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1 Executive Summary

Introduction

Parts which are a millimeter or less in size or parts with features in this size range are becoming increasingly important in industry and daily life, for example when it comes to scaling down technical equipment, reducing power consumption or saving raw materials. Quality assurance for these parts is a major challenge, as measurement is required below the micron scale in a range of complex geometries and surface characteristics. At present, tactile coordinate measuring machines (CMMs) are limited by the probe size, speed of measurement and wear. Alternatives are optical sensors or Computed Tomography (CT), but although these are fast they are not as accurate as tactile CMM and the measurements are not traceable. This project developed smaller tactile probes and aimed to achieve traceability for optical sensors and CT. It also looked at improving the accuracy of optical sensors and CT, and combining the data from the different techniques to implement multi-sensor measurements. Working closely with three manufacturers, the project developed and categorised workpiece-like reference standards, which could be used to achieve traceability of industrial measurement tasks.

The Problem

Improvement of metrological capabilities for measuring microparts such as fuel injection systems in car engines and insulin injection needles is needed. For many applications, it is not feasible to measure using tactile sensors. For instance, objects with features which are a similar size to the probe tip cannot be measured. Therefore, other sensor techniques are required, such as CT or optical sensors. Furthermore, multi-sensor metrology combines the speed of optical measurements with the accuracy and 3D capability of tactile measurements and, more recently, the ability to measure interior features using CT, offering new opportunities for fast and accurate measurements.

However, optical and CT measurements are often not traceable to the SI units and a measurement uncertainty estimation is very difficult due to many complex influencing factors. The need for more accurate measurements with tactile, optical and CT sensors is stressed by the Co-Nanomet Strategy Document “Nanometrology 2020” (2011). Additionally, the fusion and analysis of the data from different sensors is not a trivial task. The quantity and spread of data from the different techniques is not the same, which makes combining them difficult.

The Solution

In order to address the problem, this project developed metrological tools for 3D measurement of the geometrical features of microparts in a complete, accurate and traceable way by accomplishing the following objectives:

- Improve accuracy of tactile, optical and CT sensors
- Achieve traceability of optical sensors and CT with suitable reference standards
- Reduce computational effort and increase the accuracy of data processing by applying novel methods for data linking and reduction
- Strengthen the dissemination of developed metrological tools to industrial applications

Impact

The project improved the accuracy of measurements by improving the probes, and combining different sensors and measuring techniques. It developed reference samples which could be used in industry to improve calibration and measurement. It also combined results from different sensors and techniques to reduce uncertainty.

Three industry specific workpiece-like reference standards were calibrated and handed over to the industry partners to investigate the practical application of the metrological tools and techniques.

- **Bosch Cone standard**: Robert Bosch GmbH, a major supplier to the automotive industry, produces fuel injection systems.
- **Injection Needle**: In this case a real product was used as the reference standard, in form of a tiny insulin injection needle from the Danish healthcare company Novo Nordisk

- **LEGO connector**: An example of a plastic reference standard is a connector from the well-known Danish toy company LEGO, famous for their toy bricks.

Preliminary investigations into two other industrial examples demonstrated that manufacturers could go to the NMIs with confidence and develop reference samples that could be used in production.

- METAS carried out measurements on a part of the watch gear mechanism, a micro-wheel.
- A cornea artefact, developed by the Swiss healthcare company Haag-Streit, was calibrated at METAS.

During the project, several products which were particularly difficult to measure, were examined. The potential of the methodologies and techniques developed was demonstrated.

- PTB made first the CT measurements of a razor part, proposed by the Dutch stakeholder Philips, to demonstrate the benefits of this technique.
- VSL made multi-sensor micro-CMM measurements on a 5 GHz wave guide block, manufactured by the international industrial and manufacturing company VDL Groep. Results will be used to improve the manufacturing of these types of structures and test against specifications.
- The German company m2c is working with PTB on custom-made ‘designed roughness’ samples on different carrier materials, which will become commercially available in the near future. These require precise, traceable measurement.
- A laser fusion target called “Hohlraum” from the British Science and Technology Facilities Council (STFC) was measured with a tactile micro-CMM, a tunneling current sensor on a nano-CMM and with CT (synchrotron and industrial). This research object is a hollow cylinder with the outer diameter of 150 µm made from pure gold. The challenge was to carry out measurements on an object with wall thickness of only 30 µm.

2 Project context, rationale and objectives

2.1 Context

In our everyday life, more and more products contain parts of a couple of millimetres in size or even smaller, where smartphones are a good example because they contain a high number of sensors with small dimensions. Other industrial sectors also require miniaturisation of components. Car engines, for example, have highly sophisticated fuel injection systems to reduce fuel consumption and emissions. To this end, fuel injection pressures become higher which leads to ever tighter fabrication tolerances and higher demands on quality control for the parts. Improvement of metrological capabilities for measuring microparts is therefore important to addressing these challenges.

People with chronic diseases like diabetes need to inject insulin several times a day, and smaller diameter needles reduce the pain for users. Today’s insulin injection needles have outer and inner diameters of only 240 µm and 150 µm respectively (as a comparison, the diameter of a human hair is 80 µm). To guarantee that the same amount of liquid is flowing per shot, quality control needs to measure the inner diameter of each needle. Several billions of such needles are produced every year, and therefore reliable, traceable, and fast inspection methods are necessary.

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2.2 Scientific and technical objectives

The overall objective of the project was to develop metrological tools for the 3D measurement of the geometrical features of microparts in a complete, highly accurate and traceable way, and to disseminate information about these tools to industry. In order to achieve this goal, multi-sensor coordinate measurement techniques, covering tactile and optical sensors, and CT were studied. It also aimed to reduce measurement uncertainties significantly in the sub-micrometre range. The project objectives were:

Sensors and measurement systems including tactile, optical and CT probes

- Production of tactile probes with very small probing elements (diameter < 100 µm) for measurement of geometries that are currently not measurable by the existing probes.
- Enhanced accuracy of tactile probes by desirable and suitable methods to characterise and calibrate tactile probes in 3D, including full 3D mapping of the probing sphere, with uncertainties below 10 nm.
- Enhanced probing accuracy in industrial applications by investigating workpiece-probe interaction, friction and wear (e.g. roughness characteristics, material properties, surface layers, cleaning, coatings). The investigation regarding workpiece-probe interaction will also cover non-tactile probes.
- Development of numerical modelling to correct for systematic errors, and to enhance the accuracy of optical sensors and CT systems by optimising sensor parameters, with aim to achieve measurement uncertainties < 100 nm (optical sensors) and < 1 µm (CT).

Establishment of traceability, determination of measurement uncertainty

- Development of suitable methods and reference standards to achieve traceability for optical sensors and CT.
- Development of tools for reliable determination of task specific measurement uncertainty (e.g. by numerical simulation) in industry. This includes research on virtual instruments.
- Development of cooperative reference standards and calibration methods to assess the parameters of different sensors and to link the coordinate systems of the different sensors to each other, with reduced and established uncertainty.

Intelligent data processing

- Intelligent filtering of the large number of data points generated by optical sensors and CT systems, and methods for data reduction.
- Development of automated procedures for registration and fusion of measurement data from different sensors with unknown relative position and orientation. This will represent a substantial improvement over the existing methods that rely on manual operations.
- Development of correction procedures to reduce the measurement deviations of less accurate but volumetric sensors (e.g. CT) with measurement data of more accurate sensors (e.g. tactile probes).

Creating impact for industrial applications

- Demonstration of how different probes and technologies for 3D measurements can be combined and used in industry to characterise items for obtaining necessary information for controlling and optimizing production.
- Transferring the results to a wide community, e.g. by creation of Good Practice Guides and training activities.

3 Research results

3.1 Reduce the size and enhance accuracy of tactile probes

Over the last decade the main focus for micro coordinate measuring machines (micro-CMMs) research and development activities has been associated with the CMM probing systems. The detection mechanism of micro-CMM probes makes a major contribution to the probing error and uncertainty in micro-CMM measurements. However, in recent years, with complex miniature products being manufactured in increasing volume, research in the field of micro-CMMs has focused on shrinking the dimensions of the stylus system itself. Demand for dimensional metrology of miniature products, with dimensions below 50 µm, is increasing, and currently available stylus systems for micro-CMMs with diameters down to 125 µm are becoming unsuitable. It is a challenging task to shrink the tip diameters of stylus systems to 50 µm and below, as there is a lack of established development methods able to address the known scaling issues.

Therefore, at NPL, a set of design rules and design considerations for the development of a sub-10 µm stylus system was developed. Seventeen samples were manufactured using WEDG (wire electro-discharge grinding), OPED (one-pulse electro-discharge machining), ECM (electro-chemical machining) and micro-assembly (glass spheres on shafts manufactured using WEDG). Styli with tip diameters smaller than 10 µm were possible to manufacture (currently the smallest tip using this method is 8 µm, as demonstrated in this project and shown in Figure 1).

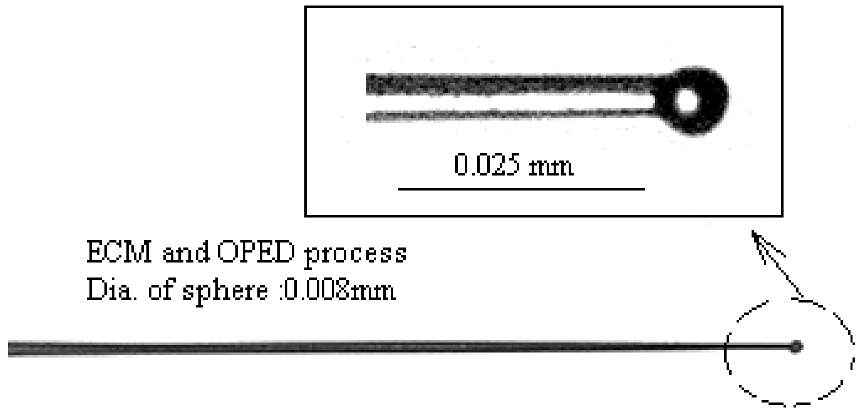


Figure 1. Test stylus manufactured combining the WEDG, ECM and OPED method, with a tip diameter of approximately 8 µm

Experimental methods to study the mechanical properties of new styli were developed at NPL and the stiffness and "maximum safe tip force" of the styli (the transverse force on the tip that causes initial plastic behaviour in the stylus) was investigated to determine the suitability of these new manufactured styli. The smallest probe diameter tested was 21 µm, which, as NPL concludes from the tests, is not currently useable on a majority of the existing probing systems, as the maximum safe force is similar to the probing force of many existing micro-CMM probing systems (hence, if used, the stylus will be irreparably damaged during use). Therefore, although NPL has demonstrated the ability to manufacture Ø < 10 µm probe styli, the conclusion is that further work is needed before these can be used in modern micro-CMM probing systems e.g. increasing the stiffness of the styli (particularly those manufactured using the hybrid process of WEDG, ECM and OPED), or decreasing the probing force of current micro-CMM probes. An article in a peer-reviewed journal was published based on the results of this study (Testing the Mechanical Characteristics and Contacting Behaviour of Novel Manufactured and Assembled Sphere-Tipped Styli for Micro-CMM Probes; Sheu D-Y., Claverley J., Leach R.; *Precision Assembly Technologies and Systems*, Vol 435, pp 15-21, (2014)).

At METAS several technologies have been investigated in order to build probes with smaller diameters than the typical 125 µm. For that purpose melted glass spheres, melted tungsten wires and electro-eroded tungsten carbide tips were considered. From all these technologies METAS identified the last one as the most promising one, as it combines many advantages: tungsten carbide is a very hard material with a high elastic modulus which enables the styli to have long shafts. The electro-erosion process enables manufacturing the probe sphere and its shaft out of a single rod and, thus, the weak spot from the glue or the solder between the sphere and the shaft is eliminated. The main disadvantage of this technology is the fairly rough surface finish achieved by electro-erosion. Therefore, a post-process-polishing procedure of the probe sphere was developed at METAS.

METAS designed and manufactured tungsten carbide probes with a diameter of 65 µm and 50 µm with a shaft length of 0.55 mm using EDM. A two-axis polishing setup was built for the post-process finish. The critical point is that the micro-probe easily breaks, thus an extremely weak force needs to be applied during polishing. For this purpose, a system on springs for centreless spherical polishing was conceived. Once polished, the probes were characterized in terms of surface roughness using an atomic force microscope (AFM) and in terms of the shape using a micro-CMM. They typically exhibit a very smooth surface (Ra < 5 nm and Rz < 40 nm) and a form deviation in the order of 250 nm (see Figure 2).

The manufactured probes are now being used for calibrating very fine structures such as watch micro-gears on the micro-CMM at METAS.

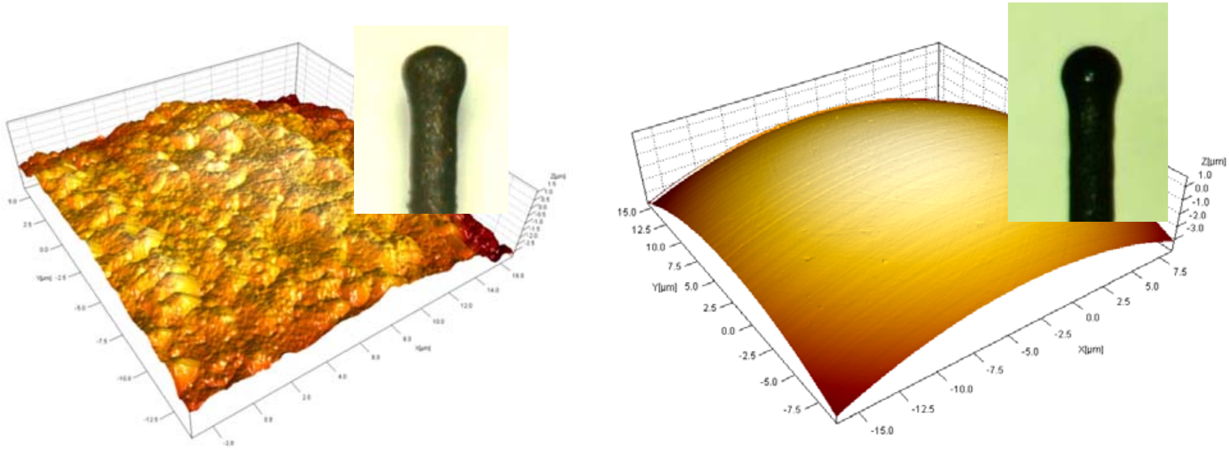


Figure 2. Left: Probe before polishing as manufactured by EDM. Right: Probe after polishing: Ø = 64 µm, sphericity = 250 nm, Ra = 5 nm.

