MULTISENSOR COORDINATE MEASUREMENT TECHNOLOGY APPLIED TO MICROPRECISION DIMENSIONAL METROLOGY PROBLEMS

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Abstract: The miniaturization of components and structures and the increasing demand for more accurate measurements have led to ongoing development in the field of dimensional metrology. The development of new measuring sensors mounted on coordinate measuring machines, has enabled metrologists to handle the current dimensional engineering challenges. New probing systems, which combine optical and mechanical principles and provide three-dimensional information about micro-scale features in micro- and meso-scale components, are outlined in this paper. Application cases are reported and their practical issues discussed under a metrology view.

Key-words: multisensor coordinate metrology, optical-tactile probes, microprecision dimensional metrology.

1. INTRODUCTION

Scientific and industrial metrology developments need to be closely related to ongoing trends in production processes and their products. Factors such as the increasing demand for more efficient, economical and robust mechanical parts have led to commensurate progress in product dimensional engineering. Particularly, it has been observed the growing trend towards miniaturization of parts, components and their geometries and more accurate measurement [1]. Coordinate metrology as a multipurpose and an efficient measurement technology has been widely used in the industrial sector, and thus deserved considerable efforts to extend its capabilities to new engineering needs impelled by the market.

Classical probing systems attached to most coordinate measuring machines find two major problems when micro-geometries need to be evaluated. The first is related to the size of the stylus tip, technically limited to several tenths of a millimeter, which makes impracticable measuring inner geometries with sub-millimeter size. The other constrain is linked to the contract force applied to collect the measuring point, which may damage the part surface during probing or even when clamping the part to avoid physical movements.

The use of optical techniques in coordinate metrology, based on high-resolution CCD camera integrated to an image processing unit, has shown productive to inspect 2-D features. Several metrology equipment suppliers provide coordinate metrology equipment that use optical methods to sample the workpiece surface. The specific advantages over classical probing systems are the reduced measuring time of the points of concern, although the evaluation time might be even greater, and the contactless attribute, which makes possible inspecting materials easily deflected and distorted by physical contacting.

However, optical measuring sensors could not be the right choice for complete dimensional characterization of holes, tapers, and other inner geometries. Spray holes of injection nozzles, spark plugs holes and micro-turbine blades holes are some examples of components that require different approaches to measuring their characteristics and evaluating their functional parameters (e.g., cylindricity of a bore surface, perpendicularity of a bore axis related to a datum system). The combination of optical and tactile measuring principles in a single sensor has been observed in recent developments, the so-called optical-tactile measuring probe [2,3]. Optical-tactile probes have been made available for some years as part of commercial multisensor coordinate measuring machines.

Significant efforts have been undertaken by the Institute for Technological Research of the State of São Paulo - IPT to redefine their capabilities in dimensional metrology. For this reason, innovative measurement technologies of high intrinsic value have been gradually introduced and offered to the market. Microprecision dimensional metrology is one of the areas that has received considerable investment in an attempt to provide appropriate metrology solutions to already-known market demands and even to nowadays unknown demands.

It is worthy of attention the participation of researchers in long-term training programs on cutting-edge measuring technologies and the investment in multisensor coordinate measuring machines as part of an entirely new and modern infrastructure. Product innovation through measurement services and applied research in dimensional metrology are some of the macro expectations of the initiative.

Just to name a few applications cases to be covered by the new laboratory, one can mention the measurement and evaluation of features in: (a) micro-gears and micro-threads found in mechanical parts, and medical and dental devices; (b) orthopedic and dental implants, stents; (c) cutting tools; (d) electromechanical micro-systems; (e) delicate parts such as contact lenses and woven fabrics.

In this paper, one describes the initial tests performed on multisensor coordinate measuring machines outfitted with the optical-tactile probe for measuring microstructures and the optical-tactile probe for contour and texture evaluation. In order to establish a comparison between the new sensors and well-known techniques, typical measuring artifacts have been chosen for those initial tests.

Fig. 1. Range of application of optical-tactile measuring probes mounted on multisensor coordinate measuring machines [Courtesy: Werth Messtechnik GmbH]

As a whole, the macro expectation of this work is to establish the potential applications of that new branch of the laboratorial and industrial metrology, i.e., microprecision dimensional metrology. In fact, microprobes mounted on high accuracy multisensor coordinate measuring machines could be potentially used to many other situations than those that driven the development of optical-tactile probes.

