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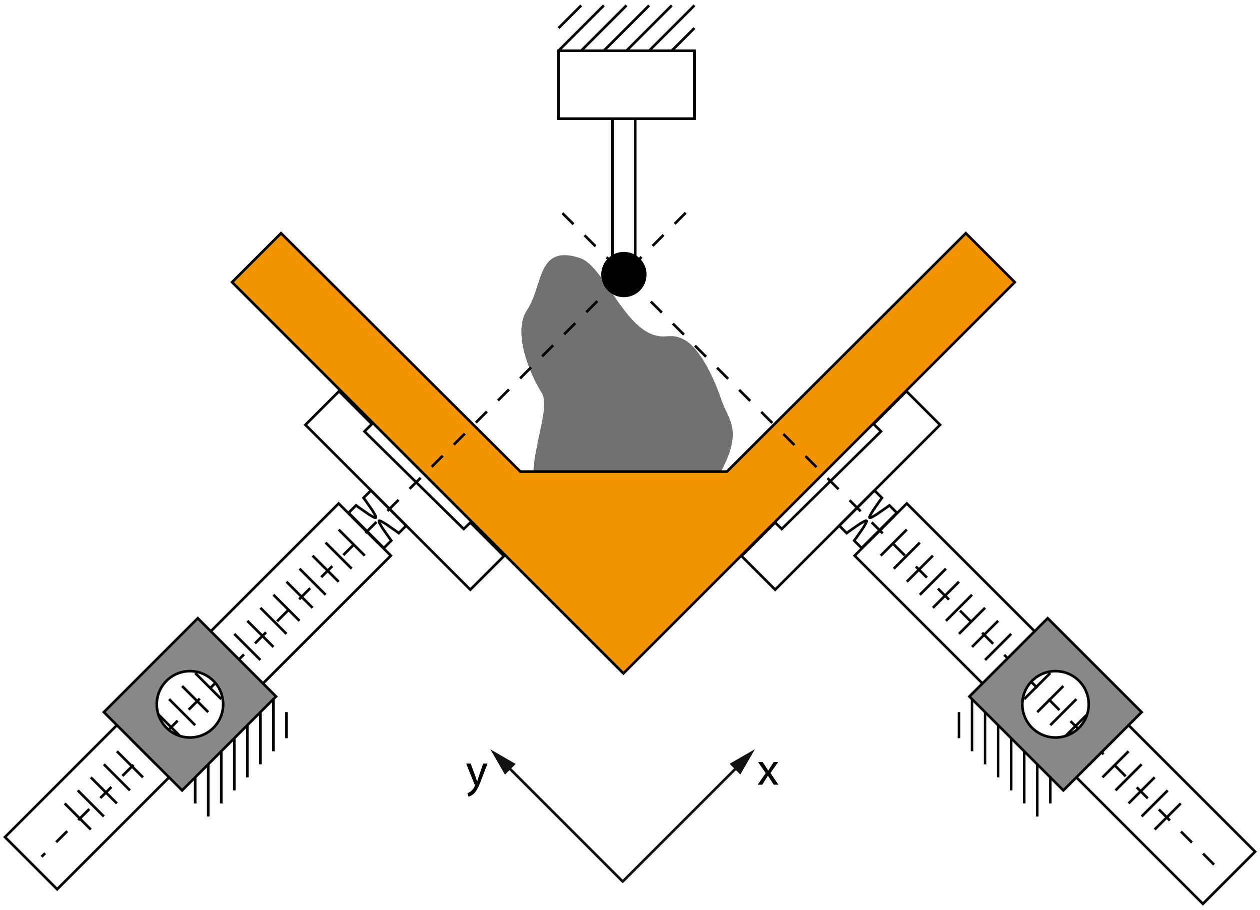

Special Issue Metrology

New line-scale facility at VSL • Displacement measuring interferometry overview
TriNano micro CMM • X-ray computer tomography • After the crisis: Mitutoyo
Piezoelectric thin-film characterization • Quality inspection of micro-parts
Euspen 2010 conference report • Company mission mechatronics Thuringia

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The cover graphic (TriNano schematic 2D operating principle) is courtesy Xpress Precision Engineering.

editorial

European Metrology Research Programme

Although we do not often think about it, measurement underpins virtually every aspect of our daily lives. It helps us ensure the quality and the safety of the food we eat, the air we breathe and the water we drink. In manufacturing, process control and virtually every other sector measurements are crucial. It is fair to say that our ability to measure often defines the boundaries of possibility. What we can not measure, we generally do not understand properly, can not make accurately nor control reliably. Research in metrology, the science of measurement, has a profound impact on how we understand and shape the world around us, and provides the tools that allow other areas of science to advance their frontiers.

