Innovations in

Every day, new products appear on the market. In order to meet the high quality standards that are expected nowadays by customers, reliable measurements with good accuracy are essential. This fuels a continuous demand for innovations in the field of dimensional metrology, the measurement of shape, size and position. Improvements have been made on various fronts : reliability, speed, range and accuracy. Partly, these innovations are realized by the improvement of existing techniques. But we also see the emergence of completely new measurement principles. To provide an overview of the most recent developments, a one-day symposium was organized on 5 February 2009 under the title "Innovations in Dimensional Metrology". What better location to hold such a symposium than at the Dutch national metrology institute VSL in Delft, the Netherlands?

• *Marijn van Veghel* •

The symposium was jointly organized by Mikrocentrum and VSL. There was a good turn-out, with a mixed audience from the Netherlands and Belgium. Apart from oral presentations, there was also an exhibition with suppliers showing their latest products. Prof. Piet Schellekens, well-known for his work in the area of dimensional metrology at the Eindhoven University of Technology, acted as chairman of the day.

Innovation in standards

After the opening statement of the chairman, the director of VSL, Albert Dalhuijsen, delivered the first lecture. He gave background information on VSL and its role as the national metrology institute. VSL (formerly NMi Van Swinden Laboratorium) is responsible for maintaining the Dutch primary standards (such as the meter and the kilogram) and providing traceability to these standards. The concept of traceability means that companies, institutes, government agencies, etc. can trace their measuring instruments back to the primary standards via an unbroken chain of calibration steps. VSL performs the last step or steps in such a traceability chain, which have to be done with the best possible uncertainty. Traceability is important, because it ensures that measurements are reliable and comparable.

It may seem that there is little room or need for innovation in this activity. This however is certainly not true. Over the years a lot of effort has been put into decreasing the uncertainty with which the standards of the SI system of units can be realized, and with which calibrations can be performed against these standards. More recently, the attention of the research at VSL has shifted to the development of new standards, which specifically target technological developments in society: biofuels, electrical power loss in the transportation grid, LEDs, breath analysis and structures on micro- and nanometer scale. Companies active in these areas can call upon the expertise of VSL in the form of calibrations, consultancy or custom R&D.

Task-specific uncertainty for CMMs

An example of innovations at VSL was given by the author of this article, in a talk dealing with realistic uncertainty estimations using virtual instruments. When doing a measurement, it is important to know the uncertainty, a parameter which indicates the possible difference between the measurement result and the true value. This forms a quantitative measure for the reliability of the measurement. The uncertainty should include all systematic and random effects. Whereas the latter are determined relatively easy from a statistical analysis of repeated measurements, the former are more difficult to ascertain. Still, it is important to have as realistic a value for the measurement uncertainty as possible. Underestimation will give unjustified confidence in the measurement result. Overestimation on the other hand is economically undesirable, as unnecessary efforts will be made to reduce the uncertainty to the required level.

There exists a well-accepted recipe for uncertainty estimation in the form of the ISO Guide to the expression of Uncertainty in Measurement (GUM). For some types of measurements, this approach however is inapplicable. A notable example are dimensional measurements based on 3D co-ordinate measurements, e.g. the measurement of the diameter of a cylinder on a co-ordinate measuring machine (CMM). The measurement result is calculated from many points, which contain correlated effects, such as the guidance errors of the machine. Furthermore, the calculation method is some numerical fit, which does not lend itself to the GUM recipe.

For these types of measurements a different approach is needed. At VSL, so-called Monte-Carlo methods have been developed for a variety of co-ordinate based measuring instruments. These Monte-Carlo methods are described theoretically in a newly released supplement to the GUM (2008). They use a software model of the measuring device, called a virtual instrument; see Figure 1. Uncertainty distributions are assigned to the measurement data and the model parameters. New measurement data and model parameters are generated, by randomly picking values from these uncertainty distributions. A measurement result (say, a diameter) is then calculated for the randomly generated data. By repeating this many times, a distribution of measurement results is obtained, from which the uncertainty can be determined.