2. TOPICS OF CONCERN

Measurement of micro-features on parts and components from a few millimeters to the micrometric range (micro-parts) or even of macroscopic devices with sub-micrometric uncertainties requires new measuring techniques on accurate coordinate measuring machines, conceptually similar over the years, but with progresses in their mechanical stiffness and thermal stability over time.

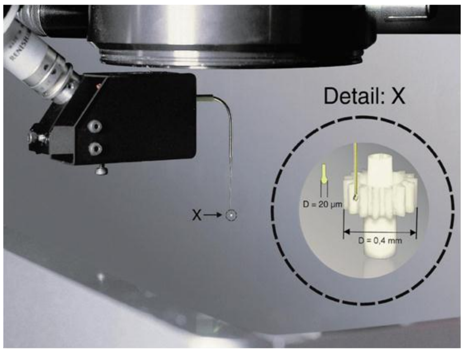


Fig. 2. Optical-tactile sensing system -fiber probe - for measuring small structures [Courtesy: Werth Messtechnik GmbH]

The optical-tactile measuring sensor, the so-called fiber probe, illustrated in Fig. 2, is based on a tiny glass contact tip down to 0.02 mm diameter on the end of an optical fiber. The ball is illuminated through the fiber and the probe tip contacting is checked by a CCD camera. The actual measurement of the position of the stylus ball is carried out by an image processing sensor integrated to the system. The deflection of the shaft is therefore not included in the measurement result [4]. Since there is no need for stiffness, the fiber can be made very thin, and the contact force is therefore only in the micronewton range.

The tactile-optical sensor for contour measurement shown in Fig. 3 combines a contact probe with a laser distance sensor. The measuring sensor detects the contact probe deflection in compliance with the comparator principle. The integration of the tactile-optical contour sensor on a multisensor coordinate measuring machine allows fully automatic contour measurement in a large volume and in the workpiece coordinate system. The sensor is capable of measuring surface contour and roughness in any direction on a plane or even on curve surfaces.

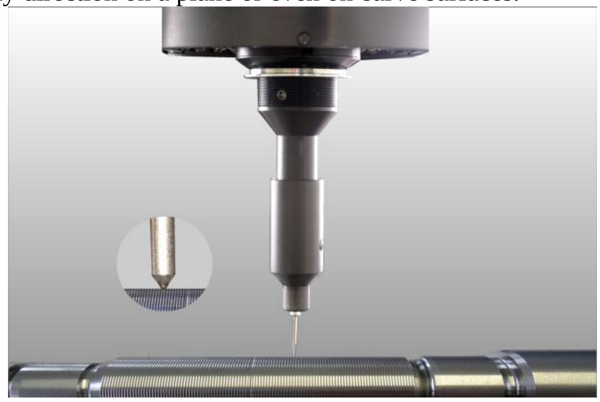


Fig. 3. Optical-tactile probe for measuring contour and roughness of flat and curve features [Courtesy: Werth Messtechnik GmbH]

Although acceptance and reverification tests for classical coordinate measuring machines are specified in ISO 10360, VDI/VDE 2617 and ASME B89.4, it is not trivial extending the methods to multisensor coordinate measuring machines for micro-features. Special parameters which describe the measuring sensor behavior, such as the measuring force and the force-induced deformation, cannot be extracted from well-known methods. Reference measuring standards have been conceived and patented [5], which enable determining metrological attributes of the measurement system under particular conditions.

Workpiece measurements, even in a reference metrology laboratory, would involve the interaction of the measuring equipment with many other influence quantities, especially those attributed to the object under scrutiny. The material, shape and key features of the workpiece, for example, may result in operational and metrological issues that need to be considered when defining and confirming the measurement process.

The studies proposed in this paper are restricted to the operational and metrological assessment of the optical fiber probe and the laser-based measuring sensor for evaluating surface texture and contour. Both optical-tactile probes are attached to multisensor coordinate measuring machines capable of inspecting small linear sizes with uncertainties down to 0.25 µm.

