measuring distance in meter [m]) in a perfect laboratory environment [82].

An application examined by Gaska et al. is the modeling of the residual kinematic errors of coordinate measuring machines using LaserTracer system [67].

A mobile measuring machine for three-dimensional measurements (M3D3) allows for high-accurate inspection and calibration of large parts directly on-site in production [189]. The system can be considered as a high-precision metrological frame (compare 3.2). The M3D3 allows geometrical features to be measured in the range of several millimeters up to 5 m × 5 m × 5 m was developed by PTB. The developed concept [60] comprises a commercial CMM, its measurement and its evaluation software and a set of at least four high accurate tracking laser interferometers [103]. The CMM is simply used as a mover which allows for measurement and evaluation of objects.

In parallel the tracking laser interferometers follow a retro-reflector located close to the stylus tip of the tactile probe of the CMM. Based on a multilateration algorithm 3D-positions are calculated from the measured interferometric displacements almost avoiding Abbe errors (Fig. 8).

Applying the principle of multi-lateration, the 3D coordinates x_{ij}, y_{ij}, z_{ij} are determined by using just these relative length measurements (Fig. 9) [168]:

$$l_{ij} + l_{0j} + w_{ij} = \sqrt{(x_{ij} - x_{0j})^2 + (y_{ij} - y_{0j})^2 + (z_{ij} - z_{0j})^2} \tag{1}$$

$$\sum w_{ij}^2 \rightarrow min \tag{2}$$

with:

i measurement point
j LaserTracer position number
x_{ij}, y_{ij}, z_{ij} coordinates of measurement points (unknown)
x_{0j}, y_{0j}, z_{0j} coordinates of LaserTracer positions
l_{0j} unknown dead path of LaserTracer j

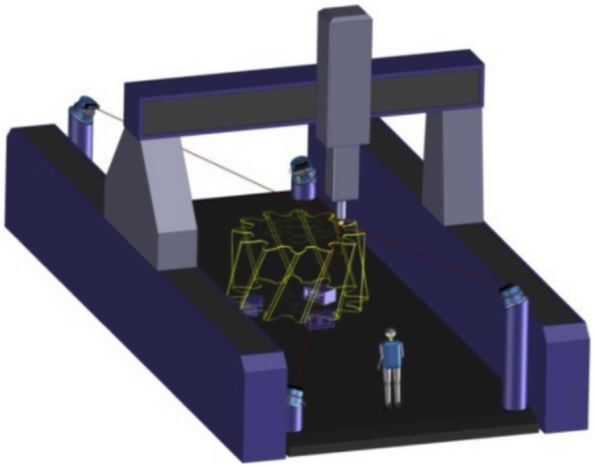


Fig. 8. Mobile measuring machine for three-dimensional measurements.

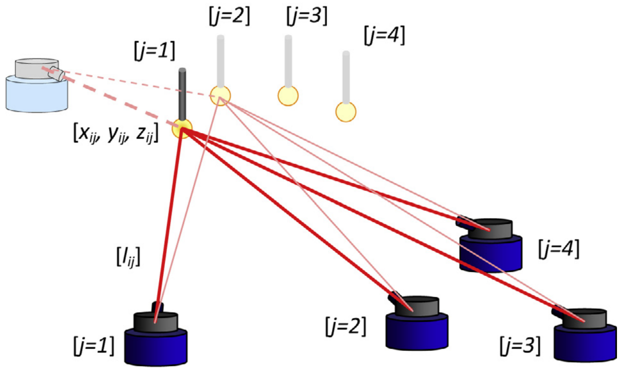


Fig. 9. Diagram showing the principle of the portable multi-arm laser interferometer.

l_{ij} measured length change from LaserTracer j to point i
w_{ij} residual between measured and fitted distance to the reflector position.

For a smooth integration of the M3D3 into the measuring process, the concept of a so-called ‘coordinate proxy’ is proposed. The basic idea is to loop in the communication between the application software controlling the mover and the controller hardware. In the loop all relevant commands are filtered out, modified by applying the M3D3-generated corrections and returned to the application software as if coming directly from the mover control. The major advantage of this solution is that it is not necessary to modify the application software as long as the interface is accessible and the communication protocol is known.

2.3. Multi-sensor architectures

LSM applications involve even more the concurrent use of multiple systems (e.g. two or more laser trackers, or local scanners, combined with an iGPS or a distributed photogrammetric system, etc.) [55]. The main advantages of this practice are:

- overcoming the limitations of the individual system;
- covering all the measurement space (this aspect is particularly relevant in LSM applications);
- improving metrological performance (reproducibility, repeatability, uncertainty etc.);
- taking advantage of the overall available instrumentation;
- reducing the risk of measurement errors.

In many cases, the concurrent use of different systems has shown a significant improvement of the obtained results in comparison to the results of each single system [63].

A significant constraint for this approach is that the use of multiple systems requires the definition of suitable strategies for data fusion [35]. Intending “sensor fusion” as the “combination of sensory data from different sources, so that the resulting information is somehow better (more accurate, more complete, more reliable, etc.) than the information deriving from the single sources taken separately”, two possible approaches can be adopted [55,188]:

Competitive fusion: Each system performs an independent measurement of the 3D coordinates of the point of interest and these position measurements are fused into a single one [63]. This fusion approach is defined as competitive, since each system “compete” for the definition of the fusion result. For example, this principle is implemented in the SpatialAnalyser®, probably the most diffused software for LSM applications. The goal of competitive fusion is to improve the measurement uncertainty while reducing the risk of measurement errors [14].

Cooperative fusion: Data provided by two or more independent (non-homogeneous) sensors, even from different measuring systems are processed in order to achieve information that otherwise could not be obtained from individual sensors [14]. According to this logic, the different sensors share their local measurements and “cooperate” for determining a unique position measurement of the point of interest. For example, data from

(i) two sensors of a system performing angular measurements, and
(ii) one sensor of another system performing distance measurements can be combined for determining the 3D coordinates of the point of interest.

Compared to the competitive data-fusion approach, the cooperative one is more difficult to implement, as it requires that the individual measurement systems are able to return “intermediate” data, such as distance and angular measurements by the relevant sensors. However it can be shown that a cooperative fusion approach could potentially make a more efficient use of the information available, resulting in improved metrological performance. Also, it is the only option when dealing with sensors that, taken separately, are not able to perform independent localizations of the point of interest (for instance a laser interferometer combined with a single photogrammetric camera) [63].

While the scientific literature encompasses several descriptions of the competitive approaches [14], the cooperative ones are almost totally ignored or confined to specific measurement applications [188].

Besides, the literature analysis reveals a trend of new systems toward multi-sensor architectures, even based on different technologies, in order to self-correct, self-compensate and cooperate. That means that dimensional sensors can be coupled with temperature, humidity, gravity, vibration, etc. sensors, in order to increase the quality of the measurement by compensating or correcting measurement errors coming from external sources.

Even if these approaches are becoming widespread, there still remain many open issues to be faced by future research. For example, the implementation of multi-sensor architectures does not eliminate the need to consider questions such as overall system calibration, measurement uncertainty evaluation and point registration.

2.4. Innovative approaches

The mobile spatial coordinate measurement system (MScMS) is a distributed system based on ultrasound and radio frequency signal transmission. The coordinate determination is based on multilateration [51–53,59,124]. The MScMS-II is based on infrared light and multiangulation [62,65,66].

Pisani et al. introduced the novel approach, Intersecting Plane Technique (InPlanT), for coordinate measurements in a Cartesian coordinate system for large volumes in harsh conditions with the objective to achieve a measurement uncertainty of approximately 50 μm in a volume of 10 m × 10 m × 5 m [148]. InPlanT uses the principle of the intersection of three orthogonal planes created by three laser light sources each mounted on a servoed linear stage. The tracking unit included in the light source controls the linear stages using a retro-reflector mounted on the object. The Cartesian coordinates are combined by the measurements of each linear stage [148].

Yi et al. propose the 3-dimensional on-demand indoor localization system (3DODIL). The measurement system uses radio frequency (WiFi) infrastructure. The measurement is based on two different algorithms: multistory differential (MSD) algorithm and Algorithm of Enhanced Field Division (EFD) [197].

Kim and Choi propose a distributed measurement system composed of a digital compass, ultrasonic beacons, a radio frequency (RF) beacon and a receiver module mounted on the moving objects [83]. Performance data of the two aforementioned systems is not available.

Ghidary et al. proposed a measuring system using ultrasonic and infrared signals simultaneously. The transmitter is mounted on the object. The receivers are located at fix locations. The infrared signal is used to trigger the time of flight measurement of the ultrasonic signal. The position is computed by measuring the distance from three receivers. The moving direction is evaluated by two successive points. The positioning error tested using a mobile robot is less than 50 mm in an area of 6 m × 4 m using one transmitter and six receivers [71].

The aim of an international research project within the European Metrology Research Programme (EMRP) called "Large Volume Metrology in Industry" is to tackle several fundamental issues affecting users of LSM equipment and techniques in industrial locations. Different approaches and developments show innovative pathway to deal with the main challenges in LSM.

As the uncertainty of interferometry techniques is significantly influenced by the ambient refractive index of air and industrial environments normally 'suffer' from spatially and temporally varying 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. To overcome this problem a tracking refractive index compensated interferometer for absolute length measurements, the '3D-Lasermeter', is being developed by PTB and SIOS within the European Joint Research Project (JRP) IND53 "Large Volume Metrology in Industry". 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 LaserTracers. The absolute distance measurements allows 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 (often hand-held) reflector.

The basic technique of refractive index compensation was first described by Earnshaw and Owens in 1967 [43]. The principle idea is to measure the distance with two different wavelengths $\lambda_{1,2}$. The resulting optical path differences $l_1 = l\,n_1$ and $l_2 = l\,n_2$ differ due to the dispersion in air. The mechanical length l can then be calculated by

$$l = l_1 - A(l_2 - l_1)$$

with

$$A = \frac{n_1 - 1}{n_2 - n_1} = \frac{K(\lambda_1)}{K(\lambda_2) - K(\lambda_1)}$$

$K(\lambda_1)$ being derived from a model for the dispersion (e.g. [8]). For dry air the parameter A is only dependent on the vacuum wavelengths. For moist air A depends on the ambient temperature, pressure and humidity as well. However, if the partial pressure of water vapor p_w is determined either conventionally or optically by intrinsic methods, the temperature, pressure and humidity dependency of the factor A in moist air can be considered and the mechanical length be calculated solely from l_1, l_2 and p_w [125].

Nevertheless, for a similar setup used for measuring large geodetic distances without tracking recently deviations of less than 0.7 nm on the scale of the optical wavelengths were achieved, corresponding to refractive index compensated results with deviations of less than ±200 μm when comparing with a reference HeNe interferometer for lengths of up to 50 m [129]. Approximately 50% of the deviations can be attributed to non-linearities from the collimation, indicating achievable uncertainties in the order 100 micrometers over a 50 m distance.