Metrology presents a seemingly calm surface covering depths of knowledge that are familiar only to a few, but which most of us make use of – confident that they are sharing a common perception of what is meant by expressions such as meter, kilogram, liter, watt, etc. This confidence is achieved by co-operation, common units of measurement and common measuring procedures.
This is the task of the National Metrology Institutes (NMIs). Thus they develop measurement standards for all SI units and derived quantities and they ensure traceability of measurements to these standards with a specified uncertainty. Through regular 'key comparisons' on a global level (worldwide metrology) an internationally agreed metrological system is assured.

Recently, however, the metrology community across Europe was faced with the dilemma of demand outstripping national capability to deliver. The need for wider scope and greater precision required a paradigm shift in the way we operated. Thus, the concept of pooling resources across Europe and developing a joint European Metrology Research Programme (EMRP) was born. EMRP is a long-term strategy for joint high-quality R&D in the metrological community in Europe, ensuring collaboration between NMIs and enhancing the impact of metrology. A higher goal of EMRP is to accelerate innovation and enhance European competitiveness. EMRP is an 'Article 169' initiative funded by 22 participating countries and the European Commission. This programme has a total value of M€ 400 over approximately seven years (with the first of five calls for proposals in 2009). The programme provides the opportunity for the user community and other stakeholders to directly suggest topics that the NMI community should address with its resources. So, I challenge you all to seize this opportunity.

Albert Dalhuijsen
Managing Director VSL, the Dutch National Metrology Institute

A new standard for line-scale calibrations in the Netherlands

Extremely accurate calibration of (line) scales requires dedicated equipment and measurement conditions that are usually only implemented at the national metrology institutes. The Dutch metrology institute VSL has several facilities to calibrate scales from small micrometer scales up to leveling rods and tape measures with lengths over tens of meters to high accuracy. In order to ensure that VSL can continue to provide services for the ever increasing demand for higher accuracies, these facilities are continuously improved. This paper describes the efforts that have been undertaken recently to improve VSL's capabilities for the calibration of high-precision line scales as well as the motivation for the choices that have been made during this process.

• *Richard Koops, Ancuta Mares and Jan Nieuwenkamp* •

Line scales are important physical standards of length, used for accurate positioning or measurement in one, two or three dimensions. Depending on the application, line scales can have dimensions from fractions of a millimeter to several tens of meters. For example, small scales are used to calibrate the field of view of optical microscopes. Scales with dimensions in the meter range are used to read out the position of machine tools and measuring machines, while leveling rods find their use in geodetic surveying.

Calibration of high-precision line scales

Until recently, precision lines scales were calibrated manually at VSL using a 400 mm SIP measuring machine,

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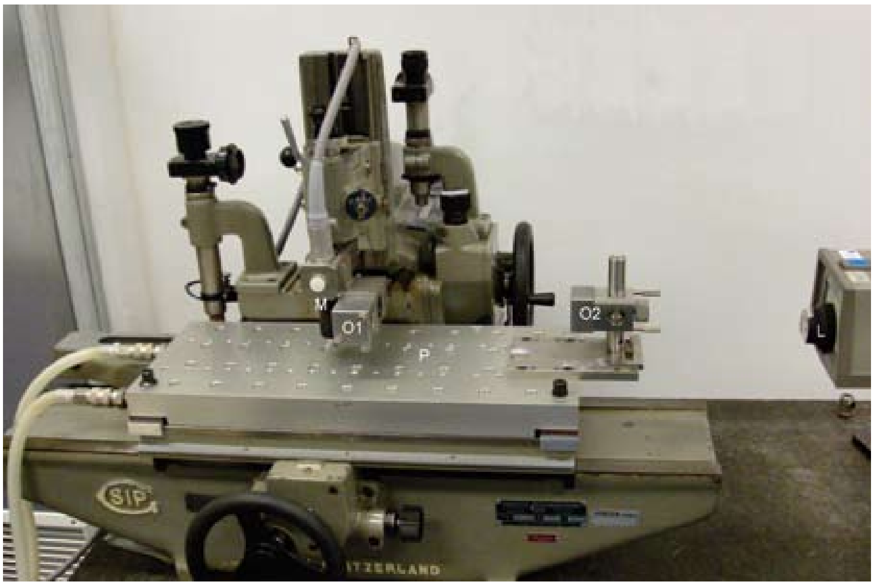