3. PRELIMINARY RESULTS

In the coming subsections the first impressions about the use of the optical-tactile measuring sensors are described and discussed.

3.1. Linear optical-tactile measuring sensor

The optical-tactile sensor for measuring contour and roughness allows the evaluation of linear, angular and circular features in contours, as well as the roughness evaluation in circular sections or free-form sections. The working principle is similar to that observed in articulated measuring arms, with a counter-balancing mechanism at one end for adjusting the measuring force.

The linear optical-tactile sensor, due to the constructive characteristics, does not enable evaluating bores and tapers; on the other hand, the laser-based roughness measurement with a tiny contact tip on curve surfaces is a substantial advance in comparison with bench-top roughness measuring instruments (they cannot measure highly curved surfaces).

In order to evaluate the performance of the laser-based sensor mounted on a CMM, geometric features of a contour standard and their intrinsic characteristics were evaluated with the linear optical-tactile sensor and compared against the results provided by a contour measuring system. Fig. 4 illustrates the contour standard used and the nominal values for some characteristics. For measurements with the contour measuring system, the following parameters were defined: diamond tip with 2 µm radius; measuring force of 1 mN; measuring speed of 0.1 mm/s; Gaussian filter with a cutoff wavelength of 2.5 µm.

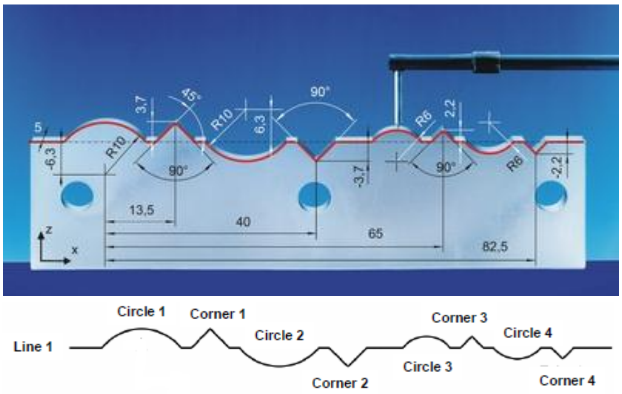


Fig. 4. Contour standard sketch illustrating geometric features and their nominal values

Both measuring setups were carried out on a temperature controlled laboratory and good laboratory practices observed (e.g. thermal stabilization of the artifact for 2 h). Each setup was repeated under (nearly) repeatability conditions in order to evaluate measurement consistency and the same software (and criteria) used to evaluate the measured points.

From the evaluation results for each measuring setup and run, the average and standard deviation of each parameter for each setup and the respective average deviation from the laser-based system results to the contour measuring system results were computed. The statistical measures just defined for each feature characteristic type, i.e., position, diameter and angle, were plotted on charts, shown in Fig. 5 to Fig. 7, and commented in the coming paragraphs.

The position relative error of each significant coordinate is exhibited in Fig. 5 (top). For Z-coordinates, relative errors were mostly within the interval of ±0.0002 mm. The largest error was found for the X-coordinate of corner 4. From the spread chart shown in Fig. 5 (bottom), one could evidence a reasonable degree of statistical control for both setups. That means the average standard deviation for both setups can be considered a consistent estimation of the variation (laser-based sensor: 0.42 µm; contour instrument: 0.24 µm).

The worst repeatability for the laser-based sensor can be explained by the machine dynamics, which encompasses the movement of larger masses than the contour instrument. The sewing shape of the position relative error could be imposed by non-compensated scale errors. However, further analyses would be required to confirm that hypothesis.