A system based on divergent beam frequency scanning interferometry (FSI) and multilateration is under development at NPL [85]. 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 frequency scanning interferometry, and all sensors measure simultaneously. 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.

If the sensors are at unknown positions S_i $(1 \le i \le n_S$, n_S = number of sensors) and the targets are at unknown positions T_j $(1 \le j \le n_T$, n_T = number of targets) then the relationship between these unknown parameters and the measured distances between the ith sensor and jth target, d_{ij}, is given by,

$$T_j - S_i = d_{ij}$$

After applying appropriate constraints, for example by setting one target to be at the origin, one on the x-axis and one on the xy-plane, and if at least six targets are visible from four or more sensors, these equations can be solved to determine the unknown target coordinates and the sensor coordinates. The model equation (above) can be extended to include additional parameters that represent systematic bias e.g. a length offset due to optical effects, which are also determined during the bundle adjustment. This ability to determine systematic bias together with a built-in atomic frequency reference makes this coordinate measurement system self-calibrating and traceable to the SI.

2.5. Contributions to the achievable measurement uncertainty for Large-Scale Metrology processes

Measurement processes are influenced by different factors that can be grouped with the help of an Ishikawa diagram (Fig. 10). Factors of particular interest for large-scale measurement processes focus on the measurement system, the workpiece, and the measurement process. Each of these factors is described in the sections that follow.

Measurement systems are subjected to many different influence factors, especially if the measurement system is located in a non-isolated shop-floor. Two major factors that are a result of the measurement system itself are the geometrical errors, as well as probing errors. These two factors describe how well the system sensor can be located in space, and how well the sensor obtains information about the part surface.

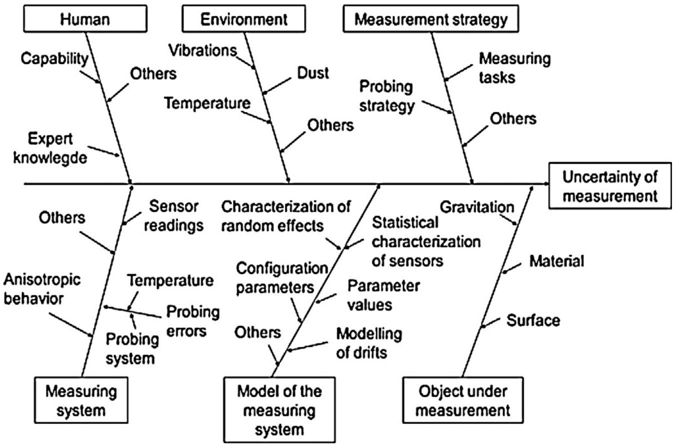


Fig. 10. Influences on measuring processes.

2.5.1. Geometrical machine errors and probing errors

Geometric machine errors originate from limits on the precision of instrument manufacturing and assembly. Misalignments, eccentricities, nonlinearities, and offsets of mechanical and optical components all lead to errors in the measured coordinates. As these errors influence the measurement directly, they must be considered carefully. Geometrical errors can be compensated when they are repeatable and known; therefore their analysis, quantification, and compensation can directly reduce systematic measurement errors which would otherwise contribute to the measurement uncertainty. Mathematical models representing geometrical alignments and other physical parameters provide a powerful instrument for correcting raw sensor data. Practically all coordinate metrology systems employ some form of “error map” or “parameter file” containing correction data for the specific instrument. Furthermore, sensitivity analysis of such models is invaluable in designing performance verification and calibration tests. The following chapter focuses on kinematic/geometric models of various classes of instrument e.g. laser trackers, laser scanners, iGPS and coordinate measuring machines.

For example, Loser et al. [114] described a geometric error model for LaserTracker with a gimballed mirror and a series of tests for determining the model parameters. Their model includes fifteen parameters that consider offsets and tilts of the transit axis, mirror, and beam as well as offsets of the horizontal and vertical encoder axes. The angular position error of the vertical encoder is also taken into account just as displacements of the beam with respect to the vertical axis.

Muralikrishnan et al. and Hughes et al. analyzed the geometric errors of laser trackers based on theodolite-like geometry [84,137].

The model of Muralikrishnan et al. was composed of a superposition of the individual geometric errors, which were analyzed in isolation [137]. The model was valid for measurements made in front-face only. Their sensitivity analysis identified that the ASME B89.4.19 test was insensitive to some parameters and therefore they proposed additions to the standard test to overcome this shortcoming. Muralikrishnan et al. [137] used a similar approach to develop a model of a large volume laser scanner employing a spinning prism on a rotating head. They proposed a series of tests that were sensitive to 14 of the 18 parameters of the model.

Hughes et al. [84] proposed an alternative model for laser trackers with theodolite-like geometry that uses no linearizations so that non-linear effects are treated without significant approximations. This model also caters for measurements made in front-face and back-face and exploited this feature to determine the geometric error parameters with greater sensitivity.

Coordinate measuring machines (CMMs) consist of many different components which interact to achieve the final precision. Changes in the geometry of each component lead to deviations between actual and nominal probe position. The deviations result in relative positioning and orientation errors.

Since the geometric inaccuracy and instability of large CMMs are main sources of measurement uncertainty, the analysis and compensation of geometrical machine errors are of particular interest in the context of Large-Scale Metrology [169]. Therefore an understanding of error sources is required. Moreover, the interactions between the different error sources have to be considered carefully [169]. In the following, the main sources of geometrical errors are described in detail.

Kinematic errors are caused by imperfections of individual machine components and their configuration within the machine assembly, by axis misalignments, and by errors of the machine’s measurement system [169].

The presence of internal or external heat or cold sources leads to thermo-mechanical errors. Since the expansion coefficients of the machine part materials often vary, various machine components act differently under a given thermal load. This may lead to thermal stresses and distortions which, in turn, result in location and component errors of the machine. It has been shown that thermal influences have a great impact on the measurement uncertainty. Since the thermal conditions change, they typically result in time-varying errors, which require dynamic compensation.

Other sources of errors are the internal or external forces that produce deformation in the coordinate measuring machine, although the kinematic model relies on an assumption of rigidity. Factors such as the different weights of measuring objects and the movement of machine components have an influence on the overall performance of the machine. In comparison to the residual kinematic errors, errors due to loads can be significant.

The measurement uncertainty of large coordinate measuring machines is also influenced by dynamic forces. These are caused by acceleration and deceleration of different machine components. Vibrations may also be considered, because they also contribute to deviations of the probe position relative to the measuring object. The compensation of vibration effects is very difficult as their amplitude and exact phase angle are often unknown. The parameter settings of the machine motion as controlled in software will additionally affect the geometrical errors.

Machine tools may be modeled in a way very similar to coordinate measuring machines. Tests for the quantification of geometric machine errors of machine tools are described in standards as ISO 230-1 [92] and ISO 230-7 and in different national guidelines. The conventional geometric error model is based on the assumption that the machine shows rigid body behavior [92]. It considers positioning errors, straightness errors, roll errors and tilt error, so that six error components per axis are needed for the description of linear movements. Six error components per axis are also needed in order to describe rotational movements. The error parameters consider radial and error motion, angular positioning errors and tilt error motions.

Several factors connected to the probing system contribute to the uncertainty of the measurement process in Large-Scale Metrology. Weckenmann et al. addressed many of these influencing factors with a focus on tactile probing systems in the CIRP keynote paper in 2004. It is stated that the temperature deviation from the reference temperature of 20 °C is the most important influencing factor on the workpiece and the measuring system, including the stylus [17]. The stylus is often the least massive of the measuring system components, and is especially susceptible to thermal variation. Large scale measurements are often not carried out in a temperature-controlled measuring room but in the production environment as it takes great efforts to move such large workpieces. Therefore, Weckenmann’s statement regarding the importance of temperature deviations is especially important for large scale measurement processes.

Another important factor that influences the measurement uncertainty of tactile measuring systems is the tip ball. Its diameter influences the measured surface of the workpiece as the stylus is not able to penetrate into all the surface valleys as for example also stated by Lonardo [113]. Therefore, the true surface cannot be detected. The magnitude of the deviation between the true surface and the measured surface depends on the roughness of the surface on the one hand and on the tip ball diameter on the other hand as it defines which valleys of the surface can be penetrated and therefore measured. The diameter of the tip ball also accounts for the difference between the measured point (usually the center point of the tip) and the contact point. To get the position of the probed point – or corrected measured point – a correction vector is needed, perpendicular to the surface and having a magnitude of the tip radius. For this correction, the calibration of the probing system is very important [187]. Still, the form deviations of the tip from the ideal sphere should be negligible as it can otherwise result in a difference between the real distance between the measured point and the contact point and the applied correction vector. Other compensation methods have been studied as e.g. stated by Park et al., who has developed a normal force measuring touch probe which measures the probing force as well as its direction [143].

Further factors that can influence the measurement uncertainty based on the probing system are the length of the probe and its stiffness [187]. For large and complex structures, it can be necessary to find a compromise between the length of the probe that is necessary to measure a feature and the bending that occurs with a specific probe length and stiffness, contributing to the measurement uncertainty.

The bending of the probe is also influenced by the applied probing force and the probing velocity. When the spherical probe touches the surface of the workpiece elastic deformations are caused due to the Hertzian stress as for example stated by Puttock et al. [153]. Brau et al. compared four different probing systems and showed that the influence of the probing force does not differ significantly using an active versus a passive probe [16].

2.5.2. *Influences on the object under measurement*

Measurement processes are influenced by the measurement systems as discussed above and, especially for large-scale measurands, by the object under measurement. Temperature changes in the environment or process heat lead to temperature changes of the object that can influence the geometry of the part significantly. Gravitational forces effect the geometry even of heavy and apparently stable objects. These influences are evident during handling or clamping for machining, assembly, and measuring. They will be discussed in the following sections.

Dimensions of material objects, whether of complex or simple geometry, vary with temperature. The amount of variation depends on the material of the object [176,180]. Thermal expansion of components is defined with regard to their state at a defined reference temperature (usually 20 °C). The variation of workpiece temperature, with its attendent geometric variations, represents a significant uncertainty source for measurands 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 [22,23,127,152,155].

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 (Fig. 11). 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.

Determination and compensation of thermal effects are mainly investigated regarding the uncertainty of measuring systems and instruments or machine tools [95,126,127]. Modeling of thermal effects is also popular regarding the machining process [38,102,142].