Figure 1. Previous facility at VSL to manually calibrate line scales up to 400 mm. The position of the platform P with the scale (not shown) is manually translated with respect to a video microscope M and measured by a laser interferometer consisting of laser L and optical components O1 and O2. For improved temperature stability the temperature of the platform can be controlled separately.

see Figure 1. Although this machine has three axes, only one of them is used during the calibration process. The measuring machine is equipped with a camera system to visualize the scale markers and a laser interferometer system to measure the position of the camera relative to the scale.
During the calibration procedure the image from the camera is converted to a single curve that represents the intensity of the image features – manual alignment of the scale marker to the exact centre of the image is performed by adjusting this curve to its mirror image. After each alignment step the position of the camera with respect to the scale is stored manually.
The uncertainty that has been realized by this facility and that is registered as part of VSL's calibration and measurement capabilities in the CMC database at BIPM [1] is 100 nm + $10^{-6}L$ where L is the length of the scale.

During the past decade this facility has been upgraded, but due to mechanical, optical, thermal and electronic limitations further improvements are not feasible without major modifications. Additionally, this facility has the drawback that it requires realignment of the entire optics for the laser interferometer for each scale. Finally, given the fact that a large part of the calibration procedure is performed manually, the amount of scale markers that can be calibrated is limited due to time constraints.

New calibration set-up

In order to improve the quality for precision line-scale calibrations, it was therefore decided to design and build a new facility. This facility should enable lowering the measurement uncertainty to 30 nm + $5{\cdot}10^{-7}L$ for an increased measurement range of 1,000 mm. To minimize the manual labour during the calibration process, the measurement sequence should be fully automated, allowing calibration of every marker on the line scale. The basic design concept chosen for the new line-scale set-up is similar to that realized at the Finnish metrology institute MIKES [2].

A schematic overview of the new set-up is shown in Figure 2. The system can be divided into four main parts: a granite guide, an actuation mechanism, a movable vision system and a laser interferometer. The vision system captures images of the scale markers on the fly while moving over the line scale on an air-bearing platform that is translated by the actuation mechanism. Along with the image acquisition of the line-scale markers the position of the vision system is captured synchronously by a laser interferometer. In the following sections the individual components will be described in more detail.

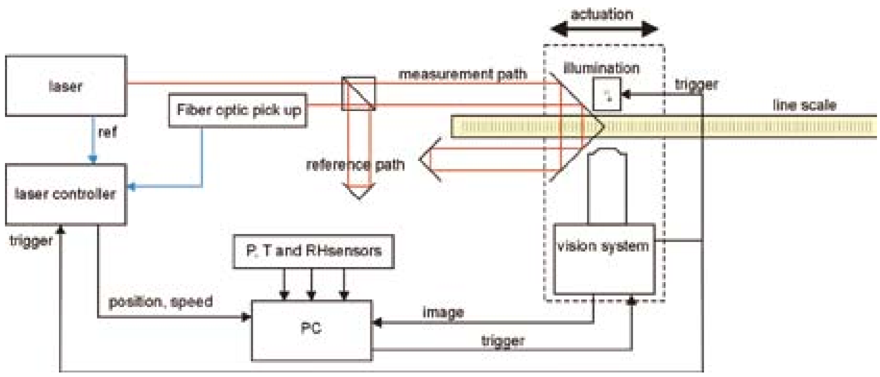

Figure 2. Schematic view of the new set-up. The vision system is mounted on an air-bearing platform that is connected to a motor by a wire. The position of the platform with respect to the stationary line scale is measured by a laser interferometer.