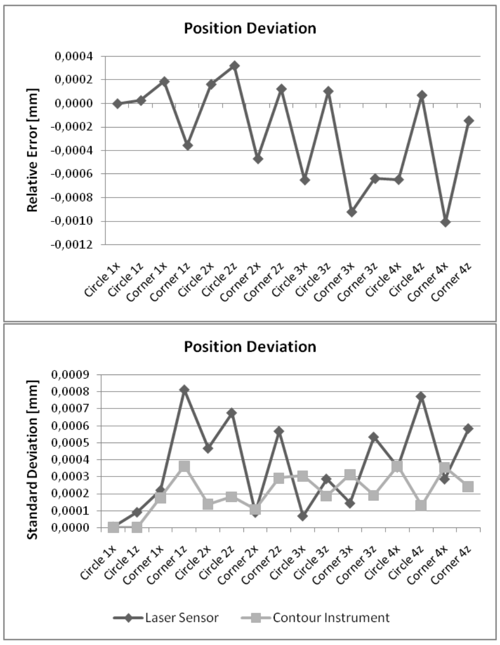
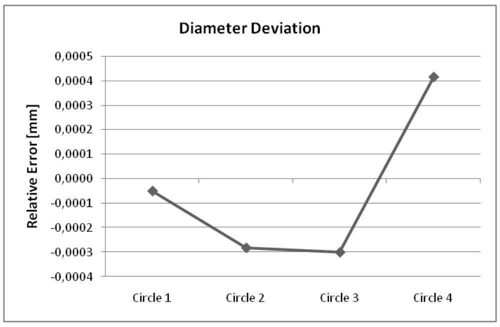


Fig. 5. Relative error for contour standard feature positions and standard deviation of readings with both measuring systems

The diameter relative error of the partial circular features is illustrated in Fig. 6 (top). All relative errors were found within the interval of ±0.0004 mm. From the spread chart shown in Fig. 6 (bottom), one could evidence a reasonable degree of statistical control for both setups (average standard deviation - laser-based sensor: 0.55 µm; contour instrument: 0.41 µm). Again, the worst repeatability for the laser-based sensor can be explained by the machine dynamics.



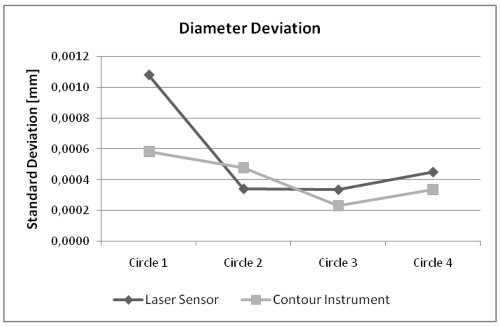


Fig. 6. Relative error for contour standard diameters and standard deviation of readings with both measuring systems

The angle relative error of the corner features is shown in Fig. 7 (top). The maximum deviation was of about 0.01°. From the variation chart shown in Fig. 7 (bottom), one could evidence an increasing variation for features away from the origin (circle 1 center). The assumption of uncorrected scale errors may be applied to explain the non-random variation.

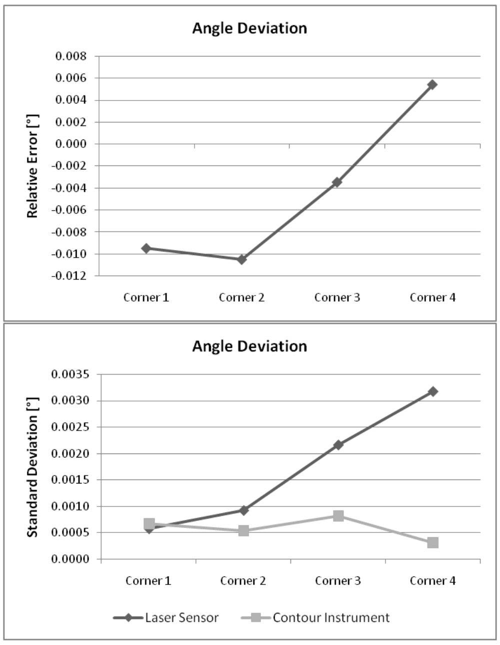


Fig. 7. Relative error for contour standard feature angles and standard deviation of readings with both measuring systems

Part of the relative deviation encountered in the results may be also attributed to the different scanning path traced by each measuring system. In fact, the relative alignment of the contour standard with the contact tip is done manually on the contour measuring instrument and automatically on the CMM (better alignment repeatability).

3.2. Optical-tactile measuring sensor

The optical-tactile measuring sensor could operate in two modes. If the glass fiber supplies light to the probing tip, measurement can be performed in the self-illuminating mode, which is indicated for measuring blind elements. It is also possible to use the sensor in the transmitted-light mode, which uses the optical system of the coordinate measuring machine and ensures illuminating the part from the bottom.