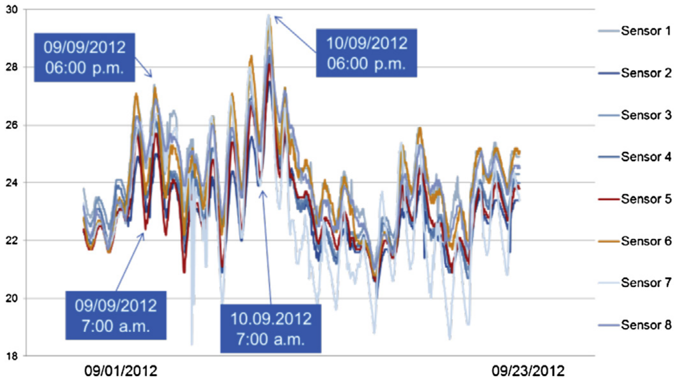


Fig. 11. Temperature changes in a shop floor for manufacturing of large turbine housings during working hours [17].

The impact of temperature variations during measurement processes is well described for the measurement system [87,104,156]. Numerous research activities focus on determination of the uncertainty contributions caused by thermal effects; one potential solution is the explicit modeling of the thermal characteristics of the measured workpiece [145].

The situation in industry shows the need for the fast and user-friendly estimation of uncertainty influences. Finite element models (FEM) provide commercialized solutions to simulate the workpiece behavior under different thermal loads. Within the joint research project "Traceable measurement of drive train components for renewable energy" funded within the European Metrology Research Programme (EMRP), models are developed that reduce the complexity of thermal modeling and reduce the calculation time. The trade-off between complexity reduction and precise uncertainty determination has yet to be resolved. Investigations of the temperature characteristics of the involute gear standard of PTB in Germany have shown the model's capability to simulate the temperature distribution inside the structure, predicting tempering ("soak-out") times and thermally induced geometric deformations.

Another approach to deal with the disturbing factors of unstable temperatures could be comparable to the empirical approach of the Thermal Error Index (TEI) by the American National Standard Institute (ANSI) [5]. TEI is defined by:

$$\mathrm{TEI} = \left[\frac{\mathrm{TVE} + \mathrm{UNDE}}{\mathrm{WT}}\right] * 100\% \leq 50\%$$

TVE is a temperature variation error, which is determined by a series of measurements on a fixed object over 24 h. This reflects the sensitivity of the machine to the environmental conditions. UNDE is the stated uncertainty due to the nominal differential expansion between the workpiece and the machine scales. WT is defined as the working tolerance, which may also be thought of as an MPE for measuring instruments.

According to the ANSI-standard procedures TEI should be less than 50%. SWYT proposes to replace WT by an engineering tolerance τ specific to a given situation [180]. The index can help to estimate the significance of thermal expansion in specific situations, that for the dimensional measurement of large-scale components can be very harsh.

All geometry measurements carried out on earth are affected by deformations caused by the measured object's dead weight. For objects with diameters or lateral dimensions less than 300–500 mm (e.g. most automotive components), these deformations usually can be neglected. For measuring objects with diameters greater than 1 m, these deformations can exceed the 2-digit μm limit, depending on the design, mass and material of the part. For some high-precision large-scale components such as large

a) b)

Fig. 12. Internal WES ring gear: (a) measurement using large CMM. (b) Storage, tempering and clamping of internal WES gears within a large air conditioned measuring room.

bearings and large gears, several quality features have to comply with tolerances in the range of 20–50 μm. Fig. 12 shows an internal ring gear and some of its specification parameters, designated for a wind energy systems (WES).

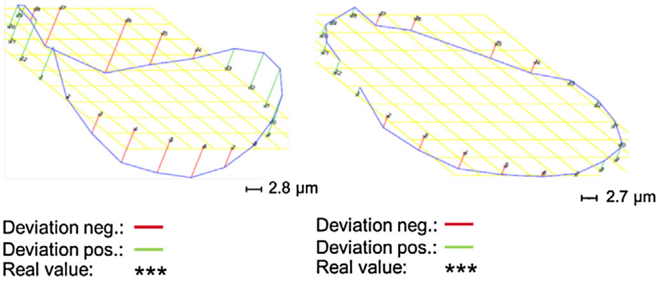
The gravitational deformations of these parts are increased even further by the handling restrictions due to the components' mass and geometry. They typically amount to several metric tons, depending on the size of the component. The mass of large gears and bearings for WES varies between 2 and 5 tons, such that they can only be placed on (and removed from) a measuring device by traveling overhead cranes, fork lifters or lift carriages (Figs. 12 and 13). Besides the limited positioning accuracy (for coarse alignment) possible with these handling facilities, they only allow a horizontal placement of the workpiece on the measuring instruments.

a) b)

Fig. 13. Loading a large CMM with a large WES gear via a gate and an acclimatization lock (a) preparation and placement of the measuring object (b) transportation of the measuring palette from the loading gate to the measuring device.
Source: Hexagon Metrology.

Centering pins or specific fixtures can improve and facilitate the positioning e.g. on a rotary table, but the horizontal loading neither complies with the component's final orientation during application nor reduces the gravitational deformations to a minimum. Similar storage, handling, and clamping methods are also usual for large bearings, large discs (e.g. for gas and steam turbine compressor and combustion stages) and other relatively "flat" objects. Gravitational effects on the workpiece geometry can be simulated with FEM [172,193,202].

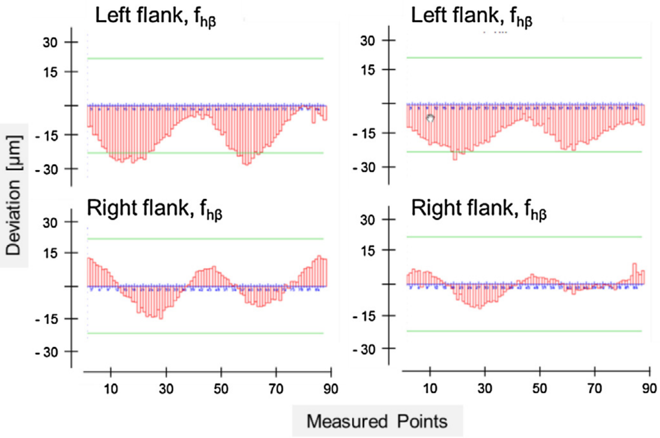
The support of large circular workpieces influences the geometrical shape significantly. The shape is differently influenced by three-point or four-point support placement (Fig. 14) [77]. Both flatness measurements show significant deviations. But even if only a fraction of these flatness deviations has a gravitational origin, a direct comparison between Fig. 14a and b shows that the deformation caused by dead weight can amount up to 10 μm or more. The flatness of the transverse gear faces themselves does not affect the performance of the gear. However, the deformation of the gear can have an impact on several decisive gear parameters such as the helix angle of the gear flanks. The bending of the gear between two supporting points causes an additional lead angle deviation termed helix slope deviation, superimposed on the helix angle. A direct comparison of Fig. 14 a and b exemplarily illustrates that the gear's deformation due to its dead weight increases the measured values for lead deviations.



a) b)

Fig. 14. Flatness measurement carried out on the upper reference plane of the ring gear shown in Fig. 12: (a) 3-point support, (b) 4-point support [77].

Taking into account that for the inspected gear (Fig. 15) the tolerance for the deviation parameter $f_{H\beta}$ amounts to 22 μm (accuracy grade 5 as usual for WES drives), this gravitational effect contributes up to 8 μm, i.e. one third of the tolerance, to the measured deviation.



a) b)

Fig. 15. Measurement of the helix slope deviation $f_{H\beta}$ at all teeth of the ring gear d in Fig. 12: (a) 3-point support, (b) 4-point support (compare also flatness measurement in Fig. 13, obtained in the same clamping) [77].

Fixtures that locate, clamp, and support the workpiece during the manufacturing process directly affect the quality of the manufactured part. Precision, reliability, short set-up time (and thereby cost-effectiveness) are required of fixturing [181]. The ability to model and predict workpiece deformation induced by gravitational and fixturing loads and predict the unknown fixture–workpiece contact forces are crucial for designing functional fixtures [172].

To avoid distortion of the part by over-constrained clamping, the experience of the operator is important. Intelligent fixtures are developed which allow for the compensation of misalignment, deformation, or vibrations. These solutions are based on sensors, actuators and algorithms that measure forces and predict deviations from the ideal position and geometry. The research and development of "intelligent" fixtures has been extended during recent years [4,18,81,131,177].

2.5.3. Measurement process

The measuring procedure covers the way in which the measurement points are recorded, the suspension and clamping of the workpiece, as well as the prevailing environmental conditions. The recording of the measurement points strongly depends on the sensor type. Whereas at the beginning of coordinate metrology, tactile sensors were mainly used, optical sensors have increasingly been used in the past few years. In the case of tactile sensors, a distinction is made between single-point probing and scanning. Optical sensors are predominantly area- or line-based sensors, such as scanner systems. The advantage of tactile systems is their robustness against contaminations. In addition, the probe pins determine geometries in structures which are optically difficult to access (for example: bore holes). Another advantage of tactile systems is the independence of the measurement results obtained from almost any hard workpiece surface. In contrast to this, workpiece surface properties may influence the measurement results from optical sensors to a very large extent. However, compared to optical systems, the information density – i.e. the number of recorded measurement points on the surface – is considerably lower for tactile systems.

Measuring procedures can be best assessed and/or monitored by calibrated standards. To best fulfill this purpose, standards are selected where the shape and the material of these standards are almost identical to the workpieces from the manufacturer [70]. This has the advantage that almost all significant error influences – such as clamping and measuring strategies–are very similar. If the conditions remain constant, systematic errors can be determined and corrected in a comparatively simple way. Due to the high component costs and small part numbers in large-scale manufacturing, this procedure is generally not economically feasible in the large-scale domain.

Statistical Process Control (SPC) is a widely used set of tools for the quality control of series production, based on the idea of monitoring the variation of a feature to distinguish between inherent process variation and special cause process variation [93,134,165]. In order to provide significant results, SPC methods require a certain amount of samples (typically more than 50). In contrast, large-scale, complex parts are usually produced in single- or small-batch production processes. Therefore, adapted SPC methods need to be applied in such situations.

Currently available methods for small and single-batch SPC focus on short-run SPC [27–30,123,134], where small batches are run continuously on one machine before changing to the next batch. This is different from the reality of large components where multi-purpose machines are used for the manufacturing of a large range of parts intermittently. In such situations it is important to realize that in its current application in the industrial environment, SPC is often used for product control rather than process control [25]. Different products which are generated by the same or a similar process are looked upon as dissimilar entities. Consequently, sources of process variation can be overlooked when applying product-oriented SPC methods. Due to the sparseness of product information in small-batch situations, the focus has to be on the common element, the process.