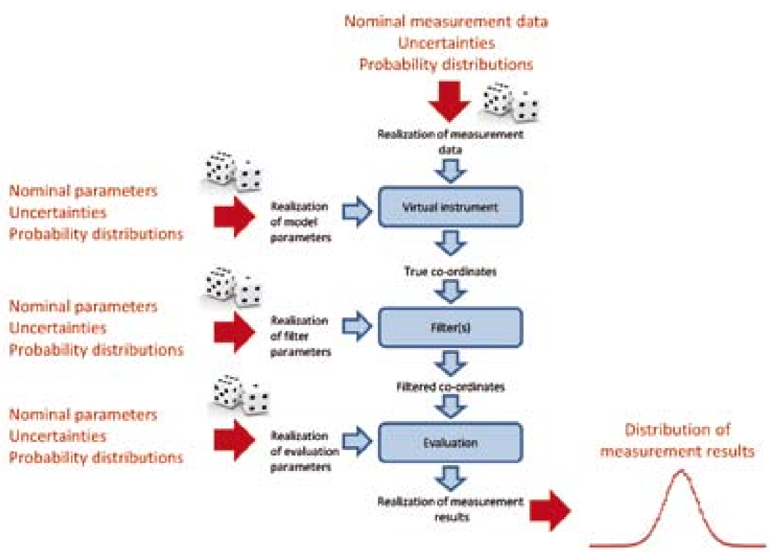

Figure 1. Schematic representation of a Monte-Carlo uncertainty calculation. (Courtesy of VSL)

Applications of this method to various instruments were shown: a stylus profiler, a scanning probe microscope (SPM) and a micro-CMM. The micro-CMM in question is the F25 developed in a collaboration between Eindhoven University of Technology, Carl Zeiss and VSL. The model parameters and their uncertainties in this case are directly linked to the results of the complete laser-interferometer-based calibration performed on the instrument by VSL. The virtual micro-CMM was tested using independently calibrated reference spheres, and the predicted uncertainty agreed well with the observed deviation in sphere diameter.

It is expected that the virtual instrument approach will be applied more and more in the future, and will also be increasingly incorporated into commercial instruments. This will enable users to obtain realistic task-specific uncertainties, instead of machine tolerances which apply to a single point only.

The topic of uncertainties of CMMs in specific measurement tasks was continued by Nick van Gestel of the K.U.Leuven. He addressed a number of influences that determine CMM uncertainty. A well-known source of uncertainties in dimensional measurements is thermal expansion. An accurate measurement of the workpiece temperature is needed to compensate for this. What is perhaps not always realized, is that temperature gradients can be more disturbing than a uniform deviation in temperature. This is especially true in large machines such as CMMs, which may deform as a result of temperature differences between two sides of the instrument. Deformations may also arise because of uniform temperature changes in materials with different expansion coefficients (aluminium, steel or granite). In planning a measurement it is good practice to keep in mind that the temperature will slowly change during the measurement, and hence measure the most critical dimensions as closely after each other as possible.

A question of great practical importance is how to distribute the measurement points over the artifact. Sampling exactly on the peaks or the valleys of the form error of the artifact will give an over- or underestimation of, say, a cylinder diameter. Van Gestel showed that for a cylinder having a 120° symmetric form error, a number of equidistant sampling points which is a multiple of three gives a large error in the diameter, but a relatively small error in the position.

Ultra-precision CMM

On the front of CMM hardware, there have also been developments, of course. One of the long-standing goals has been to reduce the measurement uncertainty. This has been realized in so-called micro-CMMs, such as the F25. These instruments realize uncertainties of down to about a hundred nanometer in a measuring volume of up to a hundred millimeter. The company IBS Precision Engineering is now developing a new ultra-precision CMM, which should realize a 3D measurement uncertainty of 100 nm within a measuring volume of no less than 400 × 400 × 100 mm³. The name of the design, which was presented by Rilpho Donker, is Isara 400; see Figure 2. The name Isara refers to a Mesopotamian goddess. It was first used for IBS's previous ultra-precision CMM, which had a measuring volume of 100 × 100 × 40 mm³.