The fiber probe applies a negligible measuring force. For this reason, the fiber probe can measure especially contact-sensitive workpieces made of rubber and plastic in point-to-point measuring mode and scanning mode. When measuring aluminum and some plastic parts in the horizontal direction, adhesive forces may be observed between workpiece surface and probing element. Some tests have revealed that measurements performed in the vertical direction are less sensitive to the effect of intermolecular attraction between components. The measuring sensor also contains a vibrating system to attenuate the adhesion effect.

Let the use of a contact tip of 0.05 mm diameter, the measurement of tiny gears with 0.12 mm module and 2 mm nominal diameter has been made possible. The measuring sensor, however, cannot measure very deep holes. In spite of the nominal length of the glass fiber wire is of about 40 mm, the effective measuring distance from the top of the surface is restricted to a few millimeters.

In order to investigate the fiber probe performance for measuring microstructures, a set of roughness artifacts were chosen - see Table 1 for details; where R_a is the arithmetical mean deviation of the profile, R_z is the arithmetical mean of the single roughness depths of successive sampling lengths, R_{max} is the largest single roughness depth in the total measuring length [7].

Table 1. Nominal roughness values of the standards used to investigate the fiber probe performance (values in µm)

	Roughness Parameter		
Standard	**R_a**	**R_z**	**R_{max}**
A	0.157 ± 0.016	1.22 ± 0.12	1.33 ± 0.13
B	0.528 ± 0.042	3.15 ± 0.25	3.62 ± 0.29
C	1.50 ± 0.09	7.77 ± 0.47	9.24 ± 0.55

For the experiments a probe tip radius of 10 µm was attached to the fiber probe head and roughness parameters identified in Table 1 evaluated. Fig. 8 depicts the measuring setup. The same standard was measured ten (10) times under similar conditions (slight variation in the measuring path would be possible).

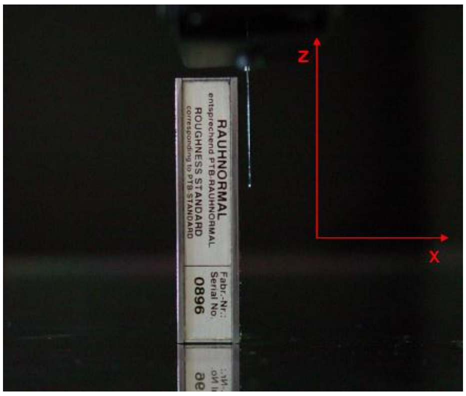


Fig. 8. Roughness standard measurement arrangement with a fiber probe mounted on a multisensor coordinate measuring machine

For standards A and B, all individual roughness values lied within the respective tolerance bands with reasonable repeatability. Fig. 9 illustrates the measurement behavior of standard A regarding the three roughness parameters. About

2000 points were sampled on each standard and used to compute the roughness parameters.

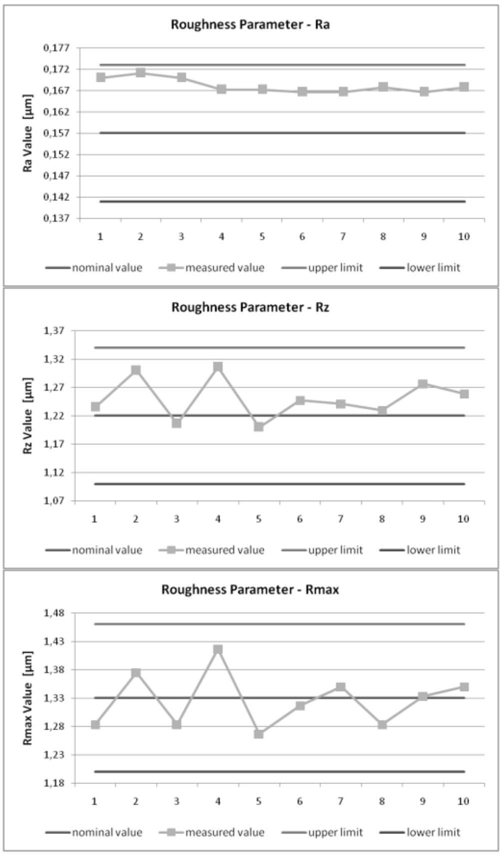


Fig. 9. Results of the roughness measurement with the fiber probe at different positions on a roughness standard - roughness parameters R_a, R_z, R_{max}