Today, diamond coated probe tips are becoming commercially available. It is therefore interesting to know how the wear of these new tips compares to the known wear of traditional ruby tips.

For this study at METAS, the probe tip under test was fitted onto a micro-CMM and the CMM was programmed to scan in a circle on a flat, fine polished material surface. The probe tip thus contacts the material surface with always the same point creating after a while a worn facet. While scanning at constant speed, the deflection measured by the probe head orthogonal to the surface was kept constant in order to generate a constant normal load force. The deflection of the probe parallel to the surface, as measured at the probe head, enabled METAS to record the friction force at every point along the scan path. Due to stick-slip effects, the friction force varied locally but its average over a few millimetres along the scan path was reproducible. The probe wear, which appears as a local roundness deviation, was periodically measured by a scan on the equator of a reference sphere (diameter 1 mm) during the experiment in order to monitor the wear trend. Figure 3 shows the evolution of the wear depth and the friction when using a diamond coated probe. As expected, the wear of the diamond-coated probe was much smaller than for the conventionally used ruby spheres. The final wear depth is then also assessed by AFM measurements at the end of the experiment.

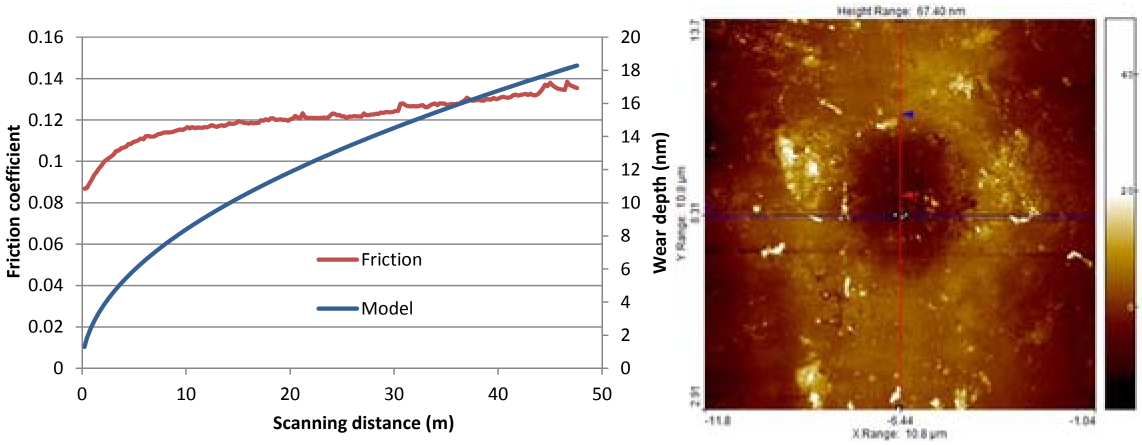


Figure 3. Left: Recorded friction coefficient and wear depth evolution as modelled using the facet diameter measured from the AFM picture seen on the right [8]. Measurement conditions: Scanning on hardened steel with a speed of 0.5 mm/s and a contact force of 1.4 mN.

The table below summarizes the benefits of using diamond coated probes instead of the conventional ruby probes.

Workpiece Material	Steel	Aluminium	Tungsten carbide
Improvement factor	x 1000	> x 4000	> x 10 to x 100

This has proven that despite their higher costs, diamond coated probes provide an improvement as they last much longer and save on calibration costs.

PTB currently uses a commercial micro-CMM F25 from Zeiss. In order to increase the accuracy of tactile probing, the behaviour of the F25 system equipped with a diamond-coated tungsten carbide probe instead of a ruby or silicon nitride probe was characterised. For that purpose tests were carried out according to ISO 10360 in scanning and single-point probing mode on two spheres with Ø = 2 mm and Ø = 10 mm. The probing error size and probing error form were determined for both measurement modes. The results of all tested parameters were significantly lower than specified by Zeiss, for example, the specified probing error for size from single-point probing MPE_{PSTU} was 250 nm, whereas for the sphere with Ø = 2 mm P_{STU} = 7 nm and for the sphere with Ø = 10 mm P_{STU} = 35 nm was achieved. This characterisation can be used for correction models of the complete probing system and to improve accuracy and reliability.

Additionally, at PTB a microprobe with an isotropic double beam configuration has been developed and characterized. The initial characterization of this probe was done with a test setup including a laser interferometer based displacement measurement system. With this non-calibrated setup a high repeatability of the measured results was achieved: the standard deviation of all measured points at a sphere was 6.1 nm, whereas the same measurements using a F25 diamond-coated probe resulted in a standard deviation of 32.4 nm. To determine the measurement accuracy a calibration routine using a reference sphere was developed, where some prior knowledge of the sphere and probe diameter was incorporated and crosstalk caused by the probing procedure was avoided. After that calibration the sensitivity coefficients were obtained by solving the system of linear equations. To further improve the calibration a subsequent slope depended correction was applied. This correction resulted in a mean deviation of 15.8 nm for 17 points at different locations of the sphere with multiple repetitions.

Additionally, the native tactile probe of the VSL F25 micro-CMM was characterized. The repeatability for single point probing was ~7 nm and the influence of the probing direction on the repeatability seemed to be negligible. However, a clear systematic anisotropy of the tactile probe, which has a similar pattern for different probes, was observed. Therefore, in order to obtain the best results for the probing correction, each probe needs its own full 3D characterisation. A procedure was developed at VSL using a 4 mm reference sphere. About 500 points have to be taken when characterizing a probe in order to have a data set, which is dense enough to be used to correct for all probing directions (Figure 4). The procedure to obtain these data points has been automated and can be easily adapted for different sizes of reference spheres. For optimal results the influence of the form deviation of the 4 mm reference sphere can be minimized by averaging the results taken from 4 measurements, where the reference sphere is rotated in steps of 90°. The scanning behaviour of the tactile native probe in the VSL F25 appeared to be unpredictable due to stick-slip effects. These arise due to the anisotropy of the probe. It is therefore advisable not to use this probe in scanning mode.

Additionally a non-native microprobe (Gannen XP by Xpress) was characterised by Xpress and integrated in F25. Although with the current setup the performance of this probe was worse compared to the native F25 probe, the obtained knowledge will help to improve the probing characteristics using a non-native probe.

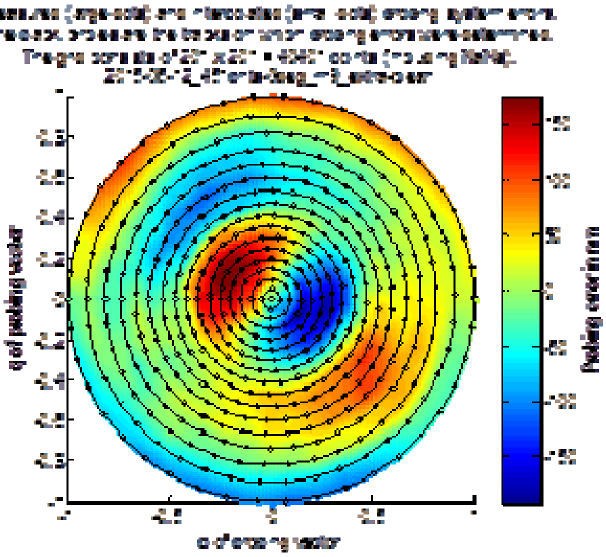


Figure 4. Measured (dots) and interpolated (colour) probing system errors derived from the measurement on the 4 mm reference sphere. About 500 points were taken to enable good interpolation.

METAS completely re-characterized the probe head of its micro-CMM. In order to improve the calibration, 3 SiN spheres with low form deviation (< 21 nm) were used. The comparison between the old calibration performed in 2005 and the new one agreed within 7 nm, proved the long term stability of the METAS micro-CMM. A new calibration procedure for scanning was also introduced. It is much more immune to dust particles and residual surface roughness of the calibration and probe spheres. It does not significantly lower the measurement uncertainty budget of the machine, but renders the calibration procedure less critical and makes it quicker.

The measurement comparison, organized among the partners of this project, was designed to demonstrate the level of accuracy achieved by the different tactile measurement systems. The measurement task was inspired by the acceptance tests described in ISO 10360-4 and -5. An artefact was built by METAS, the pilot lab of this round robin. The measurements included single point probing at 25 specific locations as well as scanning measurements along 4 paths in forward and backward direction on a Ø = 4 mm ruby sphere. All partners had to use exactly the same coordinate system in order to probe the sphere in exactly the same locations and also to have a common representation of the results.

For the single point average diameter, a relative good agreement was found between all participants. For the scanning measurements, only the scans along the equator indicated similar form deviations; the other scans showed considerably higher deviations. The scanning measurements also revealed problems with respect to the forward-backward repeatability. However, when all scanning results were combined to determine average scan diameters, the agreement was again very good (Figure 5). In single point mode, the deviation between the highest measured diameter (participant 3) and the smallest measured diameter (participant 2) was of only 72 nm. This difference, however, surpasses the sum of the combined standard uncertainties of both partners, i.e. their uncertainties do not overlap by 21 nm. Regarding the scanning mode, only participant 1, participant 3 and participant 4 participated. Here, a maximum difference of 152 nm between the measured diameters was obtained and the non-overlapping of the respective error bars was of 102 nm.

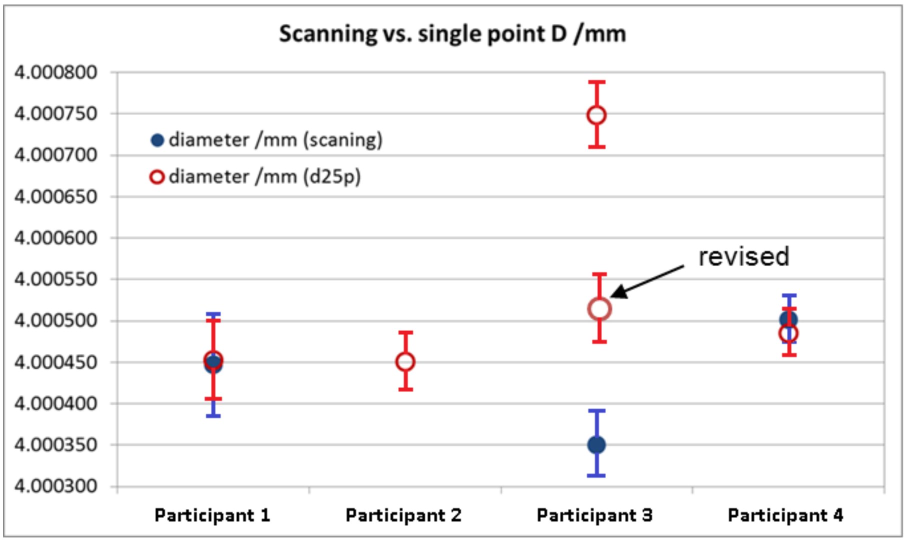


Figure 5. Comparison of scanning and single-point diameter among the participants. The error bars represent the uncertainties at a confidence level of 95% (k=2).

For microparts the adverse effects of probe contamination grow, however cleaning of microprobes is a challenging process. The topic of a Researcher Excellence Grant of UNOTT was the development of a suitable method for removing contaminant from micro-CMM probes. A review of the state-of-the-art cleaning methods for microparts has been made. From this review a list of procedures potentially suitable for cleaning of micro CMM probes was produced and the methods were further evaluated. This has included the development of repeatable methods for styli contamination, and the design and production of a cleaning stage with integrated force measurement for determining contact forces on the probe system during cleaning. Following this a series of experimental investigations have been conducted into the cleaning efficacy and cleaning forces imparted by 1) mechanical action and 2) CO_2 snow cleaning methods. The results of these experiments have shown CO_2 snow cleaning to be an effective and low force cleaning method for small diameter < 500 µm CMM styli, with cleaning forces in the same order as measurement forces for typical micro-CMM. This is an order of magnitude reduction in cleaning force compared to mechanical cleaning methods. This work has also led to a number of developments in the snow cleaning method to improve its applicability to micro-CMM styli – reduced gas pressure and reduced flow diameter by use of a significantly reduced orifice diameter, and reduced net force from the gas flow from a balanced multi-nozzle approach. This has been demonstrated experimentally to provide effective cleaning on all faces of the styli, and minimise the risk of damage. This stage of work has led to three conference publications, a publication in a trade magazine, Commercial Micro Manufacturing, and a journal publication currently under review.

Alongside the development of novel cleaning methods the project has pursued a greater understanding of the contamination mechanism in tactile CMM probing. UNOTT surveyed project partners to identify areas of application and based on this developed an experimental series to investigate the effect of part and stylus conditions on contamination rate. An initial enquiry was performed on a range of industrially relevant parts, later followed by a systematic study of variables of contact pressure, surface roughness and surface morphology, i.e. machining fingerprint. Experiments were conducted on two CMM systems: (1) a Mitutoyo CMM Euro-C-A121210 equipped with Renishaw TP200 low force probing module and (2) Zeiss F25. Controlled sample contamination, repeated probing, and quantification of contamination were conducted. From this a guideline document has been produced on the relationship between contamination rate and number of contacts, machining process, surface roughness, and contact pressure. Initial findings suggested the contamination process during probing is highly stochastic in nature and large variance is present in the data. Further to this, the study was extended beyond the original proposal in order to increase the statistical significance of the data. To support this extended investigation UNOTT developed and demonstrated a method of styli contaminant imaging that can be applied in-situ as part of the CMM operation. This presented a number of challenges – typically CMM styli tips are formed from ruby spheres, which with their high surface curvature, transparency and specularity, are a significant challenge to image optically. Through a combination of image stacking and controlled lighting conditions those challenges have been effectively overcome. A video demonstrating the developed device working with a Mitutoyo CMM Euro-C-A121210 was made available for distribution, and UNOTT delivered training to JRP partners (METAS, VSL, NPL, PTB, LU, IBSPE) regarding the developed stylus cleaning and inspection methods in May 2016. The in-situ inspection device was then used in the extended experimental study on contamination build-up. A presentation at the Microparts workshop and a conference publication has been produced on this subject, and a journal publication is currently under review.

