Final Publishable JRP Summary for IND59 Microparts
Multi-sensor metrology for microparts in innovative industrial products

Overview

Parts which are a millimeter or less in size 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.

Need for the project

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.

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 sensors are required, such as CT or optical coordinate measuring machines. 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.

EMRP
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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.

Results

Sensors and measurement systems including tactile, optical and CT probes

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 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.

Establishment of traceability, determination of measurement uncertainty

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, 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 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 a calibrated part 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.

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.

Intelligent data processing

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.

Creating impact for industrial applications

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.

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.

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. The cone standard investigated in the project is used as a factory reference, and is a simplified version of the cones on their production lines. The angles of the two very small cones and the diameter of the transition were the most challenging features and required highly accurate and traceable measurements.
- **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. More than a billion needles are sold per year and each one has to be measured in order to check compliance with the strict quality regulations of the medical industry. The needle is made from stainless steel and has inner and outer diameters of only 150 µm and 240 µm, respectively; representing a challenging task for dimensional measurement. The company was keen to have a calibrated reference standard which would allow fast and reliable monitoring of the inner and outer dimensions of all needles during production.
- **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. To ensure high quality of the toys, strict tolerances have to be met for all parts. The calibrated LEGO connector was used to analyse and develop uncertainty budgets of CT measurements of the part and resulted in lower measurement uncertainty estimates for CT measurements. 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 can use for evaluating and optimising measurement procedures and protocols.

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. This part contained measurement tasks of radii of as small as 8 µm only. The manufacturer of this wheel is going to use the results for further development of such gear parts.
- A cornea artefact, developed by the Swiss healthcare company Haag-Streit, was calibrated at METAS. The measurement task on the object, which looks like a contact lens, was the accurate determination of its centre thickness. The results will be used for further development and improvement of ophthalmologic instruments.

Potential Impact

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.

Dissemination of results

The project results were widely communicated to industry and NMIs, as well as standardisation committees. The project has been presented internationally at 25 conferences and workshops, including euspen 2014, 2015 and 2016, Macroscale 2014 and iCT 2014 and 2016. In total 30 oral presentations were given and 17 posters presented. 14 articles have been published in scientific peer-reviewed journals and trade magazines, and 6 additional articles are awaiting publication. Additionally, the project has been presented at the trade fair "Control" in Stuttgart (26th–29th April 2016). Project partners participated in 13 national and international standardisation committees. Based on the project results, contributions to draft standards in the technical committees VDI/GMA 3.31 and ISO/TC213 WG10 have been made. The consortium has co-hosted a workshop along with the euspen Micro/Nano Manufacturing workshop on 24th-26th November 2015, where the contents and achievements of the project were presented. Training courses were organised to support the knowledge exchange with industry and to broaden the application areas for the results of the research.

List of publications

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