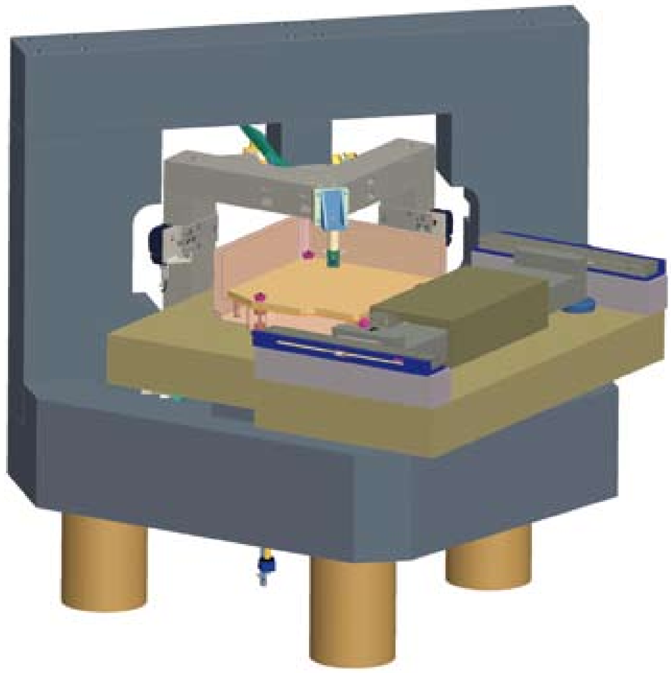

Figure 2. The new Isara 400 ultra-precision CMM being developed by IBS. (Courtesy of IBS Precision Engineering)

What the new Isara has in common with its predecessor is the 3D Abbe concept. In this concept, the x, y and z co-ordinate measurements are done with plane mirror laser interferometers. The laser interferometers are stationary with respect to the probing system and aligned in such a way that they intersect in the center of the probe sphere. The object to be measured is placed on a monolithic three-sided mirror block, with can be translated with respect to the probe. The main benefit of this construction is that the measurement always satisfies the Abbe principle, since there is no offset between the measurement axis and the probing point. Because of this, there is to first order no effect from parasitic rotations.

In the practical realization of the instrument, there are some noteworthy differences. In the original Isara, the mirror stage was translated in three dimensions, while the probe remained stationary. The new Isara uses a 2D translation of the mirror block over a stationary granite table for the x and y motion. Translations in z direction are accomplished by moving the whole metrology frame, including the laser interferometers and the probe, in vertical direction. The metrology frame, which has to be at the same time light, stiff and thermally stable, is constructed from SiC. All guides are equipped with air bearings, instead of the roller bearings in the original Isara. The cylindrical air bearings for the z drive moving the metrology frame double as a weight compensation mechanism, to minimize the power needed to hold the metrology frame in place.

The Isara 400 is intended to be a multi-probe machine. One of the probes it will use is an ultra-precision touch probe designed by IBS; see Figure 3. This probe consists of a 0.5 mm ball attached to a very thin, yet stiff stylus. The stylus is mounted onto a leaf spring design, so that it can rotate around the x and y axis and translate in z direction. The probe deflections are measured using capacitive sensors. Measurement errors in 3D for this probe were shown to less than 20 nm.

Figure 3. The IBS ultra-precision touch probe which will be used on the new Isara 400. (Courtesy of IBS Precision Engineering)

Laser scanning

Nowadays, 3D measurements are not restricted to tactile instruments. Contactless measurements make it possible to acquire a lot of data points in a short time without making physical contact with the object to be measured. Philip Bleys from the Belgian technological center Sirris presented the latest developments in laser scanning. In laser scanning based on triangulation, the workpiece is illuminated with a laser beam; see Figure 4. Reflections from the workpiece surface are captured by an imaging lens which is positioned somewhat to the side of the laser aperture in the sensor head. The lens projects the reflected light onto a digital sensor (CCD or CMOS camera). The position of the imaging lens is fixed, so that the illuminated position on the sensor is dependent on the angular direction of the light falling on the imaging lens. This in turn is directly related to the distance between the sensor and the workpiece. To improve the data acquisition rate, a line of laser light can be used instead of a single spot. This line can be generated by projecting a laser beam onto a resonating mirror or by special optics. The latter method generates a more homogeneous line.

One of the developments in the field of laser scanners is the integration of multiple scanners in a single sensor head. In a so-called cross scanner, three line scanners placed under angles of 120° are combined. This will increase the point density, but also provide a more uniform coverage of features such as circular holes. These are now covered by scan lines in three different directions, so that there is always a scan line intersecting the edge of the feature.

Other important improvements are in the digital camera and the illumination. The acquisition rate of the digital camera increases, allowing a higher point collection rate. Dynamic laser power control is a technology which actively controls the laser intensity dependent on the amount of reflected light from the surface. This is especially helpful on difficult surfaces : shiny materials, surfaces with multiple colours or with sharp reflection angles.