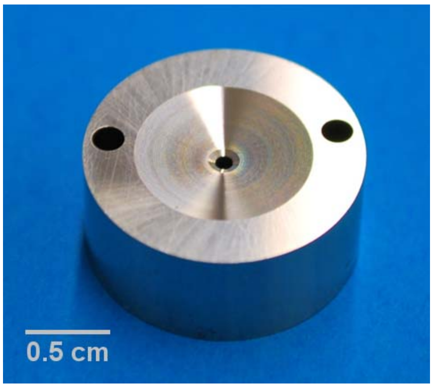
The results of the extended study confirmed the previous finding that contamination process during probing is highly stochastic in nature, however a small positive correlation between contamination rate and increasing contact pressure was found. The influence of machining process and surface roughness (Ra from 0.8 µm to 3.2 µm) was not found to be significant.

Key research outputs and conclusions

New probes were developed and fully characterised in terms of their size and shape, and measurement and calibration is now possible for much smaller structures. Diamond coated probes were tested e.g. on aluminium samples and the wear was found to be 4000 times lower than for conventional ruby probes, making them more cost-efficient than expected. Low force cleaning methods and low cost inspection methods for micro-CMM styli have been developed and successfully tested. This is important to support the use of the new, smaller (< 100 µm) probes and for tactile measurements with high accuracy because absolute cleanliness of the probe stylus is essential. In summary, the small probes developed in the project will allow measurement and calibration services to be extended for the benefit of end users and the knowledge on wear of probe tips will help to optimise the costs and save time needed for probe characterisation. Better understanding of micro-CMM behaviour will enable measurements with higher accuracy.

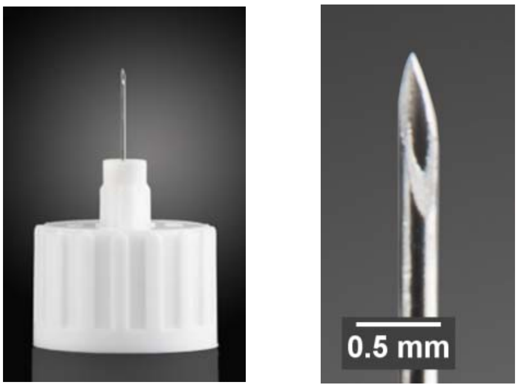
3.2 Enhance accuracy of optical and CT sensors

In order to achieve traceability for optical and CT measurements, four different workpiece-like reference standards have been produced and a tactile calibration of three of these standards has been completed. As reference standards a cone standard from automotive industry, a plastic connector from toy industry, a needle for insulin injection from healthcare industry and a laser target (hohlraum) for laser fusion experiments have been selected (**Error! Reference source not found.**) by the consortium. These standards are made of different materials and represent a large variety of measurement tasks on microparts such as lengths, small diameters, cone angles or radii. The tasks are challenging due to the small feature sizes or wall thicknesses, and limited accessibility of the geometries to be measured. Partners have successfully decided on the measurement strategy for each workpiece and have carried out measurements on these standards with tactile and optical sensors, as well as with industrial CT. In addition, two standards (injection needle and hohlraum) were measured with synchrotron CT at BAM’s synchrotron facility.

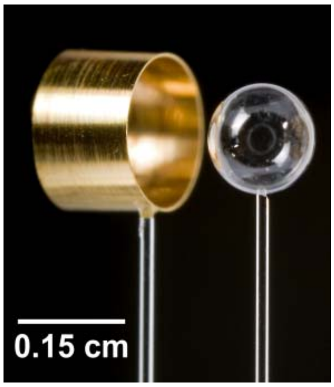


a) Cone standard from automotive industry provided by BOSCH

b) Connector standard from toy industry provided by LEGO



c) Injection needle from healthcare industry provided by Novo Nordisk



d) Hohlraum standard from laser fusion research provided by STFC

Figure 6. Selected workpiece-like reference standards.

The calibration and measurement results were further used to asses the measurement uncertainty for similar workpieces as a part of end-user demonstrations. The demonstrations have transferred project results to the project partners, who are end-users of measurement technologies for microparts in different industrial fields and allowed industrial partners comparing their measurement results with reference values to increase the accuracy of their optical and CT measurements.

The progress, particularly in the field of optical and other surface measurement techniques, drives the demand for a reduction of measurement uncertainty, which requires, among others, a better understanding of the instruments' measurement properties including their roughness-related measurement errors. In order to allow systematic investigations of these effects, one of the aims in this project was the development and test of reference samples with a precise well-defined surface texture (aim: field size of 300 µm x 300 µm) both on flat substrates as well as on different curved bodies. Here, cylinders and spheres (diameter ~1 mm), which can be mounted under different angles in surface measurement instruments were used. While a large variety of roughness standards is commercially available for classical stylus profilometers, most of such samples are not suitable for high-resolution optical surface measuring techniques, such as confocal laser scanning microscopy (CLSM) because the surface texture should contain adequate higher-frequency components to check the resolution of optical techniques. Moreover, most of the available samples show a unilateral roughness and therefore cannot satisfy the requirements of areal surface measurement techniques, which require, at least in addition, roughness standards with angular isotropy. Additionally, many of the surface treatment techniques, conventionally applied to create the roughness, can hardly or not at all be used at curved surfaces, as, e.g., the envisaged cylinders and spheres of about 1 mm in diameter. Furthermore, they yield only certain types of roughness, i.e. they do not allow creating roughness flexibly. Therefore, focused ion beam (FIB) technology was used.

FIB technology is known to be a reliable tool for defined local surface modification on the nanoscale and therefore a promising technique to "write" a predefined texture on a point-by-point basis onto the surface and thus create fields of roughness in the Sq-range of interest. For surface texture creation by FIB, it does not matter, whether measurement data of a real surface or artificial surfaces, with a mathematically defined roughness model, are used. PTB has started with measured topographical data from rough surfaces, which have already been proven to be suitable for a number of measurement instruments. As AFM provides the highest-resolution topography images, AFM images were chosen for this purpose. The model topography data was converted into control commands of the FIB instrument by a developed automated procedure. Starting with small roughness areas of 27 µm x 27 µm for test purposes to fine-tune the FIB parameters, the size of the fields has been increased up to about 180 µm x 180 µm without the need of stitching FIB writing fields.

In order to achieve the target in this project to produce roughness fields of about 300 µm x 300 µm also on curved surfaces, an idealized surface model (e.g. symmetric height distribution, adjusted lateral and vertical scales) of a roughness with Sq = 123 nm and Sz = 1420 nm was developed as input for the FIB process. Additionally, stitching of FIB writing fields was implemented, as it turned out that such large fields cannot be written at once with the necessary resolution. With the FIB machine at hand (FIB Helios Nanolab 600), stitching of 2x2 fields of 145 µm x 145 µm was the best option to obtain a total field size of 290 µm x 290 µm.

Special steps, such as the use of alignment marks, helped to partly reduce the occurring FIB stitching gaps, but it was not possible with the available resources to eliminate the gap completely (Figure 8). The key parameters of the FIB-roughness on flat substrates agree within a few percent to the design values and are not significantly influenced by the gaps.

For the creation of roughness field on curved surfaces a Cu wire with *r* ~ 400 µm as a cylindrical body and hard metal spheres with *r* ~ 600 µm were chosen, and subsequently coated with a Ni[P] layer, followed by ultra-precision polishing in the scientific instrumentation workshops at PTB. This resulted in a smooth roughness about 10 times smaller in amplitude than the roughness to be written by FIB.

Figure 7 shows the roughness fields of 290 µm x 290 µm created on a flat Si chip, the polished Ni[P]-coated Cu wire and on a polished Ni[P]-coated hard metal sphere. Investigations by CLSM (Olympus LEXT) and AFM (SIS Nanostation II) reveal that the key roughness parameters agree with the FIB input data model to within 10 % to 20 % for the curved surfaces. It needs to be taken into account that the process chain for this comparison is rather long: the input data is converted and used for the FIB process (FIB artefacts), the carrier material is curved, leading to FIB effects caused by curvature, form deviations and waviness, and finally, also the measurement instruments, even the reference instruments used here, introduce some further artefacts for the same reasons.

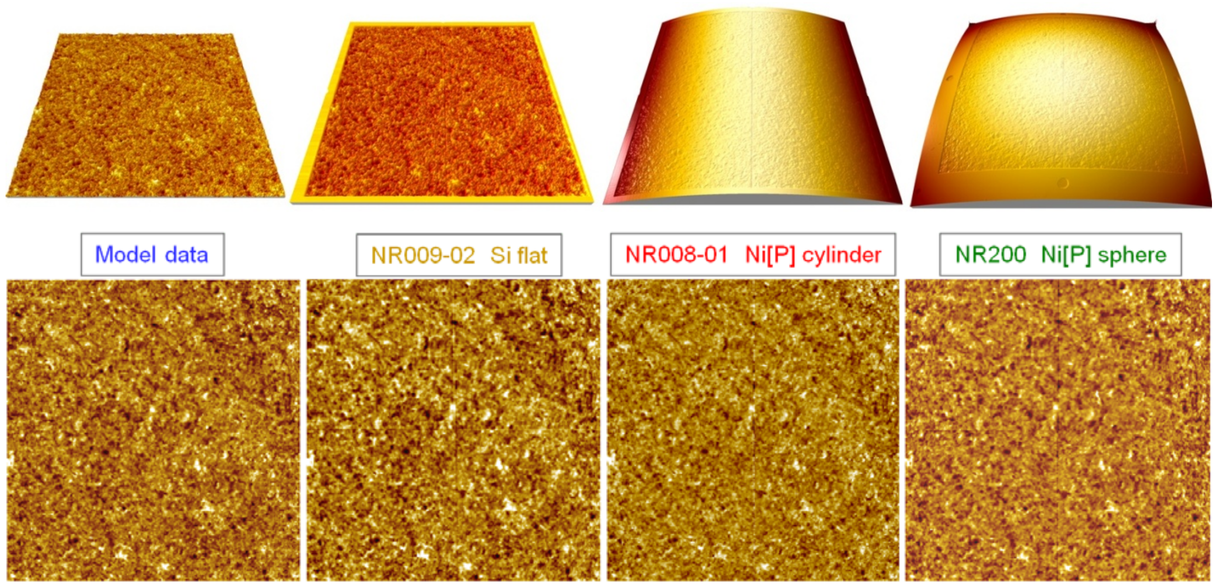


Figure 7. Fabrication of a roughness field of 290 µm x 290 µm on different carrier materials by FIB-Milling. From left to right: model data used as input; the 290 µm x 290 µm roughness field written into a flat silicon chip; into the Ni[P] coating of a Cu wire of 400 µm radius; into the Ni[P] coating of a hard metal sphere of 600 µm radius. Upper row: 3D views (left image model data, all other images recorded with the Olympus LEXT CLSM; Bottom row: The same images after form subtraction and waviness elimination, all of them with the same colour coding (black-to-white equals 1 µm in height).

The great advantage of these samples is that they allow comparing measurement capabilities of various surface measurement microscopes at the same marked field. Figure 8 gives an example of such a study involving one AFM and three different optical surface measurement techniques and instruments. While in this case the first three measurement instruments agree fairly well, both in their imaging properties and the deduced main roughness values (by some percent), the fourth instrument yields values about 30 % higher and does not allow to distinguish the higher-frequency components of the roughness.

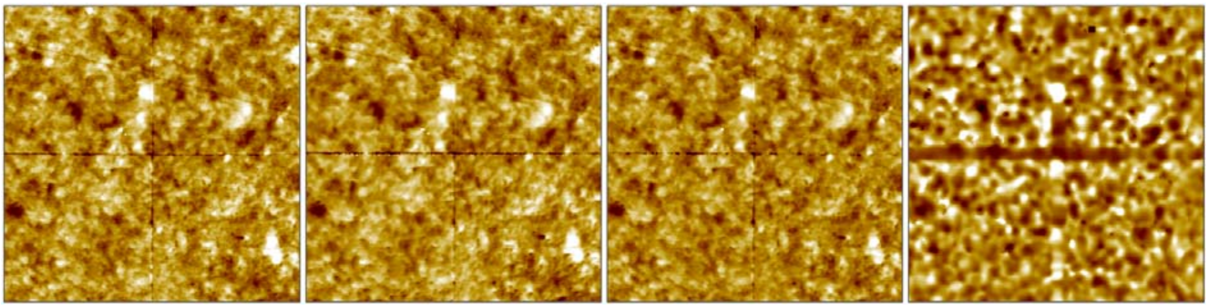


Figure 8. Central section of the roughness field produced by FIB measured with 4 instruments for comparison. All images size 100 µm x 100 µm with the same colour coding of height (1 µm dark-to-bright) for better comparability. From left to right: SIS Nanostation II AFM, Olympus LEXT CLSM, Zygo NewView white light interference microscope, Alicona G4 Infinite Focus (focus variation).

The results of optical measurements are known to be influenced by characteristics of the measured object, such as roughness. To evaluate the impact of roughness on optical measurements, two of the objects with defined roughness manufactured by FIB and two additional test bodies (contour standard manufactured by wire-EBM and a plate with balls which were roughened by etching) were used at PTB. Measurements were carried out with a focus variation microscope (FVM) and a coherence scanning interferometer (CSI) using different magnifications as well as different settings for oversampling and extended scan range. The tilt angles for the FIB-objects reach from 0 ° to 35 °.

The contour standard has a constant roughness and was measured under altering conditions, whereas the ball plate has a variable roughness and the measurement parameters were kept constant. For the evaluation several quantities were defined, like maximum measurable angle and measurement error (comparison to the calibrated value). As an outcome, for objects with larger roughness larger maximum angles could be measured with both instruments, whereas higher accuracy was observed for the CSI. The impact on the measurement error or form error was found to be negligible as long as a proper measurement mode was selected.