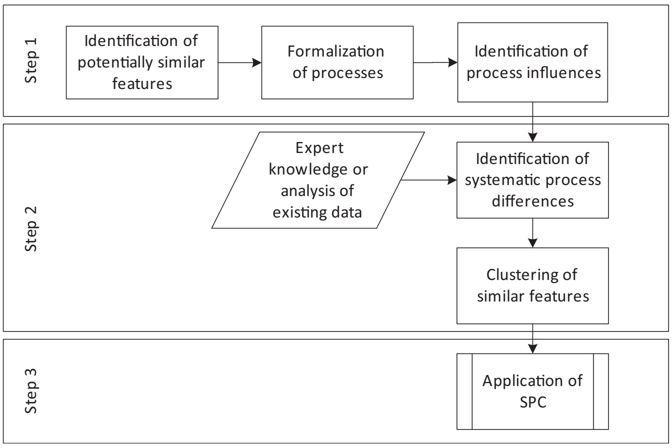


Fig. 16. Clustering of similar features for the application of SPC to small- and single-batch production.
Source: WZL RWTH Aachen.

A solution for increasing the sample size is to cluster similar features, i.e. features of the same type and similar characteristics that are produced by essentially the same production process. Fig. 16 shows a systematic procedure for the elicitation of such clusters.

This procedure is based on the identification of systematic differences between production processes through the application of expert knowledge, simulation, experiments, or analysis of historical data [190].

This procedure was exemplarily applied to control the grinding of linear guide surfaces at Alesamonti Srl, Italy, a manufacturer of five-axis boring/milling machine tools. Over a period of three years, 233 measurement records were analyzed statistically for differences in process mean between groups.

2.6. Approaches to determine measurement performance and measurement uncertainty

The continued development of measurement systems, combined with increased computing power, has enabled new solutions for LSM applications. Innovative measurement set-ups have increased the performance of measurement processes. In addition, mathematical modeling of the measurement process and new approaches for the data evaluation can help to assure the traceability and better estimate measurement uncertainty. Material standards are another approach to ensure the traceability of large-scale measurement processes on the shop-floor.

2.6.1. Measurement and evaluation strategies

Performance verification testing of conventional coordinate measuring machines is well established. ISO 10360-2 prescribes a series of measurements of a calibrated length artifact positioned in multiple locations and orientations within the measuring volume [69]. If all measurements of the artifact fall within the specified MPE (maximum permissible error) of the instrument, the test is passed. In practice, the volume over which this test can be conducted is limited by the physical length of the reference artifact. High geometric accuracy and stability of length artifacts such as length bars and step gauges can only be realized over lengths up to around 1 m.

To overcome this limitation, the latest revision of ISO 10360-2 allows an interferometer to be used as a virtual length artifact.

The basic principles deployed for fixed CMMs have, more recently, been applied to articulated arm CMMs (ASME B89.4.22) and laser trackers (B89.4.19, ISO 10360-10 and VDI/VDE 2617-10) [3,91,138,182]. In these tests the length of a calibrated length artifact (or artifacts) is measured by the device under test at different positions and orientations within the instruments working volume, and the measured lengths compared with the calibrated length. Any deviation in apparent length of the artifact from its calibrated value can be indicative of uncompensated geometric errors.

In addition to these so-called "volumetric tests", a series of "two-face" tests are performed in which the apparent location of target point is compared when observed in front-face and back-face. Any difference between the two measurements may be indicative of uncompensated geometric errors. The standards also prescribe a range test that tests range measurement uncertainty of the IFM or ADM over up to 70% of its specified range.

The AMSE volumetric tests for laser trackers (B89.4.19) use a single length artifact of at least 2.3 m in length. It is oriented vertically, horizontally and on right-hand and left-hand diagonals and its apparent length is measured by the tracker under test from three distances and with the tracker at four different rotations. The VDI/VDE 2617-10 test achieves a similar geometrical positioning of the tracker relative to the artifact by having multiple artifacts fixed to a wall, for example, the reference wall at PTB, shown in Fig. 9. In each case these tests were devised to be sensitive to the geometrical errors of the tracker.

The ISO 10360-10 standard prescribes a standard requires set of measurements that satisfy the sensitivities identified by Muralikrishnan. Additional, user-selectable measurements follow the spirit of either the B89.4.19 test or the VDI/VDE 2617-10 test.

Other than the range test aspect, these performance verification tests are relatively simple to perform and require no specialist equipment other than a calibrated length artifact. The artifact could, for example, be a thermally invariant scale bar incorporating magnetic nests at either end. However Sawyer et al. have shown that great care is required in the design and construction of such length artifacts. Alternatively, two magnetic nests fixed to rigid stands or other structures could form a reference length artifact [160]. Moreover, calibration of the reference artifact can be achieved in situ using the laser tracker under test provided the IFM (or ADM) has been calibrated and the reference measurement is performed in a “pure ranging” configuration.

The volumetric tests could, in principle, be performed by end-users of laser trackers. However, the time required to perform the full range of tests means that end-user “field checks” are normally restricted to a limited number of two-face tests and a bird-bath test, which will quickly reveal many common geometry errors of the laser tracker.

Conte et al. proposed a kinematic model of a laser tracker based on Denavit–Hartenberg method [33]. They determined the parameters of the model by measuring the location of a number of targets from multiple tracker locations. The nominal positions of the targets were determined by pre-calibration on a CMM.

Hughes et al. have developed a method of determining the geometric error parameters of a laser tracker using a simple and quick “network test” [84]. This involves measuring a number of fixed targets from a number of different locations and requires no specialist equipment. The recorded data is then processed in a similar way to the photogrammetric bundle adjustment to obtain estimates of the target coordinates, the tracker positions and orientations and the geometric error parameters. No prior knowledge about target coordinates is required. The analysis also provides the uncertainties associated with the parameter estimates in the form of a covariance matrix. This information can be used for subsequent uncertainty analysis when making measurements.

In standard dimensional metrology systems, the link between the measurand, for example, the length of a gauge block, and the observed sensor reading, for example, the number of interferometric fringes, is straightforward so that sensor reading leads directly to the estimate of the measurand. Furthermore, these measurements are usually made in laboratory conditions so that environmental effects that could potentially complicate this relationship are effectively supressed. Two of the characteristic features of Large-Scale Metrology are that (a) the sensor readings (angles, distances) are related somewhat indirectly to the measurands, usually the locations of targets or quantities derived from such, and (b) environmental effects are not tightly controlled. A general approach for estimating target locations from sensor data in Large-Scale Metrology is discussed in [48,147]; see also [11,48,117]. The model of the measuring system usually has parameters $\boldsymbol{x}_j$, $j = 1, \ldots, n_X$, representing the point or target locations and other parameters, $\boldsymbol{b} = (b_1, \ldots, b_{n_0})^T$, referred to in [1] as configuration parameters, that specify other aspects of the system, for example, the location and orientation of a laser tracker. The frame of reference of the target coordinates can be specified in a number of ways, e.g., by constraining a laser tracker to be positioned at the origin, removing six degrees of freedom [48,147]. The model is used to predict what a sensor reading should be given the state of the system as specified by the model parameters. If the ith sensor reading involves the jth target, the model prediction s_i^* can usually be written as an explicit function of the model parameters: $s_i^* = s_i^*(\boldsymbol{x}_j, \boldsymbol{b})$. The model also provides a statistical characterization of random effects associated with the sensor system, for example, $s_i|\boldsymbol{x}_j, \boldsymbol{b} \in N(s_i^*(\boldsymbol{x}_j, \boldsymbol{b}), \sigma_i^2)$, that is, given that the system is characterized by $\boldsymbol{x}_j$ and $\mathbf{b}$, the sensor reading is a draw from a Gaussian distribution centered at $s_i^*(\boldsymbol{x}_j, \boldsymbol{b})$ with standard deviation σ_j. Estimates of the model parameters are generally determined using a least squares adjustment procedure that finds the values of the parameters that make the model predictions match the actual recorded sensor readings in the least squares sense, using appropriate weights for each sensor reading. Strategies for adjusting the weights for different sensors are discussed in [49]. If the random effects are characterized by Gaussian distributions, then the least squares adjustment procedure determines the maximum likelihood estimates of the model parameters.

The fact that each sensor prediction involves only one target location means that the matrices involved in the calculations have a block-diagonal structure that can be exploited to make the calculations efficient [115,116,147,152]. If the fitting problem involves m sensor measurements and n_0 configuration parameters, then the computation takes $O(mn_0^2)$ floating point operations and scales approximately linearly with the number of targets n_X. Without exploiting the block-diagonal structure, the computation is approximately $O(n_X^3)$.

2.6.2. Measurement uncertainty evaluation

Uncertainties associated with the sensor readings, derived from the statistical characterization of sensors, can be propagated through to those associated with the parameter estimates using linearisations and the law of the propagation of uncertainty and the model parameters associated with a multivariate Gaussian distribution. In a Bayesian setting the statistical characterization defines the likelihood of observing the sensor readings, given values of the model parameters. For Gaussian models and noninformative priors, the posterior distribution for the model parameters is substantially the same as that associated with the least squares estimates.

A third characteristic feature of Large-Scale Metrology is that the uncertainty behavior can be very anisotropic. For example, using a laser tracker, (changes in) radial distances are usually measured much more accurately than angle measurements so that the uncertainty ellipsoid associated with a single target estimate is ‘pancake shaped’ with much larger uncertainty orthogonal to the line of sight compared to along the line of sight. This means that (a) the uncertainties associated with distances, for example, cannot be summarized by a simple $A + B/L$ formula as for the case of CMMs [31,32], and (b) the estimates of the target locations can exhibit strong statistic correlation. Uncertainties that are calculated on the assumption of statistical independence can be over- or under-estimated and provide a poor guide to the capability associated with a particular system or measurement strategy. It is better to evaluate uncertainties associated with derived quantities based on the full $3n_X \times 3n_X$ variance matrix V_X associated with the target locations. The block-diagonal structure associated with the matrix calculations can be used to store V_X compactly as $V_X = SS^T + S_0S_0^T$ where S is a $3n_X \times 3n_X$ block-diagonal upper-triangular matrix with 3×3 upper-triangular blocks S_j on the diagonal (so that S can be stored as a $3n_X \times 3$ matrix) and S_0 is a $3n_X \times n_0$ matrix. Hence the information provided by the $3n_X \times 3n_X$ matrix V_X can be retrieved from a $3n_X \times (n_0 + 3)$ matrix. The variance component SS^T represents the contribution of the random effects associated with the sensor measurements while component $S_0S_0^T$ represents the contribution from the uncertainty in the configuration parameters $\mathbf{b}$. Uncertainties associated with derived quantities such as distances between targets can be computed efficiently in terms of S and S_0 and at no point does the full matrix V_X need to be explicitly computed.

The variance matrix V_X will reflect how well the target locations have been determined from the measurement data. An aggregate measure of the performance of the system is given by the trace $Tr(V_X)$ of V_X, the sum of its diagonal elements. The effectiveness of proposed measurement strategies can be determined in simulations by monitoring such an aggregate measure, possibly using optimization algorithms to determine a good placement of measuring stations, for example [50,186].