Due to the tip radius size, roughness standard C could not be properly measured and evaluated, as the tip radius causes a mechanical filtering effect. In addition, the limited lateral stiffness of the fiber probe would give rise to an unknown systematic error (measurement values would be too small). Thus, from the measurements one can conclude that the results for values up to about R_a = 1.5 µm are directly comparable with diamond probe tip measurements.

4. DISCUSSION AND CONCLUSION

Metrology needs directly related to component and part miniaturization, have been partially answered by developing new measuring sensors. Improvements in machine hardware and software have been also relevant to reach an appropriate metrology solution. The principal object of this work, the optical-tactile sensors showed essential features to satisfy recent microprecision engineering developments.

The very small sizes of the sensors and their features of concern, i.e., negligible contact force and scanning mode capability, combined with multisensor coordinate measuring machines, allows direct measurements of micro- and meso-scale structures with uncertainties down to a few tenths of micrometer. The fiber probe scanning of a cylindrical micro-gear profile at different positions is illustrated in Fig. 9. The measured points can be compared against the mathematical model and considerations about part conformance might be drawn.

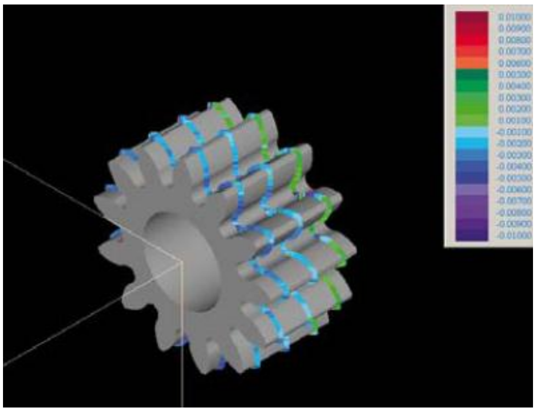


Fig. 9. Color-coded deviation map of the micro-gear profile at three probing paths

Due to the size of the probing element, roughness can be checked along with measurement of the part geometry when using an accurate coordinate measuring machine with low uncertainty under some conditions. Re-chucking of the part and alignment for roughness measurements can be avoided, and higher reproducibility can be reached due to automatic positioning of the machine.

REFERENCES

[1] A. Weckenmann, T. Estler, G. Peggs, D. McMurtry, *"Probing systems in dimensional metrology*", Annals of the CIRP, pp. 657-684, Vol. 53, No. 2, 2004.

[2] B. Muralikrishnan, J. Stone, J. Stoup, C. Sahay, *"Micro-feature dimensional and form measurements with the NIST fiber probe on a CMM*", Cal Lab: International Journal of Metrology, pp. 25-30, July/Aug/Sept, 2010.

[3] H. Schwenke, F. Härtig, K. Wendt, F. Wäldele, *"Future challenges in co-ordinate metrology: addressing metrological problems for very small and very large parts*", Proceedings of the IDW, pp 1-12, Knoxville, USA, 2001.

[4] H. Schwenke, F. Wäldele, C. Weiskirch, H. Kunzmann, *"Opto-tactile sensor for 2D and 3D measurement of small structures on coordinate measuring machines*", Annals of the CIRP, pp. 361-364, Vol. 50, No. 1, 2001.

[5] U. Neuschaefer-Rube, M. Neugebauer,W. Ehrig, M. Bartscher, U. Hilpert, *"Tactile and optical microsensors: test procedures and standards*", Measurement Science and Technology, Vol. 19, pp. 1-5, 2008.

[6] A. Weckenmann, G. Peggs, J. Hoffmann, *"Probing systems for dimensional micro- and nano-metrology"*, Measurement Science and Technology, Vol.17, pp. 504-509, 2006.

[7] DIN EN ISO 4287: Geometrical Product Specifications (GPS) - Surface texture: Profile method - Terms, definitions and surface texture parameters, 2010.