PTB, NPL and Researcher Excellence Grant of LU have independently observed that measured roughness parameters for, e.g., focus variation microscope (FVM) vary with the tilting angle. However, there was little definitive and exhaustive work carried out to determine whether this variation is reproducible across a range of samples. The partners therefore have concluded that the use of one roughness parameter *Sq* is not sufficient to determine the complete effect of the measurement of rough surfaces at high slope angles.

Additionally, it was concluded by LU that tilting the surface will change the composition of the apparent surface, regardless of the technique used, and any lack of knowledge of the true path of the light when interacting with a rough surface, especially one that is tilted, will result in a lack of knowledge of the geometric properties of the resulting calculated surface. Therefore, further work was carried out to understand and interpret optical data collected from the measurement surface and to model the interaction of light with a surface.

In order to quantify the effect of surface characteristics on optical measurements a better understanding of the interaction of the light with the measured surface and creation of more realistic models of the measurement process for optical instruments is desired. Accurate theoretical and numerical investigation of metrological problems in the cases of high aspect ratio surfaces, i.e. where multiple scattering of the incident light takes place, is not possible without using rigorous models for light scattering. Researchers from LU with support from NPL have worked out an improved high-order non-linear surface scattering model to simulate the measurement behaviour of optical sensors. A solver, based on the boundary element method (BEM) for rigorous calculation of light scattered from high aspect ratio surfaces, has been implemented. With this solver the output of surface measurement instruments, including CSI, confocal microscope and FVM has been modelled. In this way the instrument's response to rough surfaces has been rigorously computed for the first time.

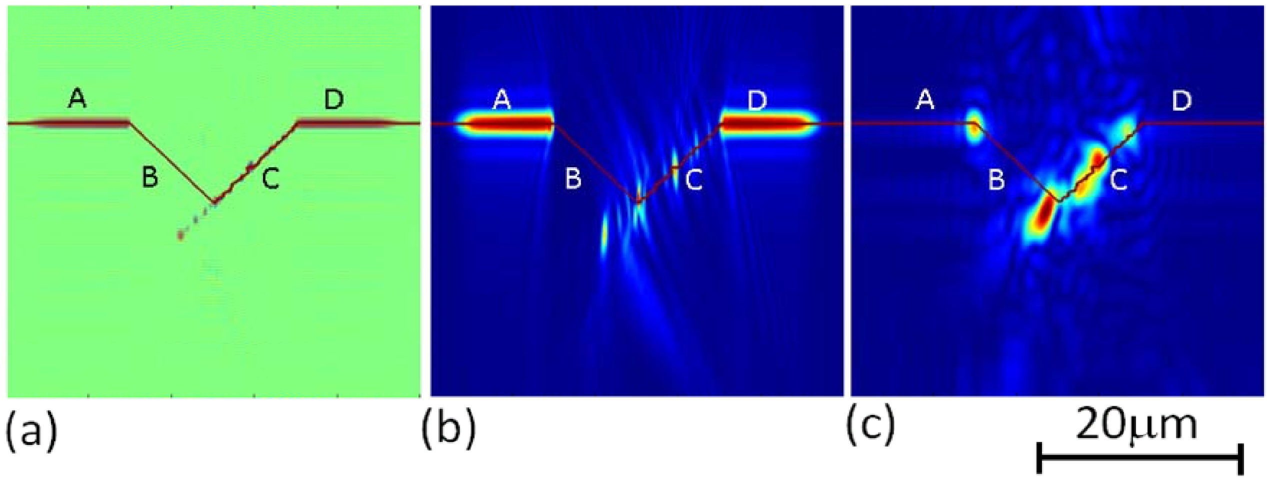


Figure 9. Results of simulation of optical sensors by LU using an improved high-order non-linear surface scattering model. Simulated outputs from: (a) CSI, (b) Confocal Microscope (CM) and (c) FVM. The red line is the real profile of the measured surface.

For the case of FVM, image formation has been considered from first principles. The theory developed by researchers from LU explains why surface roughness experimentally measured with FVM by PTB and NPL is found to depend on surface tilt. This work was published in a peer-reviewed journal (The Focus Variation Microscope: Linear Theory and Surface Tilt Sensitivity; N. Nikolaev, J. Petzing, J Coupland; *Appl Opt*. 2016 vol 55(13)). Additionally, a new method of analysis for optical instrumentation that fully takes account of multiple scattering to find the deviation from ideal form has been developed by LU. The method sequentially improves surface estimates and was shown to reveal the position of the vertical wall of a step feature.

It is becoming critical to measure the spherical form of stylus tips used on micro-CMMs, as the spherical form error of the stylus tip is a significant limiting factor to the accuracy of the micro-CMM itself. However, there is a very limited number of traceable measuring instruments that are able to measure the form error of spherical stylus tips with diameters less than 300 µm. CSI was used to facilitate stylus tip characterisation through the use of a calibrated spherical micro-CMM reference artefact. To realise calibration of the commercial CSI instrument, the 3D spatial frequency response, or Transfer Function, needs to be determined. Currently, there are very few universally-accepted methods available for determining the spatial frequency response of these instruments. Through extensive analytical modelling, NPL determined that one of the main suggested calibration methods is unable to fully determine the Transfer Function of the instrument, and suggested several solutions to this problem. Regardless of the known limitations of CSI instruments due to the inability to determine the 3D spatial frequency response, a strategy for the measurement of micro-spheres with diameters approximately 300 µm was developed. Using a stitching and self-referencing technique, 36 measurements taken over the top 60 degrees of spherical reference artefacts (mounted on flat datum surfaces) were combined to create a surface map. To investigate the uncertainty in the measurement of these reference spherical surfaces, simulations of the measurement result were run which show that the limited set of spatial frequencies passed by the CSI instrument can lead to errors in excess of 200 nm for surfaces with curvature. In addition, a method that takes the uncertainty in the amplitude and phase of each element of the transfer function and provides the upper and lower limit on the location of the surface provided by the Frequency Domain Analysis (FDA) method was determined. This provides an idea of the level of accuracy that the spatial frequency components must be known to in order to reproduce curved surfaces well. From this work, it was concluded that an uncertainty budget cannot yet be constructed for surfaces with curvature (such as those used in the Microparts project) based on first principles. Although certain errors can be estimated, such as the metrological characteristics of the CSI instrument, and the stitching errors of the spherical caps, the underlying uncertainty of the topography determination step is a major contribution which cannot yet be quantified. This work from NPL resulted in 2 publications in high impact journal and the third publication was recently submitted.

To enhance the accuracy of CT-based sensors, measurements on calibrated workpiece-like reference standards were conducted by BAM, PTB and other partners with industrial CT systems. Additionally, BAM has made measurements of two workpiece-like reference standards at the synchrotron facility BESSY II. The comparison of the measurement results for one workpiece-like reference standard (injection needle) shows a good agreement between the values measured on the industrial CT data and on synchrotron data (see Figure 11). The results of this comparison were presented by PTB at the 16th euspen conference.

DTI has led a round robin of two micro-tetrahedrons (i.e. four spheres forming a tetrahedron) with a sphere diameter of 500 µm on CT systems of different partners. This was done to study the specific measurement characteristics using various parameters on different CT systems. The participants have delivered results, which agreed to within 2 µm compared to a synchrotron CT reference measurement.

Six existing reference standards to correct systematic errors of CT were proposed by PTB in agreement with other partners. These standards embody calibrated lengths based on regular geometries. With the help of some of these reference bodies task-specific correction of systematic errors due to magnification errors and distortion was applied for the CT measurements of workpiece-like reference standards made at PTB during the project.

Additionally a reference standard for determination of the structural resolution has been developed by Researcher Excellence Grant of FAU with support from BAM. This standard helps to characterise the structural resolution of a CT system and therefore to adapt the virtual CT (simulation) accordingly. The structural resolution is obviously an important influence factor for measurements of microparts. The standard can also be used to determine the structural resolution of tactile and optical sensors. This work was presented at the SENSOR+TEST 2015 conference (CT measurements of microparts: Numerical uncertainty determination and structural resolution; M. Fleßner, M. Blauhöfer, E. Helmecke, A. Staude, T. Hausotte).

FAU has developed a model for numerical uncertainty determination and verified it using the results of the experimental uncertainty determination. Consistent results were obtained for the measurement tasks, where little or no artefacts are present. For measurements with severe artefacts, e.g. streak artefacts in measurements of the connector part, there were still some discrepancies. It was concluded that the numerical approach for dimensional measurements on simple workpieces made of one homogeneous material is a reasonable alternative to the uncertainty determination according VDI/VDE 2630 Part 2.1. This work has been presented at the iCT conference 2016 and a paper in the conference proceedings is available (Numerical measurement uncertainty determination for dimensional measurements of microparts with CT; E. Helmecke, M. Fleßner, M. Kaufmann, A. Staude, T. Hausotte).

A method to identify the local (single point) uncertainty of the surface dataset of a CT measurement has been developed by FAU. This method delivers information about the impact of error sources at the local scale and helps to adapt the measurement task to minimize this impact. This work has been presented at the iCT conference 2016 and a paper in the conference proceedings is available (Assessment of the single point uncertainty of dimensional CT measurements; M. Fleßner, A. Müller, D. Götz, E. Helmecke, T. Hausotte).

Key research outputs and conclusions

Workpiece-like reference standards were produced for better monitoring of three manufactures production processes. The new reference samples were based on the produced parts: a needle, a cone and a LEGO connector. They incorporated features from real parts and represent a large variety of measurement tasks on microparts such as lengths, small diameters, cone angles or radii. The trials of these reference standards transferred project results to the project partners, who are end-users of measurement technologies for microparts in different industrial fields. The availability of calibrated parts will enable the industrial partners to compare their measurement results with reference values and increase the accuracy of optical and CT measurements at their site. The different test samples were measured using tactile and optical CMM, as well as CT, to compare the results from different machines and from the same type of machines, placed at different laboratories. The dependency of measurement deviation on roughness of the sample surface was determined experimentally and was used to achieve traceability of measurements with optical sensors. The workpiece-like reference standards developed in the project allowed the end users to perform traceable measurements of similar parts and to improve and accelerate their quality control processes. Better knowledge of systematic errors and error sources for CT and optical measurements enabled error reduction and correction, leading to more accurate measurements.

3.3 Task-specific uncertainty determination

To increase the accuracy of optical and CT measurements and to achieve traceability a systematic error correction is essential. Measurements with optical and CT sensors are influenced by many complex factors, so that the uncertainty budget cannot be easily formulated. Therefore, measurements on workpieces with known geometries are necessary. To this end, calibrated workpiece-like reference standards were used to determine the uncertainty of CT and optical measurements by a method based on approaches for CMMs in ISO 15530-3. The influence of the most relevant measurement parameters on the uncertainty was investigated and methods for estimating their contribution to the uncertainty were developed.

The first standard selected for an estimation of the uncertainty of real products was the LEGO connector. The connector was calibrated using a tactile CMM by FAU, and afterwards 20 CT measurements were repeated at FAU and LEGO. The uncertainty estimation was carried out according to the VDI/VDE Guideline 2630-2.1 and the following contributions were taken into account:

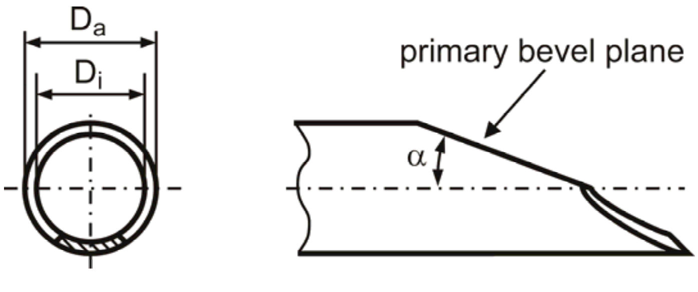
- Standard uncertainty of the calibration procedure $u_{cal,}$ which was calculated from the uncertainty of the calibration U_{cal} as $u_{cal} = U_{cal}/k$, where $k = 2$
- Standard uncertainty of the measurement process u_p (standard deviation calculated from 20 CT measurements of the part)
- Systematic error b, which is the difference between the mean value of repeated CT measurements and calibrated value

Therefore the estimated uncertainty U is calculated in the following way

$$U = k \cdot \sqrt{u_{cal}^2 + u_p^2 + b^2} = 2 \cdot \sqrt{u_{cal}^2 + u_p^2 + b^2}$$

The observed measurement uncertainties of the tactile calibration and CT measurement were of a high significance (several µm). One identified reason for the uncertainty of the CT measurement was the fixture of the part, which introduced artefacts to the surface determination. To reduce this uncertainty, it was proposed to redesign the fixture in future, as better accessibility allows using shorter probing shafts for the tactile measurements and a larger geometric magnification for the CT measurements. The usage of the connector part to estimate the task-specific uncertainty budget of a CT scan of equivalent LEGO items resulted in a higher accuracy and smaller uncertainty formulated for the CT measurement at DTI. LEGO is using the results for an evaluation of existing measurement procedures and protocols.

Another reference standard for uncertainty estimation was a calibrated injection needle. The tactile reference measurement was carried out by the collaborator Werth Messtechnik using two 3D fibre probes. The calibration results and the estimated expanded measurement uncertainties U are listed below.



Outer diameter: $D_a = (238.05 \pm 2.50)$ µm

Cone angle: $\varphi_{cone} = 0.35\,° \pm 0.036\,°$

Inner diameter: $D_i = (154.07 \pm 0.9)$ µm

Bevel angle: $\alpha = 10.81\,° \pm 0.092\,°$

Figure 10. Detailed view of the tip of the injection needle with relevant measurement tasks and result of calibration. The shape of the needle is conical, and the cone angle φ_{cone} is defined on the outer surface of the needle.

Three measurements with industrial CT (1: PTB, 2: Industrial partner, 3: PTB) and one measurement with synchrotron CT by BAM were carried out. Additionally, PTB measured the calibrated needle with an optical instrument (focus variation microscope). The results are shown in Figure 11.