The variance matrix will also indicate how well the frame of reference of the targets have been fixed and how well the geometry (or shape) of the cloud of points has been determined. It is often useful to separate out the uncertainty associated with position from that associated with shape since often it is only the uncertainty in shape that is of interest. A straightforward approach is considered involving projection matrices P_1 and P_2 with $I = P_1 + P_2$ where $V_P = P_1 V_X P_1^T$ represents the variance component associated with position and $V_S = P_2 V_X P_2^T$ represents the variance component associated with shape. Uncertainties associated with distances and angles calculated using V_S are the same as those calculated using V_X, for example. In general, $V_X \neq V_P + V_S$ but $Tr(V_X) = Tr(V_P) + Tr(V_S)$. The variance de-composition can be computed efficiently for structured variance matrices and can be extended to include the component representing uncertainty in scale [48].

The approach described in Peggs et al. for example, for analysing sensor data associated with multi-station systems is basic but includes the main components and enables uncertainties to be calculated in accordance with the GUM [89,90,147]. This basic approach can be extended in a number of ways.

Target assemblies. In a number of applications, e.g., [50], the metrology systems are used to monitor the position of a rigid body such as a robot head. For these applications a target assembly of three or more targets are mounted on the object being tracked. The primary parameters of interest are the six parameters $\boldsymbol{t}_k$ (three translation, three rotation) describing the rigid body motion of the target assembly. The same general computational approach can be applied, only now the target location parameters $\boldsymbol{x}_j$ are replaced by the six transformation parameters $\boldsymbol{t}_k$. A similar situation arises in iGPS systems where a hand-held vector bar is used as a probe. The vector bar has two receivers (targets) and these are aligned with the probe center on a common axis. In this case, there are five transformation parameters (three translational, two rotational) associated with the vector bar target assembly.

Measurements in a dynamic context. Standard applications of Large-Scale Metrology involve the determining the fixed geometry of a large structure. The data analysis methods aim to integrate all the measurements taken during measurement campaign to determine best estimates of the geometry. In the context of drifting stations, estimates of the configuration parameters at time *t* can be improved by incorporating measurements a later times and therefore the estimates of the target locations made at time *t* can also be improved, as discussed in Peggs et al. [147]. For applications in which the metrology system is used to control robot assembly, for example [50], the improved knowledge of the configuration parameters at time *t*, due to later measurements, will generally be of little value as the robot will have completed its actions and will not be in a position to improve on them. In this situation, the value of the configuration parameters at time *t* is used to predict the value at the next time step and can then be discarded, as in dynamical state estimation using a Kalman filter approach. For these applications, the overhead associated with updating the configuration parameters can be minimized. The performance of the measurement system itself, used dynamically, also needs to be considered.

Refractive index compensation. The extensions of the model discussed above involve more explicitly compensating for the systematic effects influencing the measurement systems in the data analysis and the associated uncertainty quantification. The classification of influences into systematic and random effects depends, to some extent, on timescales. Practically all Large-Scale Metrology systems are affected by the perturbations in the refractive index of air in the operating environment. Generally these are treated as uncorrelated random effects. However, temperature gradients in the operational environment can persist over significant timescales and introduce correlations in optical path length estimates for paths that temporally and spatially close. Regarding these effects as uncorrelated could lead to misleading uncertainty statements. Conversely, measuring or modeling these effects could lead to improved performance in practical environments. If the air temperature is monitored at a number of locations in the operating environment (along with pressure and humidity), spatial statistics [34] can be used to determine the refractive index map, with associated uncertainties, as a function of location and form the basis for converting optical path lengths to geometric path lengths as a function of the position of the path (and time). Alternatively, novel techniques such as acoustic tomography [9] could be used to provide (additional) information about air temperature as a function of location and time. On the downside, accounting for such spatial correlations leads to algorithmic and computational complexity.

2.6.3. Material standards

Particularly in the case of large workpieces, the dead weight and inhomogeneous temperature profiles may influence a measurement result very strongly. A reproducible and stiff suspension is, therefore, of great importance. An example is the extra-stiff suspension which has been developed at PTB (Fig. 17). Its flexible and statically determined six points of support allow gravitational forces and acting moments to be optimally recorded so that the deflection of the workpieces becomes minimal.

Likewise, the influence of the temperature is particularly large in the case of solid components. This is due to the inertness of the heat propagation in large masses. To achieve a homogeneous temperature distribution, the temperature of the workpieces must be regulated for several hours up to several days. If the homogeneous temperature is known, the systematic geometry deviations can be compensated numerically. Inhomogeneous temperature distributions cannot be compensated for and must, therefore, be assigned to the measurement uncertainty [80].

In Fig. 18a large involute gear standard representing a cut-out gear of 1 m in diameter of approx. 450 kg is shown. Its design

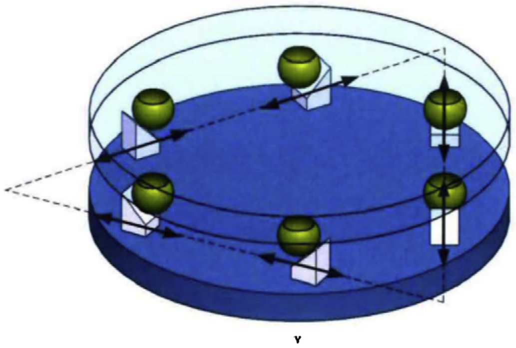


Fig. 17. Extra-stiff coupling with six points of support.

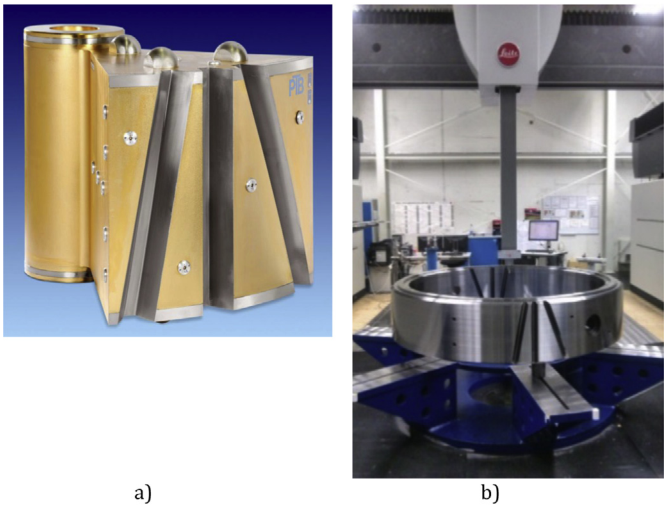

a) b)

Fig. 18. Involute gear standards segment (a) and workpiece-like (b). *Source*: PTB Braunschweig.

allows the representation of an external gear with different helical and spur gear parameter. It was designed for easy handling and shipping. In Fig. 18b a workpiece like a large involute gear standard is shown [80].

The 2 m ring design allows the representation of internal and external gear parameters of different hands. Both gear standards represent a typical size of gears used for wind power plants. Special attention should be drawn on the temperature sensors which are equally distributed around the gear standards. They facilitate monitoring of the temperature behavior inside the gear standard before and during the measuring process.

Within the European Metrology Research Programme Project (EMRP) called "Traceable measurement of drivetrain components for renewable energy systems" a ring standard is designed to examine solutions for measuring and characterizing 2D and 3D size, form, waviness and surface roughness parameters in large drivetrain components, establishing functional characterization parameters in accordance with the GPS requirements defined in ISO 14253 and ISO/TS 17450 (see example WES Fig. 2).

2.6.4. Compensation based on simulation

Modern IT systems in production environments are used for data acquisition, processing, storage and computer numerical control for manufacturing, assembly or measurement tasks. Their computing power and number of network links allow new solution approaches for handling process variations. Simulations for the compensation of the most important and complex influences during measurement or production processes in general become possible [2,102,150,199]. When it comes to large machines and structures, gravitational and thermal influences are crucial due to high dead loads and dimensions [44].

Knowledge about thermal measurement influences on the shop floor is growing in importance since measurement technology is increasingly integrated into manufacturing environments with continuous temperature variations. The requirement is to avoid time-consuming transportation to temperature controlled measuring rooms due to high costs or because work pieces have to be measured in short time after a production step. Then, measurements are performed by CMMs on the shop floor or directly on the machine tools by optical systems or the machine itself [154,200].

Complex work pieces with small tolerances, or work pieces with strongly varying environment temperatures or large process heat flows that are measured a short time after manufacturing, are subject to temperature related changes of the work piece geometry that are unsteady and inhomogeneous [102]. With a simulation of thermal effects on measurement results instead of a less precise, conservative uncertainty approximation, measurement uncertainties can be stated more exactly and thus be reduced. Furthermore, simulation results are applicable as input for compensation algorithms.

Section 2.5 describes gravitational deformations of components. These elastic deformations depend on the positioning and orientation, the material characteristics, the geometry, and the mounting conditions of the component. As orientation and mounting conditions change during the process, the deformations through gravitation are variable and need to be compensated for in each process step. These varying gravity influences on the component geometry also affect measurement processes during production. Changing clamping points and orientations, necessary for the different process steps, leads to deviations in the geometric measurement results. Conventional methods use massive and stiff tools or jigs that map the components geometry and prevent (or minimize) gravitational deformations. Simulations of the gravity influences on the component during the processes, could reduce these efforts in production. With the knowledge of the component deformation, the process control could be advanced in order to consider the gravitationally deformed component. A main tool used to simulate the gravitational deformations is a model that describes the component deformation behavior according to the varying handling positions.

Methods and tools required for modeling the component's behavior according to temperature and gravitation influences are presented in the following.

FEM software is widely used in production science and engineering. Structural behaviors, including the geometric accuracy of machine tools in relation to temperature variations and vibrations, is simulated with FEM programs as well as the wear of components and cutting tools, process heat flows, and the surface quality or the thermal deformation of work pieces during the process [7,100,101,199].

Methods and tools used for simulating the thermo-mechanical behavior of machine tools and work pieces can be adapted to predict shop floor measurement behavior of machine tools or CMMs a short time after manufacturing or in between successive process steps.

The boundary and initial conditions used for simulating these measurements, including environment temperature profiles, component support locations, and temperature distributions at the beginning of the process step, are the same as the ones for the manufacturing processes. This is because identical physical effects are modeled: unsteady, three-dimensional heat conduction with convection heat flows for a solid body, coupled with thermal expansions. In comparison to the manufacturing process, the measurement simulation is simpler since there are no heat flows due to the process or to cooling fluid, which require complex calculations. The measurement process simulation builds on the manufacturing process simulation, and uses its results for temperature distributions and thermal expansions of the work piece or the machine tool as initial conditions.

