Dimensional metrology for advanced manufacturing technologies

Background

A sustainable success in European key industrial sectors as machine engineering, automotive industries, renewable energy, medical applications and microelectronic is based on high accurate and innovative products. For their testing, advanced coordinate metrology techniques are needed. The need for these measurement techniques is documented by several stakeholders [1-12]. One lasting challenge is to ensure the traceability of the results. In the field of coordinate metrology this is required for 1D to complex 3D structure sizes in between 1 µm and 20 m. Therefore, measurement techniques used in high precise measurement rooms as well as in harsh environmental conditions have to be improved and validated. In particular traceable measurements inside the strong growing market of inline and in production measurement are the future challenges for NMIs and calibrations services.

In compressing such a wide field of metrology into a single diagram, some concessions have been made to aid readability. These should be borne in mind when reading the roadmap. In particular:

- the boxes of the targets give a rough impression on timing and uncertainty
- all other boxes express the technical subjects and their dependencies
- colours show the correlation to the targets: yellow for short range (roughly 1 µm to approximately 10 mm), green for longer range (up to 20 m);
- metrology under industrial conditions means metrology in measuring rooms close to the production line as well as in-process metrology.

Roadmap targets and associated routes

Robust 3D short range metrology 1 µm < L < 10 mm and 3D metrology L < 20 m

3D metrology is an indispensable prerequisite for production. Complex geometries with decreasing tolerances, miniaturisation and 100% inspection demand new measuring technologies. They are facing requirements of extended information content, higher measuring speed, increasing accuracy and in-process integration. In addition, normative requirements become more and more important: The well-known GPS (Geometrical Product Specification) standards are implying basic requirements for tolerancing and verification as well as for calibration of measuring equipment. Furthermore the introduction of the concept of measurement uncertainty penetrates as far as the production level improves and is a prerequisite to the assessment of conformity with specified tolerances.

Against this background there is a need for the development of robust 3D short range metrology (1 µm to several millimetres) as well as 3D metrology up to 20 m both at measuring lab, production environment, and in-process conditions. The features to be measured range from spray holes of injection nozzles with diameters less than 50 µm over machine components up to fuselage of airplanes. To satisfy future production requirements, the measurement uncertainties have to be reduced by at least one order of magnitude.

Procedures for verification, optimization and calibration of non contact and large scale measuring systems are essential as error sources and influences of measurement instruments of laser- and vision-based systems, laser trackers, photogrammetry are less known to metrologists. To overcome this lack, it is necessary to develop adequate models for these instruments and adequate techniques to optimize the model parameters, in order to reach high measurement accuracy. New sensors and measurement instrumentation as well as fast and traceable data processing have to be developed together with test facilities and methods that can verify the performance of these developments under a wide range of reproducible environmental conditions, from lab environment to rough industrial production situations.

The basis for future developments is the large variety of existing sensor principles and positioning systems. New light sources, x-ray computed tomography and optoelectronic components, new materials, advanced computers and information technology (pushed by automotive, medical and consumer products) will serve as an enabling technology for new developments in metrology.

Using these technologies, a next generation of sensors and measuring instruments will continuously be developed. Examples with a high potential are x-ray tomographic instruments (micro- and macro-CT) with higher measuring speed and lower cost, absolute and robust interferometers using broadband light
sources, laser interferometers and laser trackers with refractive index correction, advanced sensors based on multilateration techniques, remote sensing (µ-GPS) and the use of the full spectrum of radiation (e.g. radar sensors).

The new generation of sensors will deliver a huge number of data points to produce a comprehensive characterisation of the objects measured. This is necessary to assess the quality of complex and demanding products and to derive their functional properties as accurately as possible. The amount of measurement data will rise from $5 \times 10^9$ data points today (computed tomography) to $10^{12}$ data points expected in 2025. These data have to be processed by advanced computers and IT.

These large data files combined with the need of 3D segmentation and 3D complex and freeform geometries require certified evaluation software. Test data sets (numerical artefacts) is an appropriate means for the software certification. Online software validation will significantly improve the reliability of evaluation algorithms and provide a direct and fast link between NMIs and end users.

A further challenge results from the interaction between sensors and surfaces. Especially if small uncertainties are required, a deep understanding of the probe-surface interaction is necessary. This includes tactile probing and the interaction of light with the object surface (e.g. the influence of micro roughness influences the light wavelength).

Based on this understanding of probe-surface interaction, cooperative and non-cooperative artifacts have to be developed. Cooperative artifacts are used to determine sensor characteristics (e.g. probing error, length measuring error) and have easy measurable surfaces (diffuse reflecting, no grooves, suited roughness). For this purpose, appropriate manufacturing technologies have to be determined. In contrast to this, non cooperative artifacts (e.g. glossy or soft surfaces, change of materials and color) represent real work pieces. They serve for the evaluation of measurement uncertainty (task specific). High precise measurements shall use data fusion techniques and algorithms to combine measurement results of different sensor types in order to provide measurement uncertainties for prismatic objects in the range of few nanometers (example: piston cylinder unit for the realization of pressure unit).

To minimize complexity and costs in industry as well for calibration services, universal 3D artifacts with materialized features of size, form, waviness and structure size have to be developed. New universal 3D artifacts will be used to validate the machine performance. This will provide lean quality management systems.

With increasing feature size, the influences of the environment become more important. Mayor influences are temperature, dust and vibration. Special attention has to be paid to the refractive index of air when using optical sensors and the influence of inhomogeneous temperature distributions in machine components and workpieces. New methods to detect (e.g. via ultrasonic temperature measurement) and correct such influences have to be developed, which are feasible for the use in industrial environment.

Traceable and portable in process metrology, including sensors in machine tools, is an indispensable prerequisite for real-time quality control directly in production.

Traceability is closely connected to measurement uncertainty. For the normal user in industry the analytic evaluation of measurement uncertainty is not practicable. Therefore an automatic evaluation of uncertainty by simulation techniques (e.g. virtual CMM) will become the stronger influence on different machine kinematics and sensor types. Better knowledge of the measurement uncertainty will lead to better understanding of design and production processes.

The automatic uncertainty calculation demands a detailed understanding of the measurement processes and its uncertainty contributors. Especially the environmental effects on the process have to be understood and measures to reduce these influences have to be developed. This demands test facilities, robust workpiece-like artifacts and sensors non sensitive against environmental conditions, so giving NMIs the possibility to research and evaluate measurement processes under reproducible industrial environmental conditions.

Test procedures and artifacts supporting the new trend of kinematic measurements ensure the traceability of reliable shop floor measurements.

**Cross-links with other technical areas**

**Enabling science & technology inputs include:**

- New materials may be required for the stability and control necessary at sub-mm ranges;
- Mathematical modelling is also necessary for some of the probe-surface interactions;
Virtual instrumentation will be necessary for the estimation of real-world uncertainties on non-prismatic components, e.g. for aspheric metrology

**Outputs from TC-Length into other technical areas:**

- Clearly, improvement in European manufacturing of items in the range 1 µm up to 10 m will have an impact on a wide range of areas, enabling improvements in metrology in many other TC fields.

**References**