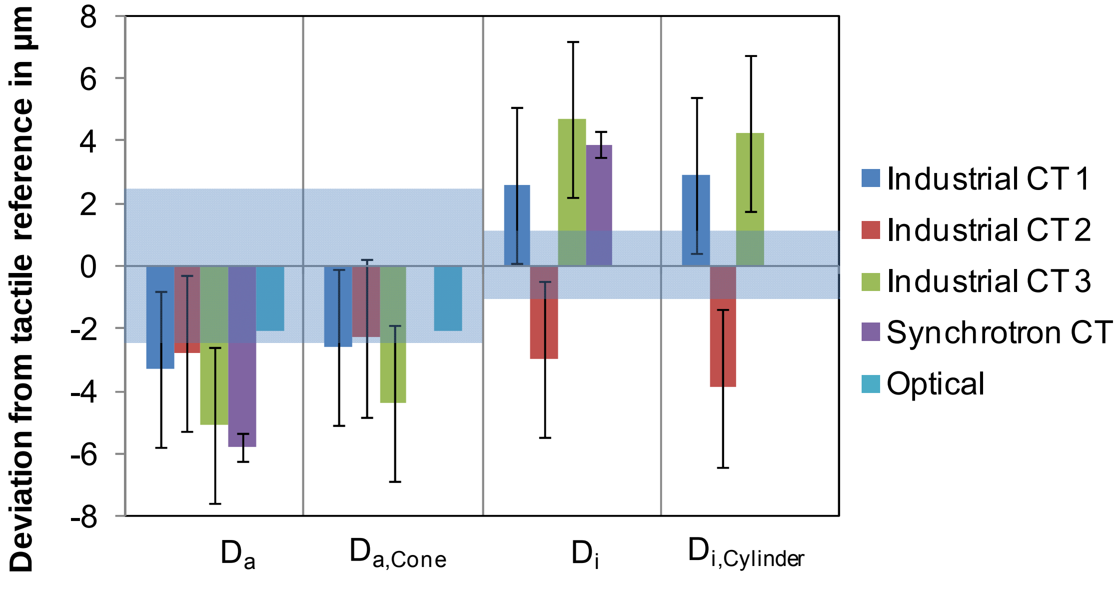


Figure 11. Differences between the non-tactile measurements and the tactile reference measurement at the injection needle (uncertainty of the tactile reference measurement is shown in light blue; error bars indicate the estimated uncertainties of corresponding methods).

With the synchrotron CT only the tip could be measured, therefore no results for the inner diameter were collected. The optical measurement included only the outer surface of the needle. The estimated uncertainties of the diameter measurements were based on experience in measurements at objects with equivalent measurement requirements. The outer diameters were measured smaller than the tactile reference measurement and the inner diameter were enlarged: that was likely caused by the comparatively large probing sphere used. The reason for smaller inner diameter measured with industrial CT 2 needs to be investigated.

Additionally, Novo Nordisk and DTI carried multiple measurements of non calibrated needles together with a calibrated one. A detailed uncertainty budget according to VDI/VDE 2630-2.1 was developed by Novo Nordisk based on the tactile reference measurement and their CT measurements. After the uncertainty determination, the E_n value according to ISO 15328 was calculated to evaluate the metrological compatibility of the results. All E_n values were significantly smaller than 1 and have shown that CT measurements and tactile calibration were compatible within their uncertainty limits. The calibrated workpiece-like reference standard therefore allows the uncertainty estimation for multiple parts at the same time and significantly reduces the scanning time for the quality control and tolerance verification.

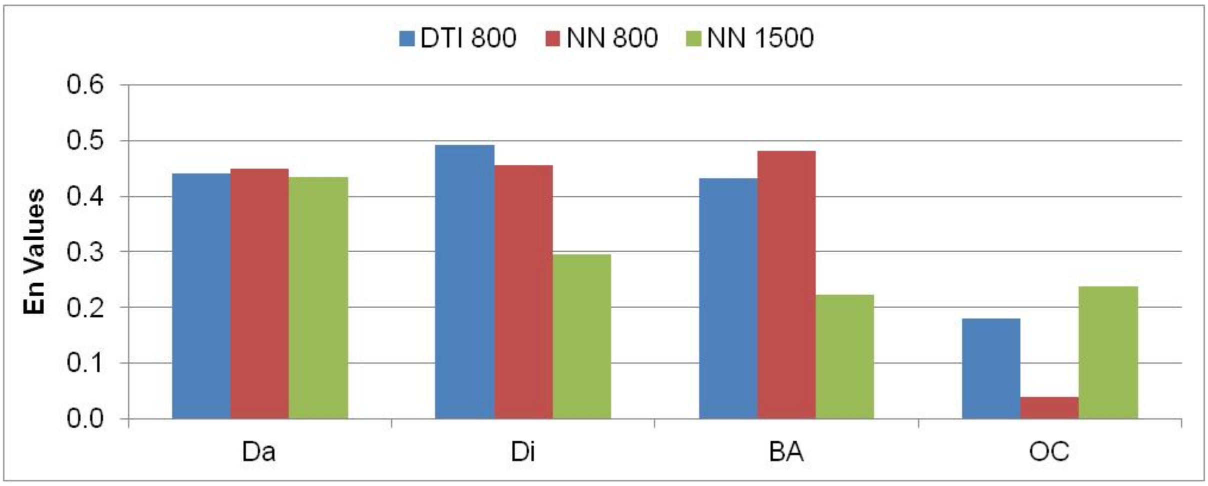


Figure 12. E_n-Values of the measurements of the calibrated needle carried out by DTI and Novo Nordisk for different CT systems. Da denotes the outer diameter, Di denotes the inner diameter, BA denotes the bevel angle and OC denotes the outer cone angle. The E_n value should be smaller than 1 to ensure metrological compatibility of the results.

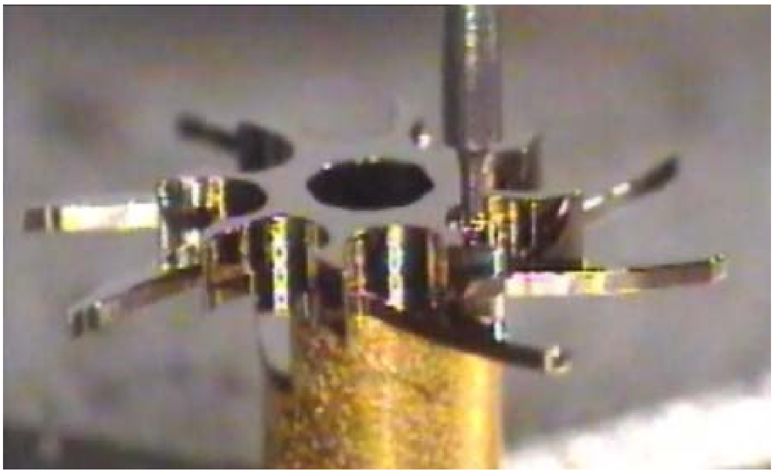
At VSL, several functionalities were added to the virtual micro-CMM which models the F25 micro-CMM. An improved numerical model of the tactile probe was implemented, where the perceived probe radius error is modelled to be dependent on the probing direction. Additionally, independent, systematic and correlated uncertainties, arising, e.g., due to asphericity of the probe as well as anisotropic probe deviations are taken into account.

A model for the optical vision probe was implemented at VSL and the uncertainty of linking was added. A numerical model was created, which adds a translation vector $\Delta x_{opt\text{-}to\text{-}tact}$ to the points $x_{opt,iexpressed}$ in the coordinate system related to the optical probe in order to obtain them expressed in the coordinate system related to the tactile probe, i.e. $x_{opt\text{-}in\text{-}tact,i}$, where

$$x_{opt\text{-}in\text{-}tact,i} = x_{opt,i} + \Delta x_{opt\text{-}to\text{-}tact} .$$

At METAS a task specific uncertainty determination based on a virtual micro-CMM model and Monte-Carlo simulations was developed, which can be applied to complex dimensional parameters of measured objects. The developed method was successfully applied in a stakeholder application. The micro wheel, is a relevant example of the new technologies and new design freedoms that are being introduced by watch makers. The functional zones of this wheel, namely the teeth end and their centring respective to the wheel axis, are the main features to be measured using the micro-CMM from METAS.

The tooth end is composed of 5 different radii of curvature with tangential boundaries. The measurement consisted of scanning the wheel profile (Figure 13) and performing a best fit for each tooth profile with the parameterized model shape. For the fitting, a LabView executable was programmed and directly integrated into the METAS CMM measurement software (Quindos). One can easily understand that giving a measurement uncertainty for the fitted parameters of the measured shapes is not straightforward. Therefore, a series of simulated measurements using a newly developed Monte-Carlo tool was conducted at METAS. Since the simulation is based on realistic variables of the METAS micro-CMM, a measurement uncertainty could be extracted for each measured parameter, here the tooth radii.



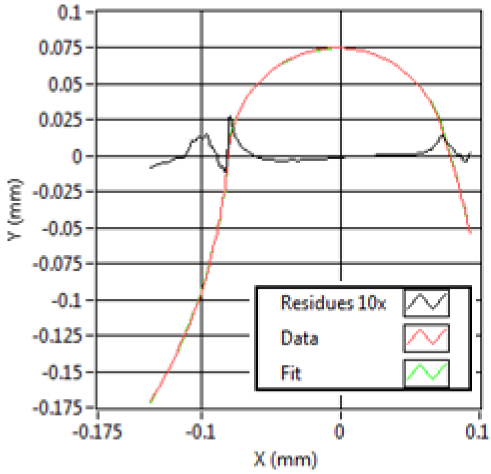


Figure 13. Left: Fitted with a Ø = 0.125 mm probe, the METAS micro-CMM is scanning the profile of the micro wheel. Right: Fitting of one of the tooth profile.

In multi-sensor coordinate metrology datasets from one object are obtained with different sensors and it is necessary to link them. Linking or registration means in this context that the same coordinate system is specified for each dataset. An obvious way to do this is to choose features (in the following called 'markers') on the measured part, which are used for the definition of the coordinate system. This registration approach is one way to perform a so-called 3-2-1 registration, as it includes definition of the reference plane with three points, definition of the reference line with two points and in the end definition of the origin by a single point.

Registration introduces an additional uncertainty to the measurement result; however, no knowledge about the value of this contribution in dependence on the selected markers existed prior to the project. To investigate whether certain markers (respectively their shapes) are more robust for linking datasets than others, a standard object, featuring different markers, was required. At the first step existing reference bodies from the consortium were tested to verify their suitability for such study. The surface characteristics, material and the size of the object must enable measuring it with optical, tactile and CT sensors. As no suitable object was available, the registration standard featuring 20 markers of five different shapes, e.g. cylinders, holes, cubes, calottes and spheres, was developed at PTB (Figure 14).

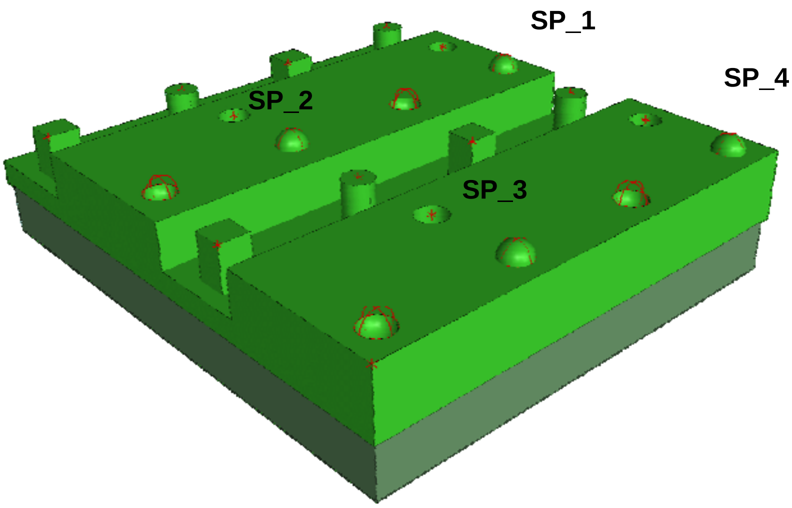


Figure 14. Standard object to investigate the influence of the marker shape on registration. The labels 'SP_1, SP_2, SP_3, SP_4' denote the spheres. In a same order the other features were denoted (counter-clockwise).

The idea was to first register the part by means of three markers of the same type (e.g. three cylinders) and then determine the absolute positions of the remaining markers – of the same, but also of different type – in this defined coordinate system. The difference between the absolute positions of the markers was taken as a measure for the robustness of the registration with a certain marker shape. As a reference the absolute positions measured with the tactile micro-CMM was used.

Results have shown that for certain marker types the registrations of the data sets from different sensors agree better than others. The deviation from the reference value was especially high for the position of the holes, or when the registration was done using holes as markers. Permutation of the marker order in the registration process changed the deviation significantly, i.e. by several µm. Therefore not only the marker shape, but the position and the quality of the measurement data are important for accurate registration.

The linking process was more robust for CT data, i.e. smaller deviations compared to optical data occurred. This was mainly caused by the large size of the object and its tilted position during the measurement with the optical instrument. However, for a smaller registration standard an accurate tactile reference measurement would be more complicated.

Alternative registration methods were also investigated and compared to the feature-based approach. Among them there was a 3-2-1 registration based on the planes, which was also used during the calibration of the standard and best-fit registrations against the CAD model and against the micro-CMM data. The best-fit registrations (using Gaussian fitting) could only be applied to the CT data, as the artefacts in the optical data were too severe and numerous for such a global approach to be reliable.

The smallest mean deviation of the feature positions, diameter and form was obtained for the 3-2-1 registration with planes using only the points corresponding to the tactile probing points. The best-fit approaches applied in the CT vs. tactile data comparison are much worse for position but comparable to the 3-2-1 methods for diameter and form. All registration approaches using automatically fitted points applied in CT vs. tactile and optical vs. tactile comparisons produce a much larger form deviation than the calibration, most likely because they sample the surfaces of the markers more densely. Therefore when calibration data is available, a 3-2-1 registration using the points corresponding to the tactile probing points is recommended.