FEM tools have been shown to produce reliable results according thermo-mechanical geometry changes of work pieces or varying positioning accuracies of machine tools during production processes [2,102,150,199].

Commercially available FEM software that allows such coupled thermo-mechanical simulations and is used for research purposes in this field include programs such as Abaqus, Ansys, Comsol, or Nastran. All programs offer 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 values that can be applied as input to the measurement software for compensating thermal geometry or material property changes to a certain homogeneous reference temperature.

Simulation results also contain underlying uncertainties. In general, they are expected to be significantly lower than conventional thermal uncertainty approximations or results from less detailed and realistic models that are commonly used for compensating thermal expansions of measured work pieces and measurement scales [7,101]. This is the major advantage of the described solution approach, which has to be quantified in future for different measurement scenarios by upcoming research projects.

3. Model based measurement processes

The idea of a model based measurement system is to estimate unknown states of the process by simulating the systems behavior. The knowledge of the factors influencing the systems and the interactions between these factors is vital for such simulation.

In semiconductor manufacturing virtual metrology refers to methods not measuring the wafers properties directly but using process parameters to predict [99]. The virtuality discussed in this paper refers to the simulation of the components. Nevertheless the idea of virtual sensors is strongly supporting virtual measurement processes.

The objective of the modeling in LSM applications is to predict and reduce the measurement uncertainty of the measuring process. The reduction can be achieved by compensation strategies concerning the used measurement system, the measurement strategy or the environmental conditions.

3.1. Model based evaluation of measurement uncertainty for a centralized measurement system

The Virtual Coordinate Measuring Machine (VCMM) is a software module for the determination of a task-specific measurement uncertainty [6]. Its use is suited, in particular, for universal measuring instruments such as coordinate measuring machines, as it determines the measurement uncertainty for each measurement task individually and quasi-automatically. A mathematical model describes all significant error influences of a measurement procedure [105].

Hereby, a distinction is made between:

- Machine characteristics, such as guideway and probe/probing errors
- Measurement conditions such as variations in temperature and air humidity
- Workpiece, such as surface roughness and surface waviness.

For mathematical modeling a distinction is made between three error types: systematically known errors, systematically unknown errors, and random errors. To guarantee for the correctness of the results, it is of utmost importance that the magnitude and the characteristic error behavior of all input parameter of the VCMM must be determined traceably to the SI units.

Taking the requirements of GUM Supplement 1 into account, the measurements are simulated under different conditions [89]. Each of the simulations leads to slightly different measurement values, whose scatter is taken as a measure of the measurement uncertainty. This simulation is continued until the values of the measurement uncertainty have reached a stable state.

In 1995, the virtual coordinate measuring machine was, for the first time, developed by the Physikalisch-Technische Bundesanstalt (PTB) for Cartesian coordinate measuring machines with tactile probing systems [178]. Up to now, it has been an essential advantage that the so-called VCMM module can be integrated into the software of commercial manufacturers of measuring instruments.

Fig. 19 explains the virtual concept. It consists of two modules.

The manufacturer's software first transfers the real measurement points to the virtual driver module. Dependent on the estimated errors and its characteristic behavior all measurement points will be distorted and re-transmitted to the manufacturer's module. This process equals a virtual measurement. This process will be repeated several times. Each time with different measurement conditions coming from the probe, the CMM geometry, the environment and the workpiece. The simulation stops when the statistical distribution of the individual measurands is stable. Finally, the manufacturer presents the complete measurement result according the international agreements; the measurement value and its measurement uncertainty.

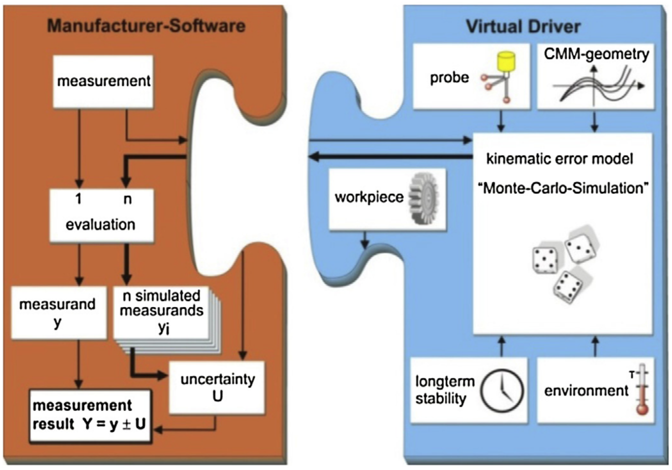


Fig. 19. Modular concept of the virtual driver.

The integration of the VCMM allows different manufacturers of measuring instruments to meet the requirement of the GUM and to indicate the measurement results completely with the measured value and the associated measurement uncertainty. In the course of the past few years, the virtual gear measuring instrument VCMM-Gear and, finally, the Virtual Laser Tracker (VLT) have been developed [79].

The different applications of the VCMM mainly differ in their measuring instrument kinematics. Depending on the type, the corresponding guide errors are recorded with ball plates or with hole plates [179]. In the field of Large-Scale Metrology, the geometry errors of the measuring instruments are recorded with the aid of laser tracers or 3D-LaserMeters [103].

The Virtual Laser Tracker (VLT) allows determining a task specific measurement uncertainty simultaneously to any measurement. It considers all influences of the different design provided on the market, the environmental influences that manly influence the beam length, the influence of the different reflector types etc. During a measurement they must be determined to stay traceable to SI units. This usually could be done by measuring calibrated length references such as the PTB reference wall in addition to calibrated spheres (see Fig. 7). Once a virtual module is integrated into a manufacturer's software, the measurement result could be listed according the requirements of the GUM. Simple measurements on calibrated cylinders could be used to validate the correct implementation of the VLT or to monitor the long term stability of the system.

The objective is the switch from virtual measuring systems (VMS) to a holistic approach of virtual measuring processes (VMP).

3.2. Distributed systems and the metrological frame

A prerequisite of self-referential systems is the availability of valid information about the system's condition. The required information about the geometrical and temporal deviation of the actual production from the planning data can be gained through the use of suitable measuring systems. Like the terrestrial "Global Positioning System" (GPS), these measuring systems are called "global reference systems".

The task of global reference systems may be the geometrical and temporal registration of the condition of an entire production facility in a coordinate system, which corresponds to the system of simulation and planning. The measuring systems are used as a reference system to the infrastructure and are not explicitly assigned to single equipment components. This means that various measurement systems may build the "metrological frame". In contrast to a rigid and dimensionally stable physical structure the "virtual metrology frame" determines the relative disposition of reference features periodically by a self-calibration technique [73,86].

Hughes and Schmitt describe a frame based on lengths measured with tracking interferometers. The targets positions are calculated using the length measurements with the multilateration principle [86,166]. In other approaches Nikon iGPS is used to measure positions of robots and distances between different robots or workpieces in the same working spaces [163].

The main objective of these approaches is the enhancement of accuracy of the used "mover". This can be a kinematic like for example a machine tool or a robot handling the measuring device. The set-up of a frame enables kinematics like industrial robots or large machine tools to handle optical or tactile measurement systems and perform measurements of large-scale parts with a measurement uncertainty significantly lower compared to the positioning accuracy of the kinematic itself.

The modeling of the GRS or "virtual metrological frame" is complex regarding the measurement systems behavior and the influencing factors of the environment.

3.3. Intelligent process control with real time measurement processes

Intelligent process control has been established in series production for several years now and has helped to maintain and improve quality levels. In the production of large-volume, complex parts, process control are a more complex undertaking and often neglected. The main reason for this is that process control is often associated with expensive, complex and specialized in-process monitoring. However, apart from such short-term control loops, there are two other types of control loops, medium-term and long-term control loops, which have to be considered in order to establish an intelligent process control [139,191]. Medium-term control loops are those that are used to optimize machine parameters between parts to be manufactured. Long-term control loops are those that ensure that production equipment is constantly kept fit-for-purpose, like for example the monitoring of machine tool geometric errors, drilling equipment tool wear or the periodic re-calibration of measuring equipment.

In analogy to the Renishaw pyramid of process control, the impact on production quality increases when the control loops get longer. In addition, long-term control loops are a prerequisite for short term control loops, e.g. in-process real-time measurements and control is usually not feasible if the production and measurement equipment used is not fit-for-purpose [158,191].

3.3.1. Real time measurement processes

Out of these three types of control loops the in-process, short-term control loops impose the biggest challenge in the production of large-volume parts due to the fact that the behavior of the process has to be completely understood and described by appropriate process models. Since there are often more process parameters to the production process of large volume parts than to the production of smaller parts, the process models for large volume parts are more complex and have to address the problem of correlations between a variety of process parameters, process conditions and influence quantities [198].

There are three main challenges for intelligent in-process control for complex, large-scale parts. The first is that most of the time relevant process information through measurements cannot be obtained from one sensor only but has to be obtained by real time fusion of data from multiple instruments or distributed sensor networks [188]. Reasons for the usage of multiple sensors are the need for distributed dimensional measurements due to the size of typical large volume parts or the need for the combination of different sensor technologies to acquire information on different material properties, especially when using composite materials. Popular examples are distributed dimensional measurement systems such as the iGPS system or Laser tracker measurements from multiple stations [122]. Another application can be found in the field of Measurement Assisted Determinate Assembly (MADA) [135] and Metrology Assisted Assembly (MAA) [120]. The use of heterogeneous sensor networks especially imposes a challenge on data structures and interfaces for data transfer which need to be clearly defined in order to facilitate data fusion [188].

The second challenge is that appropriate process adaptation rules have to be derived from combined sensory information. A prerequisite for the derivation of appropriate decision rules is always the identification of sensor signal features to be monitored. This is usually done using expert knowledge. After a number of candidate features have been identified, their effect on the process behavior and the critical quality characteristics can be classified in a number of different ways, e.g. by Design of Experiment or Data-Mining approaches like Neural Networks or Neuro-fuzzy-logic [177].

The trend in modern sensor technology of shrinking form factors, often at a low price, has led to more and more sensors being embedded into production to monitor process conditions and with it to ever-increasing data rates. This leads to the third challenge which is to handle very large amounts of data in real-time computationally. This means to set-up a computational architecture which is able to handle large streams of data along the whole control loop: From the acquisition of data over data conditioning and feature extraction to decision making and feedback into production control. If data rates are very high, traditional computational analysis approaches are not sufficient for these steps and it is necessary to use Big-Data approaches [173]. These are based on the use of special architectures and algorithms, such as the lambda-architecture that allows a combination of batch-processing (e.g. Hadoop, MapReduce) and stream processing (e.g. Storm) [39,96,146]. The architectures allow for real-time algorithms that detect abnormal process patterns and correlate them with output quality to give suggestions for process adjustment In addition, techniques like One-Click-Mining can be used to allow user feedback to be incorporated into the analysis, see section on Cyber-Physical Production Systems (CPPS) (Section 3.4) [13,74,75].