In terms of uncertainty, laser scanners are still inferior to tactile sensors. One of the main uncertainty sources is the heat generated in the sensor head, which is unavoidable given the presence of a light source. Various measures are taken to increase the thermal stability, such as separation of heat generating components, cooling fans and software compensation. This considerably reduces the warm-up time that should be observed before the sensor can be considered stabilized.

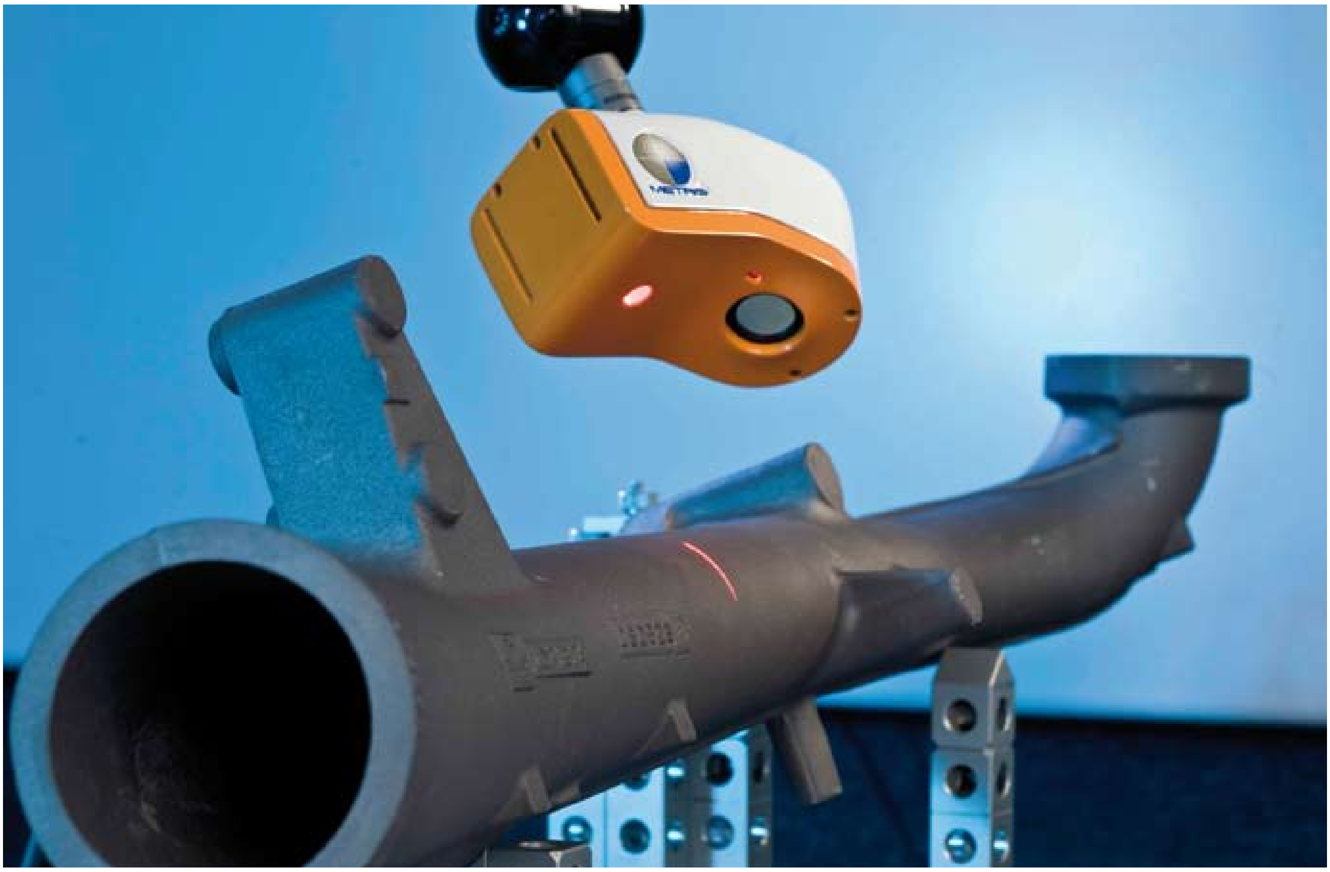

Figure 4. Laser scanner scanning a workpiece. The laser projecting the line is situated in the left part of the scanner, the lens and camera are in the right part. (Courtesy of Sirris)

X-ray tomography

The third measurement principle discussed was X-ray computerized tomography (CT). Pieter-Jan Corthouts from Metris gave his talk the title “Where tactile probes cannot reach and optical laser scanners cannot see”, to emphasize the main advantage of X-ray tomography, namely the ability to measure internal features of objects. CT started as an imaging technique, to making 3D images of internal structures, e.g. for medical applications. In the last few years, CT has made the transition from an imaging tool to a metrology tool, where accurate dimensional measurements can be taken from the data.