A specific case of linking is when the sensors are part of the same measuring instrument and share the same positioning platform. This case was investigated for the Zeiss F25 micro-CMM at VSL which has two types of sensors; tactile and optical (vision).

In order to link the two sensors, VSL has used the Zeiss F25-R02 calibration artefact consisting of a sphere and a half-sphere (Figure 15). Both 1 mm sphere and half-sphere were used for the investigation of the linking. The advantage of the half sphere is that it has a better defined surface for linking the z-coordinate. The spherical surface of the half-sphere (12 points, divided over 2 circles) and plane of the sphere cut (8 points) were measured with the tactile probe. Afterwards a circle was constructed as an intersection of the sphere and plane surfaces. Then the optical sensor was focused on the edge of the half-sphere and 4 half-sphere segments by 250 points per segment were obtained. The circle was reconstructed as the least-squares circle fit to the data. VSL has compared the geometrical parameters, centre coordinates of the circle for both sensor measurements.

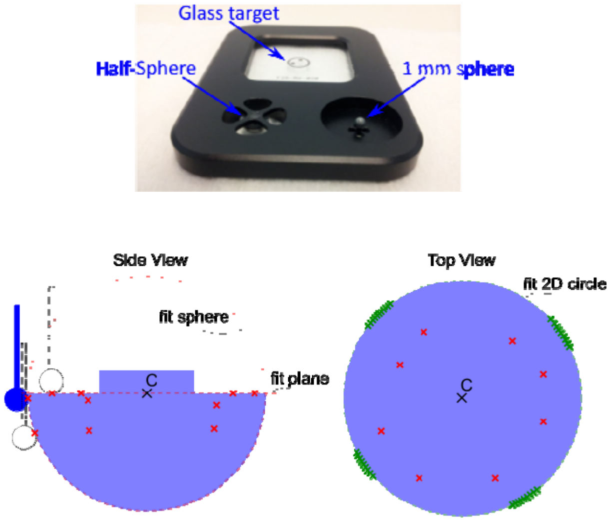


Figure 15. The Zeiss F25-R02 calibration artefact and the measurement scheme. Top: The 1 mm sphere and the half-sphere used in the linking are indicated. Bottom: The measurement scheme for the half-sphere shows tactile (red crosses) and optical (green crosses) probing points.

The experimental data for the X-coordinate (500 measurements) are presented in Figure 16 (top panel) and the measurement results for the other axes reveal similar behaviour. The measurements lasted approximately 4 hours. There was a clearly visible drift of approximately 0.7 µm and saturation for the X-axis that was later confirmed to be thermal stabilization due to camera/lighting heating effects. The error distribution of the short term measurement error, based on 20 measurement points is presented in Figure 16 (bottom panel). The standard deviation for the short-term optical measurements is σ_X = 0.017 µm. The standard deviation for the other axes is σ_Y = 0.015 µm and σ_Z = 1.085 µm for Y- and Z-axis, respectively. The standard deviations for the 1 mm sphere are σ_X = 0.023 µm, σ_Y = 0.051 µm, and σ_Z = 1.297 µm that is slightly larger than for the half-sphere. This can be explained by a poorly defined edge that is crucial for low-uncertainty optical sensor measurements.

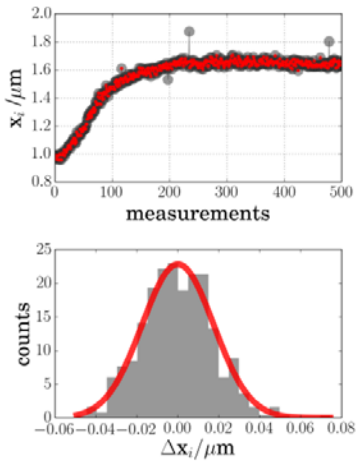


Figure 16. The linking results for X-axis of the half-sphere. Top: The linking X-axis coordinate difference between optical and tactile sensors. Bottom: The high-pass filtered distribution that results in standard deviation σ_X = 0.017 µm.

The systematic uncertainty of the linking process was assessed using the virtual micro-CMM (VCMM) developed by VSL in this project. This approach has as particular merit that an uncertainty contribution for an unknown systematic error of the probing system is taken into account, which may not appear in the variation of experimental measurement data. One of the systematic uncertainty sources assessed in this way was the influence of the height of the probing of the second circle β_2 (Figure 17 of the half sphere). At the used value of β_2 = -8° an expanded uncertainty of 37 nm was calculated with VCMM, which is close to the optimal value. The full investigation of the systematic uncertainty sources and adding to that the experimentally determined statistical uncertainty gave an overall standard uncertainty of linking of: u_x < 100 nm, u_y < 100 nm and u_z = 1200 nm.

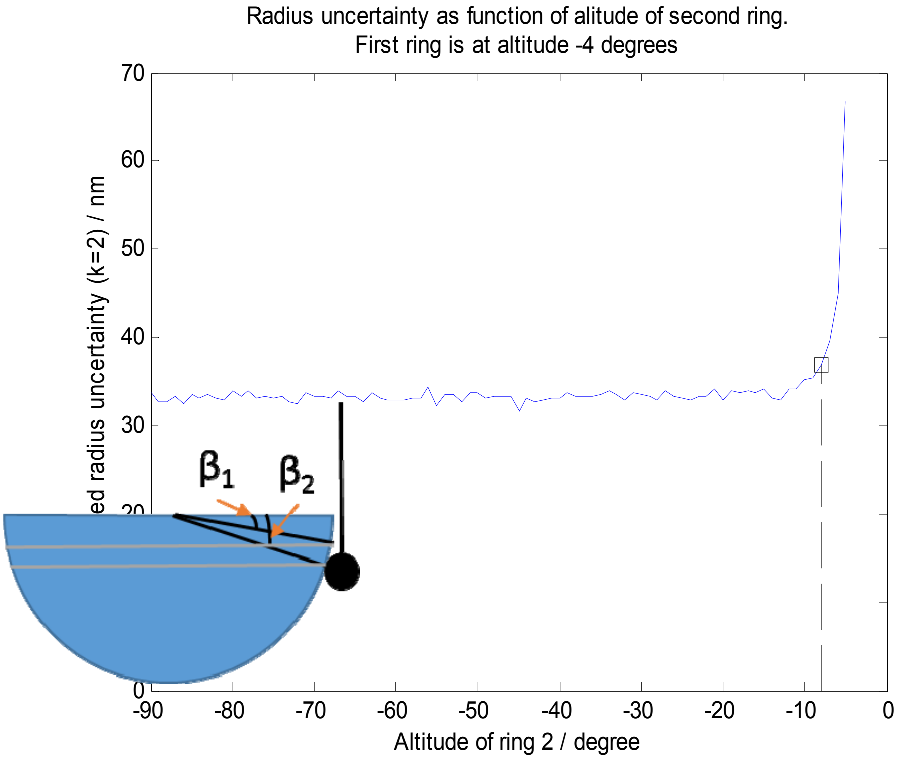


Figure 17. Uncertainty of fitted radius as function of altitude of second ring of points.

<u>Key research outputs and conclusions</u>

Methods for determining the task specific uncertainty for microparts measurements have been developed for micro-CMMs and CT. One of these methods has been successfully used for tactile micro-CMM measurements of a watch part from the Swiss Stakeholder Nivarox. For three other workpiece-like reference standards, task-specific uncertainty was estimated when measuring with different sensors. Furthermore, a method to determine the task specific measurement uncertainty for CT measurements numerically was developed. It was shown that the numerical determination of uncertainty with the aid of a virtual metrological CT for dimensional measurements on microparts is feasible. Calculations of the task-specific uncertainty for multi-sensor measurements on an F25 micro-CMM have been realised by applying a virtual micro-CMM implementation. The calculations have been successfully verified for simple cases. The multi-sensor measurement uncertainty, which is caused by the fusion of measurement data from different sensors, was determined with the help of a special reference standard that contained different markers and allowed testing data registration methods.

3.4 Enhance accuracy of data processing

In multi-sensor coordinate metrology, optical, capacitive, tomographic and tactile probing systems are used to measure and analyse the shape of freeform workpieces while controlling reliability and accuracy of the results. Data obtained from one or several measuring machines equipped with one or several probing systems are characterized by different coordinate systems, different measurement uncertainties, different and limited overlapping sections and different spatial arrangement of points. For that purpose LNE has developed a registration procedure including two phases: coarse and fine registration. At the coarse registration step two data sets are aligned with a lower resolution from a global view. The outcome alignment is thereafter optimized through the fine registration for a higher resolution.

The purpose of the LNE work was twofold. Firstly, a novel registration framework was proposed for coarse registration to allow a considerable reduction of Hough method and Ransac transformation cost. These approaches are combined with the exploitation of discrete curvature features. The curvature parameters including the principal curvatures, the principal directions, the curvedness, the shape index and its corresponding surface type are preliminarily computed using a discrete curvature calculation method.

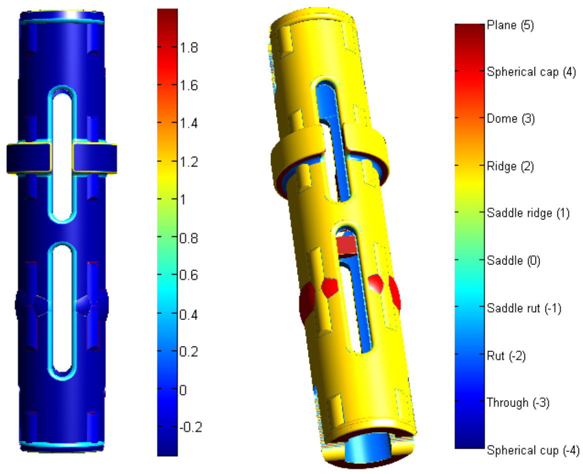
Secondly, a curvature-based fine registration method was proposed by LNE. The developed method combines point-to-plane registration with point-to-point minimization with an automatic weighting. Weights are attributed according to the curvature features previously calculated at each point. Thus, according to the obtained surface type [6] point-to-point and/or point-to-plane minimization will be more or less privileged in the objective function formulation [6]. Furthermore, curvature feature distance has been established for correspondences searching defined from the principal curvatures and combined with Euclidean distance for reliability (Figure 18).

The developed methods were applied on simulated data collected from the CAD data of a connector part (one of the selected workpiece-like reference standards) with added Gaussian noise (Figure 19).

Gaussian noise with controlled mean and standard deviation (μ = 0, σ = 5, 50 and 100 nm) was added. The considered values of the standard deviation correspond to typical noise values observed on the measurement system. (σ = 5 nm corresponds to the noise caused by the probing system integrated on ultra-high precision CMM, while σ = 50 nm corresponds to the noise that can be seen on classical CMM and σ > 100 nm corresponds to the noise produced by the measurement systems with CT sensors.

Once the model data was created, it was translated along the x-, y- and z-axis to generate the initial alignment between the two data sets. Afterwards, the developed registration methods were successfully applied to analyse the generated datasets. The proposed curvature-based fine registration approaches have provided promising results.

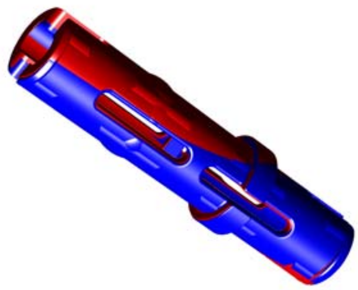
The real data set was obtained with a Zeiss METROTOM 800 in collaboration with Zeiss-France (Figure 20).



(a) Curvedness (b) Surface type

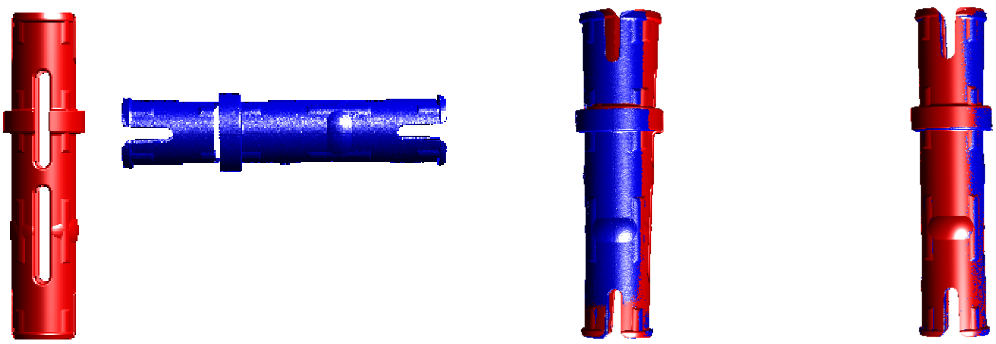
Figure 18. Curvature parameters maps of the LEGO connector:
(a) curvedness *C* map; (b) surface type *T* map

(a) Initial alignment (b) Coarse alignment

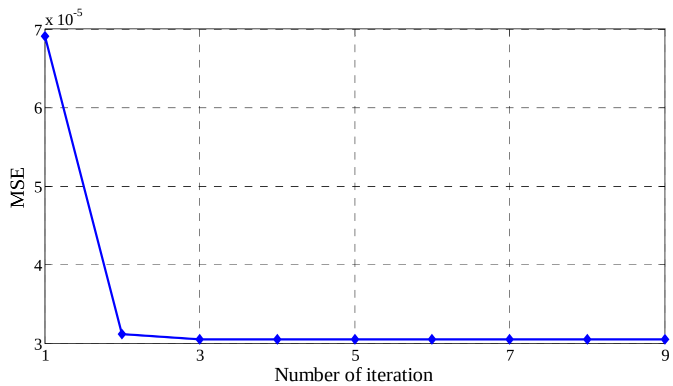


(c) Fine alignment

Figure 19. Simulated connector data without Gaussian noise (μ = 0, σ = 0 nm):
(a) initial alignment (red, model data; blue, scene data), translations (Tx = 2 mm, Ty = −3 mm, and Tz=−1 mm) and rotations (Rx = −0.5 rad, Ry = −0.01 rad, and Rz = 0.5 rad); (b) coarse alignment; (c) fine alignment.