3.3.2. Interfaces and data transfer

The definition of common interfaces serves the ideas of simplified communication and ease of information exchange. Standardized means of data transfer help to reduce the information overhead and increase trust when exchanging data across affected entities (companies, departments, processes, machines) [118]. Aiming at the exchange of product and product related information, the production domain has seen multiple standardization efforts. These are largely motivated by standardizing dimensioning, tolerancing and related metrological principles (ISO TC 213), and the exchange of product data models between various information systems, usually motivated by Computer-Aided-Engineering applications (CAE) (e.g. STEP, ISO TC 184/SC 4) [174]. Similar approaches to store product information can be found in other industries as well. Most notably is BIM (Building Information Modeling), based on IFC (Industry Foundation Classes – ISO 16739 [94]), a parametric, semantic data format that allows the storage of dimensional information as well as any other information (e.g. time, cost, materials) throughout the building life cycle [24,41,175,185], thus creating a digital twin.

Further standardization efforts address control programs for metrological equipment with a focus on CMM. These include the use of STEP-NC (see ISO 14649 part 16 (draft) [88]; especially for closed loop machining [19]) and I++DME (Dimensional Measurement Equipment) driven by the European automotive industry [149]. More recent developments include not only the control of the metrology devices but also the transfer of the metrological information. Saunders et al. proposed a reference framework for this purpose, Zhao et al. proposed an adaptation of the ISO 10303 (STEP) to include dimensional measurement data [157,201]. The Dimensional Measuring Interface Standard (DMIS), as well as QIF (Quality Information Framework) both include quality measurement plans, measurement results, measurement rules, measurement resources, and analysis of results (e.g. multi-part statistics). They find application in multiple software tools such as PC-DMIS by Hexagon Manufacturing Intelligence.

Beside the development of standards, there has been considerable research in the development of frameworks allowing the use and storage of dimensional information by multiple stakeholders. DET (Digital Enterprise Technology) is a “collection of systems and methods for the digital modeling of the global product development and realization process, in the context of life-cycle management” and as such similar to BIM but located in the production domain. DET aims to facilitate parallel and synchronous deployment of various CAE technologies especially for distributed enterprises [118,121,122]. LSM functions as a DET environment integrator, integrating the physical and the digital environments by providing real 3D location, orientation and shape of key product features. Following the paradigm of concurrent engineering this becomes especially important for the assembly and fabrication of complex and large products that were modularly designed, manufactured at multiple locations, and assembled in different parts on site. Maropoulos et al. set up a theoretical framework for the integration of aggregate process planning with

LSM on DET to support decision-making within production networks including tolerance-enriched aggregate models [118,122]. Other applications that utilize the DET framework include the specification and generation of metrology process models for the integration of metrology with assembly planning [119]. Hardwick et al. gave an outlook into digital manufacturing that relies heavily on the exchangeability of as-is data [78]. Interfaces for the connection of measurement systems vary and rely partially on technologies such as Ethernet, bus systems or are proprietary (e.g. in distributed (wireless) sensor networks). Improvements regarding connectivity, interchangeability, and real-time capability are expected from developments within the Cyber Physical System (CPS) paradigm and the introduction of SOA (Service Orientated Architectures) in production environments [96].

Interfaces and means for data transfer furthermore facilitate new business models and services such as "Metrology as a Service" (MaaS). Where traditionally everything from sensor application to decision making based on acquired data is in the hand of one business entity, MaaS proposes to distribute these tasks among multiple parties. One possible scenario would be that an operator of a producing company uses the LSM equipment owned by the company to take measurements of a part. The raw metrological information, together with additional information about the measurement process is then transferred digitally to another company that specializes in the modeling of measurements uncertainty and evaluation. This is especially suitable for LSM-applications that generally require multiple different measurement systems, as fewer highly trained and expensive specialists are required.

3.4. *Cyber physical systems for Large-Scale Metrology*

The introduction of metrology into production processes for in-process or near-process quality inspection is well established. The use of process control in LSM is a relatively new application and poses new requirements toward the metrology systems, including connectivity and real-time capability. The obtained measurements are used to supply product and process models with the necessary information about the as-is state of a product or the position and orientation of a machine (e.g. an industrial robots or a machine tool). Another example for the integration of LSM systems with factory systems is the use of temperature or humidity sensors within the factory to use their data in models to determine the measurement uncertainty of the LSM system. Such systems, that integrate physical and virtual components are referred to as Cyber Physical System (CPS) [133]. CPS presents a form of convergence of computation, communication, information, and control [133].

This paper follows a recent CIRP keynote paper by Monostori et al. and refers to CPS as physical and engineered systems that are monitored, coordinated, controlled by a computing and communication core [133]. Their cyber components are strongly connected to and coordinate with the physical resources. The development of standards for the design of CPS poses numerous research challenges including the physical integration of communication interfaces and sensors or actuators as well as the implementation of sensor networks [21,107,171], this allows the creation of systems and as such exceed existing systems in terms of, among others, adaptability, efficiency, and scalability [133,151].

CPS in industrial applications are referred to as Cyber-Physical Production Systems (CPPS) [132,133,161,184]. They consist of autonomous and cooperative elements and subsystems that connect to another dependent on the situation and across all levels of production from individual sensors and actors up to production and logistics networks. They are described as self-configurable means of production that acquire, analyze, and store physical data, act on the physical world, interact with the virtual world, are networked by global information systems and services, and dispose of multi-modal human-machine-interfaces [133]. This involves the production system as well as the product [133,192]. They expand on the idea of distributed sensor networks as described and discussed in [64,116,147] by being able to combine different sensor technologies and the ability to act on the physical world. Furthermore, this allows the use of model-based systems in production, thus leveraging the benefits that arise from networked and combined models. The decentralized acquisition and processing of sensor data allows the ad-hoc networking as well as local and global control loops [184].

At the time of writing, research on CPPS is largely motivated by both publicly and privately funded programs. Most notably are the "Industrie 4.0" (I4.0) scheme in Germany which focusses on industrial applications and standardization primarily initiated by the government, the "Made in China 2025" state-driven initiative to "comprehensivly upgrade" the Chinese manufacturing sector, and the Industrial Internet Consortium (IIC, Asia, America) activities which have a wider scope regarding addressed sectors and are primarily driven by large multinational enterprises [10,98].

A key element for the success of these programs is the development, and subsequent standardization, of system and communications architectures [12].

The "Reference Architecture Model Industrie 4.0" (RAMI4.0) specifies a three-dimensional architecture including the life-cycle of systems or products, functional hierarchy levels, and layers to represent various perspectives (e.g. data maps, functional descriptions, hardware assets) [1]. RAMI4.0 includes a definition for I4.0-components connecting and virtually representing them by means of an administration shell. Components are classified according to the CP-classification systematic (Communication and Presentation; denoted as CP-XY) [1,183]:

- X-cipher: ability to communicate (1–4; 1 being unable to communicate; 4 I4.0-conform communication)
- Y-cipher: level of awareness (i.e. is the information system aware of the component) (1 unknown component; 4 component managed as an entity).

Beside several examples for CPPS applications (e.g. [42,61,110,133,167]), Schmitt et al. have developed a framework for CPPS based on LSM for the production of large components [162]. They describe a generalized model for CPPS (Fig. 20) that focusses on acquiring information on environmental influences (e.g. sensors for ambient conditions such as temperature and humidity) and component, process, and machine state using LSM systems and utilizes this information for database-backed self-optimizing models for all aspects of the production process. Schmitt et al. gave two examples from aircraft assembly and turbine housing manufacturing (see Section 1.2).

Beside general requirements for the development of CPS [21,58,97,132,133,151] there are specific requirements for CPS in the context of LSM, including:

- improving the integration and networking of different metrological systems and the establishment of standards for the

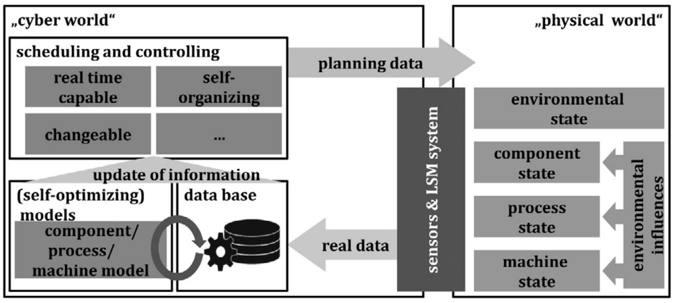


Fig. 20. Concept of a CPPS for the production of large components. Adapted from [162].

exchange of geometric data and improved exchangeability to facilitate the use in process control;
- models for the live and real-time determination of measurement uncertainty in distributed measurements systems under factory conditions for a specific operating point in a production system to ensure production capability;
- automated calibration routines for multi-technology LSM systems in CPPS applications (e.g. suitable multi-technology targets) [58];
- reference architectures for sharing, distributing, and using models of measurement systems, processes, measurement uncertainty within a CPS system.

3.4.1. Dynamic aircraft shell assembly based on Global-Reference-Systems

The utilization of more dynamic and flexible assembly systems for large-scale parts requires the use of external sensors as well as robust strategies such as "self-optimization" for interpreting the acquired sensor data. The potentials of such systems can be leveraged in the field of extreme dimensions as in the airplane industry where large components must be positioned precisely to build the final structure.

CPPS provide the basis to create a self-optimizing assembly system that can, according to the definition of self-optimization, act with inherent 'intelligence', to react independently and flexible to changing operation conditions [68]. One prerequisite for a CPPS is the consistent modeling of the complete system – the component, the handling system, and the process (Fig. 21).

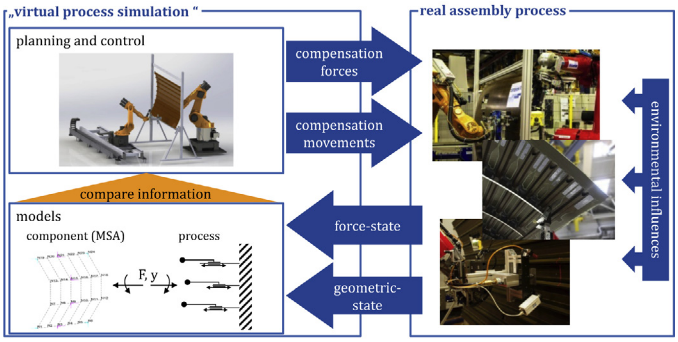


Fig. 21. Concept of a CPPS for airplane shell elements.
Source: WZL RWTH Aachen Universiy.

The depicted method for modeling the deformation behavior is based on the Matrix Structural Analysis (MSA) method [128]. The MSA applies beam theory for modeling mechanical structures by interconnecting beam elements with nodal contact points.