A CT system has three main components: the X-ray source, the object table holding the workpiece to be measured and a 2D X-ray detector. In a medical system, source and detector rotate around the patient, but in a metrological CT system, the object table is rotated. At each angular position of the object, a 2D X-ray image is taken. The different shades of gray in this image correspond to different amounts of X-ray absorption along a particular line from source to detector. A computer then constructs a 3D map of the absoption from the set of 2D images. Because the absorption coefficient is material dependent, it is possible to differentiate between regions of different material composition in 3D.

Using CT for metrology purposes puts special demands on the X-ray source. A typical medical X-ray source has a size of approximately 1 mm, leading to a blurred image, which has insufficient resolution to take useful measurements. In order to get an image which is sufficiently sharp for dimensional measurements, a so-called micro-focus source with a source size of 5 μm or less is necessary. Also, the

X-ray beam has to be 'hardened' by filtering out low-energy X-rays, which have a low penetration depth. Otherwise there will be too much gradient in the beam intensity, leading to a deformed image.

By showing a wide range of examples, ranging from diesel injectors, hydraulic manifolds to dental parts and even fossils, Corthouts demonstrated the versatility of this technique, which will undoubtedly gain importance in years to come.

Metrological AFM

The day was concluded with a presentation on 3D measurements on the smallest possible scale. Chris Werner from the Control Systems Technology group at Eindhoven University of Technology presented his PhD-project on the design of a metrological Atomic Force Microscope (AFM); see Figure 5. This AFM is being developed in a joint project with VSL and will serve as VSL's next generation AFM.

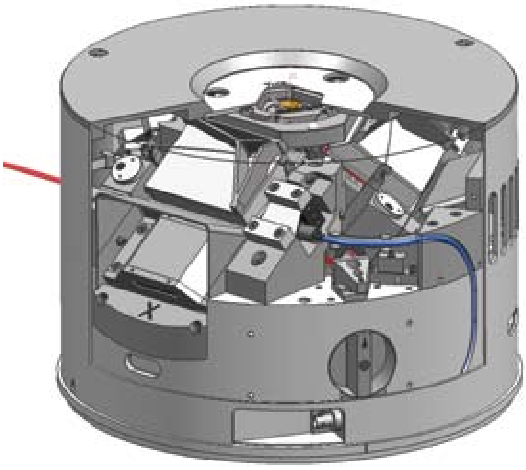

Figure 5. The new metrological AFM being developed at Eindhoven University of Technology. (Courtesy of TU/e)

An AFM measures small structures by scanning a tactile tip over a surface. The instrument Werner is developing has a target uncertainty of 1 nm over a $1 \times 1 \times 1$ mm^3 measuring volume. For an AFM, this is exceptionally large. Unlike most commercial AFMs, the tip in this instrument is stationary and the sample is scanned underneath it. The position measurements are done with three interferometers which have their virtual measurement axes aligned on the tip, so that they are always in Abbe. The interferometers are differential interferometers, which are insensitive to drift in the position of the interferometer optics. The optics are custom-made, with a beam delivery system integrated in the instrument.

A special feature of the AFM is the rotated measurement co-ordinate frame. Instead of having the x and y axes in the horizontal plane and the z axis vertical, the measurement axes are aligned on the edges of a cube with its body diagonal in the vertical direction. This means that all three axes can be constructed identically, giving a large amount of symmetry in the system. The straight guides are constructed as elastic parallel guides, having a high eigenfrequency of 1.4 kHz. They are actuated by powerful Lorentz-type actuators delivering 57 N/A. In order to minimize power dissipation, stiffness and weight compensation mechanisms are present.

One of the nice features of the design is that by a careful layout of the components, Werner has managed to contain everything within a compact table-top instrument of 250 mm diameter. The metal components are manufactured from a single piece of aluminium, a material chosen for its good thermal conductivity and diffusivity. The expansion coefficient of this aluminium has been especially calibrated by VSL. This has been used to optimize the thermal loop, so that the instrument is insensitive to a uniform temperature rise.

Author's note

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Information

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