(a) Initial alignment (b) Coarse (c) Fine

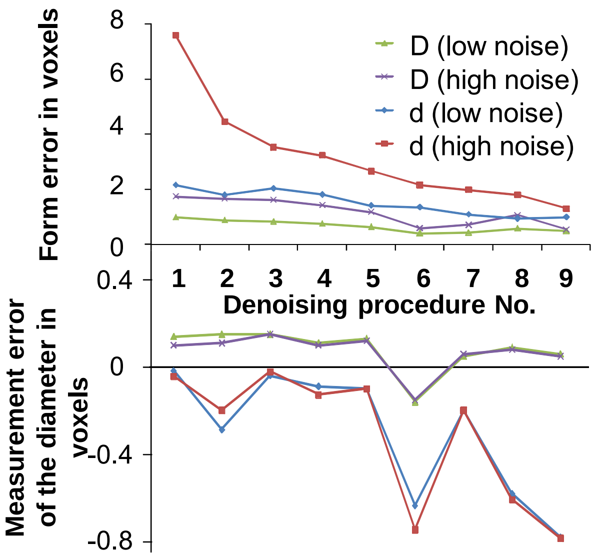


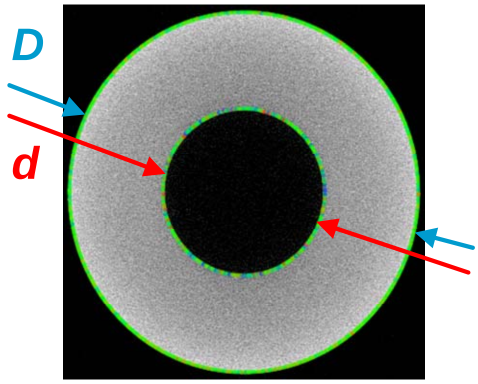
(d)

Figure 20. Real data set of the connector part (top) and evolution of the mean-squared error (MSE (in millimetres)) versus the number of iterations (bottom).

Multi-sensor measurement techniques, like CT or optical methods, sample the object surface with a high point density during a single scan. Among the surface points some noise or other unwanted signal contributions may appear. To suppress these artefacts, filters can be applied to the data. CT filtering can be used at different stages of the data processing routine, and the influence of state of the art noise reduction filters on dimensional measurements and resolution was not yet estimated. Therefore intelligent strategies for data filtering were investigated in the project, which would reduce the unwanted signal contributions, preserve the dimensions and would have only minor impact on the resolution of the data set.

To reduce the influence of factors other than filtering the experiment was carried out on simulated data using a model of a hollow cylindrical part. Two data sets with different quality were used: a low noise data set which resembled a good quality CT measurement, and a data set with high noise level, which resembled a low quality quick CT measurement. A selection of filters was based on the experience in data processing of PTB and other partners, like BAM and Siemens. Filters were applied to projection images before the reconstruction and to the resulting volume data after the reconstruction. The main observation for both procedures was that a strong reduction of the form error is always linked with the loss of resolution or with changes and distortions in the measured dimensions. All filters, applied to projection images, have demonstrated a negative influence on the length measurements of the inner features on selected objects. For one of the objects, a hollow cylinder, the deviations with a negative sign (shrinking of the inner diameter) grew with enlarged filter strength and reached 0.8 voxel for certain filters), as depicted in Figure 21.





Denoising procedures:

1-No filter (original volume); 2-SUSAN; 3-Median 3D 3 x 3 x 3; 4-Median 2D 3 x 3; 5-Median 2D and Median 3D; 6-Non-local means;7-Anisotropic diffusion; 8-Total Variation; 9-Block-matching 3D

Figure 21. Measurement error depending on the selected filtering procedure for data sets of different quality (high quality data with low noise and low quality data with high noise). The measurands were the outer diameter, D, and the inner diameter, d, of a hollow cylinder. Procedures for noise reduction are listed alongside.

Determination of the resolution, e.g. when measuring curvature of small features, depends on the amount of noise. Noise- reduction filters were therefore advantageous when measuring on the noisy data or on data taken with a low number of projections. However, if the data quality was good and the surface of the reconstructed volume was smooth, the filtering operation had most likely led to a loss of resolution. In case of the hollow cylinder with grooves and ridges, for the less noisy data the curvature of the measured features was flattened so that the measured curvature radius became larger and the resolution reduced, whereas for the bad quality data filtering improved the result compared to the measurement on the unfiltered volume.

Based on the study, recommendations are given for further usage of filters, which were presented to partners and broader audience at the Microparts workshop. Median filters with kernel sizes 3 and 5 have shown the best performance in terms of noise and form error reduction and preservation of dimensions and resolution, so that they can be recommended for further usage. Other investigated filters should be considered with care and their application strongly depends on the measurement task.

The main focus of data reduction for dimensional CT measurements is to cut down the required storage space, while preserving the measured features and resolution of the volume data set. The behaviour of several reduction procedures based on surface extraction has been evaluated on simulated CT projection data from the hollow cylinder described above. Data reduction via polygonization of the determined surface has shown to allow a significant reduction of the file size (up to 90 % reduction for the utilized dataset) compared to the initial size of the reconstructed CT volume. The influence on the measured dimensions was found to be negligible. The resolution was negatively influenced by data reduction; however no linear dependency on the size of the resulting polygon model was discovered.

Another important observation was made when reducing the size of porous objects or objects with high amount of noise at the surface. At high level of reduction a larger bias was introduced to the measured dimensions due to the fact that noise particles or pores lying close to the surface were excluded and, therefore, the surface points for fitting a geometrical primitive to conduct the measurements have changed the position. Usage of an adaptive method for data reduction via polygonization resulted in more data points in regions with high curvature compared to the regions with lower curvature for the same data size. This has led to shrinkage of the fitted diameter of the part, which was based on the lower number of points for highly simplified regions. The measurement error was however not of high significance and the curvature was better preserved with an adaptive procedure.

As an outcome of this investigation, usage of data reduction can be recommended in specific cases, where the requirements for detail preservation are moderate. For the case of microparts, further investigations with more sophisticated approaches to data reduction, e.g. from the field of computer graphics, are needed.

FAU and BAM have carried out investigations on correction of systematic errors of CT measurements by different means. It was observed that information from tactile and optical reference measurement can be used to identify and correct systematic errors of CT measurements. To ensure a valid correction, the measurement uncertainty of the reference measurement must be significantly smaller than the uncertainty of the CT measurement. Additionally, multiple CT measurements are recommended to be carried out in order to separate systematic errors from noise. In the best case: multiple reference measurements should be made with different sensors.

Simulation has shown to be a helpful tool in understanding the origins of the systematic errors. FAU, with assistance from BAM, has developed a method to identify local systematic errors of CT measurements (e.g. caused by artefacts) by simulation. This information can be stored on the 3D model of the part and later be used to correct the dataset of a real measurement. Using the mentioned method, local errors of the surface dataset can be reduced. This resulted in a reduction of the measurement deviation of the final dimensional measurements by nearly 50 % for a simple test body. A paper based on the outcomes of this study was submitted to a peer reviewed journal and is awaiting the publication.

Key research outputs and conclusions

Investigations to determine an appropriate procedure for data filtering have been carried out using a hollow cylinder with engraved features of several micrometers in size as the test sample. Median 2D and 3D filters were found to be the best choice for noise reduction, as they best preserved the measured features. Comparing accuracy and computational effort for registration methods was conducted and 3-2-1 and marker-based registration were found to be most accurate registration procedures. Processing data from the different measuring techniques can be complex as they have different numbers and varying spreads of results. Intelligent data registration, filtering and fusion enables the measuring results from different techniques to be combined with reduced computational effort. This in turn increases the accuracy and reduces uncertainty.

3.5 Transfer results to end users

Three workpiece-like reference standards were calibrated and handed over to the industry partners to demonstrate the applicability and advantages of developed metrological tools in a modern manufacturing environment.

- The "Bosch Cone standard" is used as a factory standard. A simplified version is implemented in the production facilities to replace the former angle standards used to monitor the angle measuring characteristics of the white light interferometers applied to check the cones at fuel injection systems.
- The “Injection Needle” serves Novo Nordisk as a reference standard. Novo Nordisk anticipated further developments of the product and the measurement procedure in order to perform measurements of multiple parts in one fixture together with the calibrated part. This will help to accelerate the quality control process in the production and achieve higher accuracies in the measurement of medical microparts.
- The calibrated "LEGO connector" was used to formulate a task-specific uncertainty budget for CT measurements of this part. In general, having a reference standard that can be used for performing

measurements with different sensors has added new and quantitative knowledge regarding accuracy and uncertainty that LEGO is using in evaluating and optimizing measurement procedures and protocols.

Results of measurements of further workpieces were transferred to collaborators of the project:

- METAS has carried out measurements on a watch part “micro wheel”. The results are going to be used by the manufacturer for the further development of such parts.
- A cornea artefact developed by the stakeholder Haag-Streit was calibrated at METAS. The results will be used for further development and improvement of ophthalmologic instruments.
- Additionally, there are ongoing demonstration activities at the end of the project:
- PTB made first CT measurements of a razor part, proposed by the stakeholder Philips in order to demonstrate the possibilities of multi-sensor measurements.
- VSL has made multi-sensor measurements of a 5 GHz waveguide structure of the stakeholder VDL.
- Strong interest was shown regarding the commercial availability of the objects with defined roughness.

Knowledge was transferred to the stakeholders of the project:

- A stakeholder committee was formed in the beginning of the project and regular meetings were held. A stakeholder report was distributed regularly to the members in order to keep them updated on the progress of the project. Stakeholders have actively participated in the project by proving their feedback to the presented research results and sharing their experience on specific topics.
- Several workpieces proposed by the stakeholder committee were measured to demonstrate the application possibilities of developed metrological tools, e.g. the watch part from the stakeholder Nivarox, the cornea artefact from Haag-Streit, the razor part from Philips and waveguide structure from VDL. The obtained results will be used by the stakeholders and facilitate further development of their products.
- Stakeholders have shown a strong interest towards other outcomes of the project, e.g. correction of systematic error of CT measurements using simulated data.

Throughout the project 21 training activities have been completed, covering a wide range of activities (lectures, secondments and training courses) and audiences (JRP partners, academic and industry peers). Examples of the largest activities in terms of attendees are:

- SWISSMEM SEMINAR, predominantly industry with over 100 attendees
- Shanghai University, Nanometrology - an introduction, Predominantly the scientific community (higher education, public research organisations)
- Metrology Day Denmark, various presentation to a mixed audience
- Euramet TC-L open workshop, predominantly the scientific community (higher education, public research organisations)
- German-Austrian-Danish Workshop, predominantly the scientific community (higher education, public research organisations)
- Wissenschaftliches Kolloquium des SFB 926, predominantly the scientific community (higher education, public research organisations)

Additionally, two tutorials on optical measurements (LU) and CT (FAU) were organized during the project workshop at NPL, which was co-located with euspen Micro/Nano Manufacturing workshop (24th November to 26th November 2015). Over 20 people have attended both tutorials.

Key research outputs and conclusions

The workpiece-like reference standards were transferred to production facilities of the industrial partners and are being used for controlling and optimising the manufacturing process of microparts. Several other parts were used to demonstrate the transferability of the knowledge and methodologies developed to other production situations. Training was organised for project partners and for a broader audience to facilitate the transfer of results.

3.6 Summary of the research results

- Small probes with a diameter below 100 µm were successfully manufactured at NPL and METAS. Probes with a diameter of 50 µm are available for calibration of small structures at METAS, whereas smaller probes (diameter of 20 µm and below) at NPL were found to be not usable on the majority of the existing CMMs due to low stiffness.
- For the first time the wear of diamond-coated probes on different materials was investigated under typical scanning conditions of a micro-CMM. It was shown that the wear is much smaller than for the conventionally used ruby spheres, therefore the diamond-coated probes last much longer and allows saving calibration costs.
- Micro-CMMs of different manufacturers using different probes were characterized for their behaviour in order to increase the accuracy of tactile probing.
- A round-robin for comparison of probing system performance was carried out and revealed a good agreement of results both in scanning and single-point probing mode.
- A method for effective cleaning of microprobes was developed.
- Workpiece-like reference standards have been created according to the needs of European manufacturers in different industrial fields, calibrated and measured with CMMs having optical, tactile or CT sensors. These workpiece-like reference standards were then successfully used for demonstration of improved metrological capabilities applied to modern manufacturing environment at the facilities of industrial partners.
- Areas with defined surface characteristics were successfully realized on planar and curved carrier materials. With their help measurement capabilities of various surface measurement devices of high resolution (CLSM, AFM, CSI, FVM) were compared.
- An improved high-order non-linear surface scattering model to simulate the measurement behaviour of optical sensors was developed. With the help of this model the output of surface measurement instruments, including CSI, confocal microscope and FVM has been modelled for the first time. A theory was developed by researchers from LU which explains the origin of artefacts, independently observed at measurements with FVM when tilting the sample.
- A comparison between CT and synchrotron measurements of the reference bodies was made, and the results agreed well.
- Reference standards for systematic error correction of CT measurements were proposed and applied for the measurements within the project.
- Task-specific measurement uncertainty was assessed by partners using workpiece-like reference standards (optical, CT) and numerical methods (tactile, CT).
- Uncertainty of linking data from different sensors was investigated using suitable reference bodies, and ways to minimize the linking error were proposed.
- New registration procedure featuring steps of coarse and fine alignment was developed, successfully tested and optimized.
- Recommendations are given for appropriate data filtering and reduction procedures, which would remove the unwanted signal contributions, preserve the dimensions and would not compromise the resolution of the data set.

It is important to note that the joint effort from the consortium for the decision on workpiece-like reference standards, their measurement strategy and calibration has been invaluable to the project success.

4 Actual and potential impact

The project improved the accuracy of measurements by improving the probes, and combining different sensors and measuring techniques. It developed reference samples which could be used in industry to improve calibration and measurement. It also combined results from different sensors and techniques to reduce uncertainty.

4.1 Metrology achievements

The whole content of the project was focused on the question whether and how small geometrical features can be measured or even calibrated. Moreover, there was – and still is – also the need to measure 3-dimensional features, inner features or a set of features, which are not measurable with a single type of sensor. In order to answer these questions, many investigations had to be carried out.