For describing a shell element a thin-walled, generally curved body equipped with stiffening elements (stringer, frames) is modeled. The mechanical properties of the system are represented by the stiffness properties of the beam elements (geometry and material properties) (Fig. 22).

The adaption of the component simulation to the measured deformations is realized by applying a displacement to each node (N1–N24) according to the measured deviations.

The measurement of the deformation is done with a laser tracker measuring the position and distance of different points on the shell surface. Additionally the laser tracker coordinate system provides the reference coordinate system (global reference system – GRS) for the entire process.

According to [40], GRS can be defined as follows: The task of global reference systems is the geometrical and temporal registration of the condition of an entire production facility in a coordinate system, which corresponds to the system of simulation and planning. Therefore all measuring information and process entities are references to the laser tracker base coordinate system via coordinate transformations (see Fig. 23).

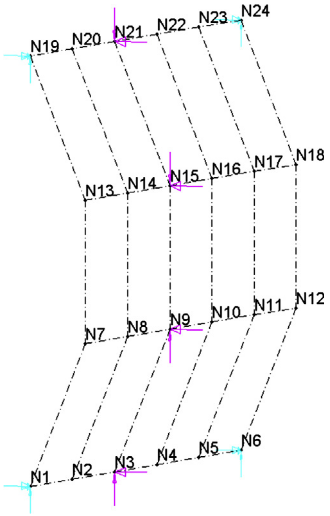


Fig. 22. MSA mesh of an airplane shell element.
Source: WZL RWTH Aachen Universiy.

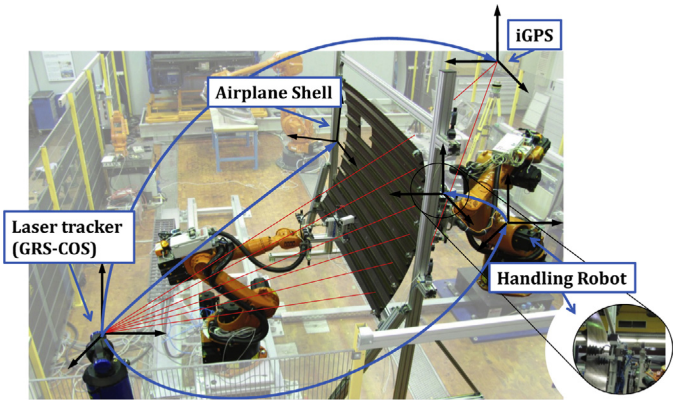


Fig. 23. Setup of the Global Reference System.
Source: WZL RWTH Aachen University.

The detected deviations between the targets of the assembly system and the current machine state are used during the self-optimizing process control to calculate the necessary compensation strategies (movements and forces of the robots) to finally eliminate the detected deviations via the flexible robotic system. For the execution of the positioning process each actuator is controlled by forces as well. This guarantees that force limits are not exceeded during the assembly. The forces affecting the shell are measured with the help of force sensitive support points and a force controlled handling robot.

The process control within a CPPS uses the interaction between a real assembly system and a virtual planning and control simulation. This interaction requires the exchange of information and the ability to react according to this information. A metrological observation of the current production state is used to identify the geometric deformations and forces during the process and transform the data into a virtual simulation of the process [97,162].

3.4.2. Manufacturing intelligence for large turbine housings

The machining of large components can last from several hours to several days. During processing the temperature of the machine, the product and the production hall can change significantly and lead to thermally induced geometry deviations in the structure of machine tool and workpiece. The resulting displacements of the tool center point (TCP) can cause deviations in the manufacturing process inhibiting to fulfill specified tolerances. Air-conditioning of the production hall may decrease these effects but is very expensive and not feasible for most industrial applications. In addition to temperature influences, gravitationally induced deviations from the desired geometry can occur, especially at thin-walled and flat components as for example turbine casings (Fig. 3). The clamping on the machine tool can affect the geometry of the components, because in many cases the setup for the manufacturing process differs from the one during assembly or the one when the product is in operation.

The named influences obstruct the measurement process of the manufactured part. Schmitt et al. discuss the solution as the compensation of these induced errors by measuring the part directly on the machine tool using the machine kinematic as the "metrological frame" [162,164]. The knowledge of the machine tools geometric errors is evident for using the machine tool as a measuring system. A laser tracker can be used to measure the geometric features of part in the original clamping and measuring the machine tool geometric errors.

The geometric data of the component and the calibration data of the machine tool are fused to the "single source of truth" data that is used to model the manufacturing and measuring process. The modeling will help to build the "digital twin" of the component as the projection of the real component. For the large turbine housing this will mean for example the geometric parameters like dimensions, diameters, position of bore holes etc. (Fig. 24). The modeling of the behavior of the part under thermal load and gravitational effects has to be implemented into this CPPS as well. Only the holistic approach of measuring system and workpiece considering the environmental influences will allow the improvement of the measuring process and of the manufacturing process as well.

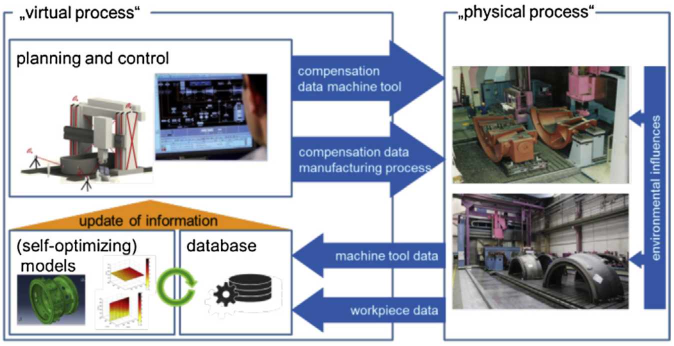


Fig. 24. Concept of CPPS for the manufacturing of large turbine housings. *Source*: WZL RWTH Aachen University.

4. Outlook and conclusion

This paper shows that the field of LSM is directly at the intersection of a wide variety of instruments, demanding industrial applications, and theoretical developments to address the dynamic use of measurements for the compensation of parts and processes. In the time since earlier studies of LSM, continuing technological improvements, conceptual changes, and innovations have been introduced and implemented. This introduction of new technologies, as well as the requirements of modern production systems, has generated new questions which represent ambitious challenges for the future research.

The characteristics and examples discussed in this paper have elucidated the special challenges that LSM applications have to face. The evolution of measurement systems, combined with increased computing power, have resulted in new solutions for LSM applications (InPlanT etc.), or have increased the performance of existing measurement processes by reducing the measurement uncertainty (3D-LaserMeter) (Section 2.4). Recent years have seen a change in the realization and definition of the "metrological frame". As opposed to a rigid and dimensionally stable physical structure, the "virtual metrology frame" periodically determines the relative disposition of reference features using, for example, a self-calibration technique. This frame allows for the portability and flexibility of the measurement systems, and provides an anchor to extend the possibilities of LSM applications by moving the frame to, or even around, the object under measurement (Section 3.2). Flexibility and speed are main criterias in the evaluation of LSM-Systems.

This paper expands the view of large scale measurement to include not only the measuring system, but the entire measurement process. The interactions between the object under measurement, the measurement system or technology, the human, and the disturbing influences provide evidence of the complexity of metrology processes for large-scale parts. Temperature, as always, is a main challenge for shop-floor-oriented measurement processes, as it influences both the measurement system and the object under measurement (Section 2.5). In addition, gravitational influences distort the nominal dimensions of the object under measurement significantly, and must either be compensated or considered as uncertainty (Section 2.5).

The main objective is the traceability of the measurement process. Ensuring traceability requires knowledge of the influencing factors and a model of the interactions (Section 3). In addition, the development of a metrological infrastructure with appropriate standards and requirements can ensure traceability (Section 2.6). International research and documentary standards development both contribute to an infrastructure consisting of reference standards for large-scale applications, and procedures for their application.

The authors of this paper suggest "virtual measurement processes" – based on dynamic process models and intelligent and learning computational support – as a possible solution to handle the complexity of LSM. The need for "intelligent" systems which integrate software procedures for data acquisition and elaboration, set-up, self-diagnostics, surface reconstruction, control of tolerances, etc., is becoming more and more pressing.

This entails the development of new procedures for the integration of different technologies and the use of specific simulation and computation approaches. Process models are the backbone of these virtual processes and the development, improvement, and the sharing of these models are essential.

Many complementary applications for metrology software already allow their integration within other existing software environments (for example, CAD, CAM, CAE, etc.). Integration is also possible with Augmented Reality (AR) or Virtual Reality (VR) applications in order to guide the operator during the measurement procedure, or to provide or supplement his training in the use of the system [56].

Simulation software also has application in assisting the operator in the design phase of the measurement process, in order to identify the optimal combination of systems (or sensors) and their layout according to a required level of performance (accuracy, uncertainty, repeatability, etc.) [21,63].

These new approaches could drive to the definition of a new concept of measurement system, currently also called "virtual instrument", based on the integrated use of simulation, dimensional sensors and sensors for external conditions.

Another additional element of future research is the integration of LSM systems with the whole production environment, known as "smart manufacturing/smart factory". The aim is to achieve completely automated systems, even for the measurement activity. The vision is to obtain "self-measuring systems", with a vanishing boundary between the measured object and the measuring system. This leads to the concept of Cyber Physical System (CPS), which aims to be the reference model of the factory of the future [21,132] (Section 3.4).

Many challenges remain; these range from the need for ever more versatile and easy to integrate systems to the need of specific protocols of communication between the sub-systems composing the CPS. In addition, a complete and sweeping system of standards supporting the entire large-scale measuring process is needed.

The application of CPPS for large scale production poses the need for additional research:

- general requirements [21,97,132,133,151]
- system architectures (e.g. SOA [96])
- standards for the development of CPPS components
- communication standards for the exchange of information (semantics)

Specific immediate needs for LSM can be seen in the current requirements for integration and networking of different metrological systems.

As described, the online and real-time evaluation of measurement uncertainty for metrology applications in CPPS rely on automated calibration routines for CPPS applications [58]. The interaction of the wide range of disturbing factors influencing the measurement process can only be resolved by a systematic approach that involves the generation of suitable models for the compensation of environmental effects. These models will introduce new challenges, balancing the complexity needed with the highest speed of simulation possible. These concepts must then be evaluated for the distributed and compatible use of these models within a network. Beneath this the expansion of the understanding of CPPS, not only from a technical viewpoint but also regarding the economic feasibility of such approaches is needed [130].

Large-scale measurement processes intrinsically reflect the importance of model-based or virtual processes for managing the complexity resulting from the interactions between the measurement system, the object under measurement, and the environmental circumstances. In this context, intelligence can be defined as sub-systems sharing process information to define, surveil, and control the measurement process, combined with the real-time compensation for any disturbing factors, to ensure the traceability of the measurement result.

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