Smaller features need smaller probe sizes

A measurement of small inner radii or sudden changes in the tooth profile of micro-gears requires small probe sphere diameters. Within the project tactile probes with diameters as small as 50 µm and sphericity deviations of less than 0.3 µm have been developed and successfully applied. Roughness values were not bigger than 5 nm (Ra) or 40 nm (Rz). However, not only the fabrication of such tiny probes is challenging, but also its implementation into a CMM. METAS met this aim and is now offering calibration services with miniature tactile probes.

Traceability on the small scale

When measurement data is needed which are traceable to the SI units to date in most cases a tactile CMM must be used. Hence, it is of utmost importance to have well characterized tactile CMMs to ones disposal. Therefore, PTB, METAS and VSL characterized their micro-CMMs and, together with an industry partner, conducted a round robin. This study has shown the limits of cutting edge tactile CMM capabilities: an agreement between all the participants could not be reached to the envisaged $U < 0.1$ µm level; an outcome, which was only possible in a joint research project.

Improved measurement conditions

Tactile probes suffer mainly from wear and contamination. This negatively influences the measurement uncertainty in different ways. On the one hand, dust particles can stick to the probe head and thus bias the succeeding measurements. A novel cleaning system has been developed within the project, which allows for automated cleaning and inspection of probe heads during the measurement procedure with maximum efficiency. On the other hand, repeated probing causes wear of the probe head and, as a consequence, a change of the probe characteristics. This leads to a biased measurement result. During the project it was shown that diamond-coated probe spheres have an increased life time of up to 4000 times the life time of usual ruby spheres. This not only reduces the measurement uncertainty, but also saves costs.

Multi-sensor measurements

More and more often inner i.e. inaccessible features and less accessible outer features need to be measured. In coordinate metrology these measurements can be currently done with optical or X-ray CT sensors, however, the obtained results are still not directly traceable to the SI-units. Besides its advantage of non-destructive accessibility of inner feature measurements, CT also permits relatively fast measurements of a high number of industrial parts. Optical sensors allow extensive and fast measurements of the surface and can be applied to the objects, for which CT measurements are not possible due to e.g. high absorption properties of the material. Fast measurements are desirable e.g. in production in-line quality assurance. In order to validate CT and optical measurements for such applications, workpiece like reference standards have been selected and calibrated. Those standards are industrial parts or contain features that are similar to real measurement tasks of industry parts. In this sense, three workpiece-like reference standards were successfully calibrated and can now be used by the industrial partners as reference standards, in order to increase their measurement accuracy.

Uncertainty evaluation of non-traceable measurements

As already mentioned before, a direct traceability to the SI-units is difficult for optical sensors and CT. These sensors require a different approach for evaluating their measurement uncertainties. The different error sources have to be identified and quantified. Within the project CT measurements have been simulated and real measurements have been conducted, in order to estimate the influences of different error sources. This gives more confidence in the measurement results and helps to reduce the measurement uncertainty. Regarding optical measurement systems, like, e.g., CSI or FVM, theoretical studies have been conducted, which successfully predict measurement artefacts. The contribution to better measurement accuracy is twofold here. First, the measurement setup can be optimized to avoid artefacts as good as possible. Second, the error contribution due to artefacts can be calculated and the bias can be corrected. A profound understanding of theoretical models of such measurement systems can help to develop further Monte-Carlo based, so-called “virtual CMMs”, as is state-of-the-art for tactile systems.

4.2 Dissemination activities

During the project, the consortium had considerable interaction with standardisation and regulatory bodies, participating in 13 different committees over the past 3 years, participating in 42 different meetings. The topics covered by these committees (which are both international and nationally focussed), are directly relevant to the project, and participants ensured that the technical outcomes of the project are transferred directly to these committees – for example, presentations of the project’s results were given at 11 of the 42 meetings, and members of the consortium gave input to draft regulations or documentary standards on further 9 occasions.

During the project, the consortium published 10 journal papers and 4 papers in the proceedings of international conferences. Five additional publications have been submitted to peer-reviewed journals. One peer-reviewed article is planned to be submitted after the end of the project. Papers from this project were published in a range of journals, including several high impact journals such as the Annals of CIRP, and Optics Express.

The project consortium was very well represented at conferences, participating in 25 separate conferences, offering 30 oral presentations and 17 posters. This includes the contributions made by the project consortium to the Microparts Project workshop, which was co-located with the well-established “Micro-Nano Manufacturing Workshop” and attracted 60 attendees (of which 29 were from outside the project consortium) and five exhibitors.

The event provided a forum for the European micro- and nano-scale metrology and manufacturing community to discuss current trends, and to consider the application of cutting-edge developments into a manufacturing environment. The event demonstrated the consortium’s continued leading role in the development of measurement technologies, procedures and standards for 3D coordinate metrology for microparts. Project partners LEGO® and Novo Nordisk were a part of the organising committee and chaired oral sessions during the workshop.

As part of the project workshop, two training courses were offered to all attendees, free of charge, to demonstrate techniques developed during the project. These were attended by more than 20 people. Throughout the project 22 other training activities have been completed, covering a wide range of activities (lectures, secondments and training courses) and audiences (JRP partners, academic and industry peers).

Trainings within the consortium on various aspects of the project were organized. UNOTT delivered training to the JRP partners (METAS, VSL, NPL, PTB, LU, IBSPE) regarding the developed stylus cleaning and inspection methods during the 16th euspen conference at Nottingham. FAU organized a workshop on numerical uncertainty determination for CT, which was attracted several project partners and external attendees. LU has made one-to-one training on the theory of optical dimensional measurements for PTB and industrial collaborator Alicona.

To support the presentation of project results to the industrial community 4 articles in trade and professional press have been published. Such articles are essential for realising immediate impact with the stakeholder community, with whom engagement is better through technical trade articles rather than scientific journal articles. Additionally, the project was presented at “Control” (26th-29th April 2016) in Stuttgart, Germany, which is a leading international trade fair for quality assurance.

Several other activities were completed during the project to facilitate further dissemination of impact and output, including: articles on partners’ websites and visits to stakeholders. Such visits are essential for partners to learn the technical needs of stakeholders, ensuring that the impact of involvement in the project is high.

4.3 Effective cooperation between partners

In this project, seven NMIs and DIs, three universities and six industrial companies worked together with support from three Research Excellence Grant researchers and thirteen collaborators from industry and universities.

The project brings together the expertise in different sensor technologies (tactile, optical and CT), a large number of different measurement systems, several simulation techniques and knowledge about industrial needs. The large number of industrial companies participating as unfunded partners and supporting as collaborators shows the big industrial relevance of the project.

Several tasks were processed in close collaboration between the partners. Good examples for this are the measurements at the workpiece-like reference standards with different sensors. After the end of the project, these standards are still available for all interested parties.

Training activities have been carried out to share the results with the partners and good practice guides have been written to share the experience acquired in the project. The large number of measurement systems available in the consortium made two comparisons possible, one about micro-CMMs and one about industrial CT systems.

To strengthen the knowledge exchange secondments were organized during the project. NPL hosted a researcher from National Taipei University of Technology to transfer expertise in micro-stylus fabrication. A researcher from FAU worked on measurements of the hohlraum standard using multi-sensor analysis during his stay at NPL.

Last but not least, due to the common activities of different partners, most of them having their expertise in a different subject, a valuable gain in knowledge could be achieved. This opens new perspectives and ideas for future common projects. Collaboration between partners, abroad the current project, became much easier. This is also true for the interaction with industry partners. More sincere discussions were possible, which showed current limitations and needs of the industry as well as academics and research institutions.

4.4 Examples of early impact

Standards

The outcomes from the project were used in the German standardisation committee VDI/VDE GMA committee 3.31 “Coordinate metrology” for the development of a guideline containing acceptance and reverification tests for optical CMMs measuring microparts. A special guideline VDI 2617-12.2 will contain exclusive tests for optical CMMs measuring microparts.

In ISO TC213 WG10, the development of an ISO standard containing acceptance and reverification tests for CMMs with CT sensors is in progress. Attention will be paid to tests at high magnification, used when microparts are measured. A draft of the standard is currently in preparation.

The FIB-created roughness fields, realised in the project, and their application, have been introduced to the committees ISO/TC 201/SC 9 and its national German mirror DIN NA 062-08-16. AFM roughness measurements are regarded as one of the top priorities in near-future SPM standardization, and various pre-standardization works were reported at the meetings. The AFM working group of the VDI/VDE GMA committee 3.41 is finalizing the draft of the future AFM roughness guideline VDI 2656-2.

While FIB-created roughness on flat substrates is preferred by AFM, FIB-created roughness on curved (e.g. cylindrical or spherical) carrier materials is appreciated for the assessment of the measurement properties, particularly of optical surface measurement techniques. Consequently, this is of interest also for the working groups on confocal scanning microscopy and white light interference microscopy in the same VDI committee 3.41. Several experts of VDI committee 3.41 are also active in ISO/TC 213/WG 16 “Areal and profile surface texture” and can transfer the concept of FIB-created reference samples also to there: As FIB allows to flexibly create predefined surface texture, according to the needs, some physical standards, listed in ISO 25178-70 (a standard developed by ISO/TC 213/WG 16), but currently not yet available, might in the future be manufactured by FIB.

User impact

- The "Bosch Cone standard", representing two typical cone angles, as can be found in automotive industry, is used as a factory standard. A simplified version of this standard is implemented in the production facilities to replace the former angle standards used to monitor the angle measuring characteristics of the white light interferometers, applied to check the cones at fuel injection systems.
- The “Injection Needle”, which was calibrated in the project, serves Novo Nordisk as a reference standard. Novo Nordisk anticipated further developments in the product design, as a consequence of the findings of this project. Also the measurement procedure will be re-evaluated, in order to perform measurements of multiple parts in one fixture together with the calibrated part. This will help to accelerate the quality control process in the production and achieve higher accuracies in the measurement of medical microparts.
- The calibrated "LEGO connector" was used to formulate the task-specific uncertainty budget for CT measurements of this part. This resulted in a higher accuracy and smaller uncertainty was estimated for CT measurement at DTI. In general, having a reference standard that can be used for performing measurements with different sensors has added new and quantitative knowledge regarding accuracy and uncertainty that LEGO is using in evaluating and optimizing measurement procedures and protocols. Higher accuracy for multi-parts measurements with CT could replace in the future currently used tactile CMMs, an aim of this industry partner.
- As proposed by the stakeholder committee, METAS has carried out measurements on a watch part (“micro wheel”). The results are going to be used by the manufacturer for the further development of such parts.
- A cornea artefact developed by the stakeholder Haag-Streit was calibrated at METAS. The results will be used for further development and improvement of ophthalmologic instruments.
- VSL made multi-sensor micro-CMM measurements on a 5 GHz wave guide block manufactured by VDL. Results will be used to improve the manufacturing of these types of structures and test against specifications.

Strong interest was shown regarding the commercial availability of the objects with defined roughness, which were developed during this project. The company that was awarded the contracts for FIB fabrication, m2c in Potsdam, Germany, intends to optimize the FIB routines developed in the course of these contracts together with PTB, so that custom-made designed roughness on different carrier materials will become commercially available soon. ISO/TC 213 /WG 16 “Areal and profile surface texture” has specified a number of material measures for thorough verification and calibration of areal roughness measurement instruments in its ISO 25178-70, although it is still unclear how the test samples proposed there could be fabricated; it is be hoped that some of them can be realized by FIB, based on the knowledge and experience gained in the work described here.

Scientific impact

The work within the scope of the project, i.e. to improve metrological capabilities for measuring microparts and to strengthen the dissemination of the developed methods among end users, has revealed some potential areas of future research. PTB and FAU are planning to cooperate on a project dedicated to the determination of structural resolution for CT and other types of sensors. PTB, BAM and FAU, alongside with other members of the VDI committee 3.33, are planning to cooperate on a project dedicated to the numerical uncertainty determination of CT measurements.

4.5 Potential impact

Improved metrological capabilities for measurements of microparts and their dissemination to industrial partners are the major outcomes of the project. To transfer the project results to the facilities of further interested manufacturers additional calibrated reference standards could be created, which cover the needs of respective industrial sectors.

The outcomes of the project will be further used in the automotive sector to e.g. design more efficient injection systems of combustion machines. Faster and more reliable measurements with reduced uncertainty owing to the use of appropriate reference standards will allow better quality control and measurements on parts with smaller tolerances. The emissions of combustion engines are strongly dependent on the dimensional characteristics of the fuel injection systems. A potential reduction of emission by using more accurate measurement technologies for the quality control of combustion machines can, therefore, be reached.

Today the society is highly influenced by the modern healthcare technology. An emerging sector is high tech medical products, which very often critically depend on micro-components, e.g. in insulin injectors, ophthalmologic instruments, cardiac pacemakers or medical endoscopic imaging systems. Accurate and reliable quality control procedures for medical microparts based on the outcomes of the project will facilitate developments of new medical products, such as portable diagnostics and treatment devices, and will significantly improve the quality of life.

The benefits of the project will support European manufacturers of microparts and systems incorporating microparts and strengthen their positions on the global market. Expert knowledge on measurement technologies from the project will improve competitiveness of European measuring instrument manufacturers. Additionally, the advances in quality control of microparts will help to reduce play or wear of components and the number of failure parts. This will result in a cut of production costs, saving natural resources and energy both for production and for the use of these products.

New measurement services and calibration services at NMIs to disseminate traceability, e.g. to commercial measurement service providers, will be emerging based on the outcomes of the project. At PTB creation of the CT calibration service is included in the long-term development plan and is planned to be launched in 2018. A potential future customer has shown interest in the developments in the area of coherence scanning interferometry, particularly in its use for the measurement of spherical artefacts at NPL. The future development of a measurement service for traceable CSI measurements based on the outputs and research from this project will be investigated further.

The project will further contribute to the knowledge transfer on the topic of measuring the microparts by establishing a network between the research institutions and industry and allowing easier collaboration between the participants in future.

5 Website address and contact details

Project website: www.ptb.de/emrp/microparts.html

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