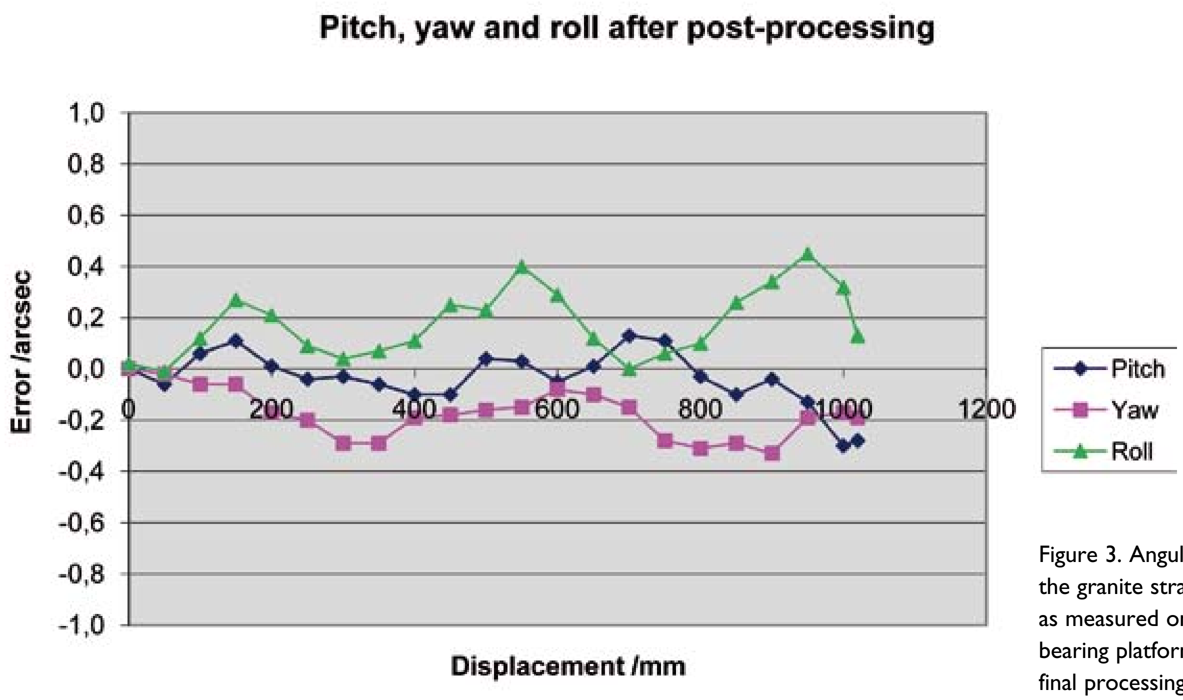

Figure 3. Angular errors of the granite straight guide as measured on the air-bearing platform after the final processing step.

Granite straight guide

The straight guide is part of a granite stone measuring 2,000 x 1,000 x 400 mm^3. The straight guide defines the movement of the air-bearing platform that holds the vision system. Shape deviations in the guide result in pitch, yaw and roll motion of the air-bearing platform and therefore result in changes in the directions of view of the vision system. Especially pitch rotates the view in the direction of measurement resulting in a measurement error. Given the total measurement uncertainty for the complete set-up, VSL's requirement for the maximum angular errors (pitch, yaw and roll) is 0.4 arcsec (approximately 2 μrad), which was met after the granite guide was post-processed by the supplier [3] in the VSL laboratory; see Figure 3.

The thickness of the granite was determined by the boundary condition for the stability of the entire set-up. When the granite deforms due to the moving platform, the supporting points of the scale will pivot and translate the scale during the calibration. A constraint of 2 nm for the maximum displacement of the scale restricts the bending of the granite to 30 nm, resulting in a thickness of the granite block of 400 mm.

During calibration the line scale is supported at the Bessel points, ensuring minimal change in the length of the scale. Since the remaining bending of the granite will result in opposite pivoting of the supports, the scale might slip on the contact points and change the position of the scale with respect to the measurement system in a non-reversible way. To avoid this, materials with different friction coefficients for the two supporting points were selected.

The stability of granite reference flats is largely determined by the stability of the vertical temperature gradient along the thickness of the granite [4]. A vertical temperature gradient of 0.1°C will result in a flatness error of about 1 μm that produces 1 μrad angular error over 1,000 mm. Therefore, besides conditioning the laboratory, the power dissipation in and around the set-up should be kept to a minimum. This was achieved by using low-power components (high-efficiency LED [5, 6] in pulsed mode, low-power dc motors [7]) and placing the dissipating equipment outside the measurement area.

Actuation

The air-bearing platform is translated over the full range of 1,000 mm using a kevlar wire that is connected to a low-power dc motor [7]. The air supply is connected to the platform by relatively stiff plastic tubing. During the travel over 1,000 mm these tubes change shape and therefore exert changing forces on the platform that could distort the linear translation. In order to avoid this, a second, smaller platform on a conventional ball-bearing guide was realized that moves synchronously to the main platform to stabilize the shape of the tubing and ensure that the movement of the main platform is not distorted.

The measurement system

During the calibration sequence, the measurement platform with the vision system is moving continuously. The position of the scale markers is calculated from both the image information and the position information, so it is very important that these two are acquired synchronously. The data-acquisition timing scheme is shown in Figure 4.

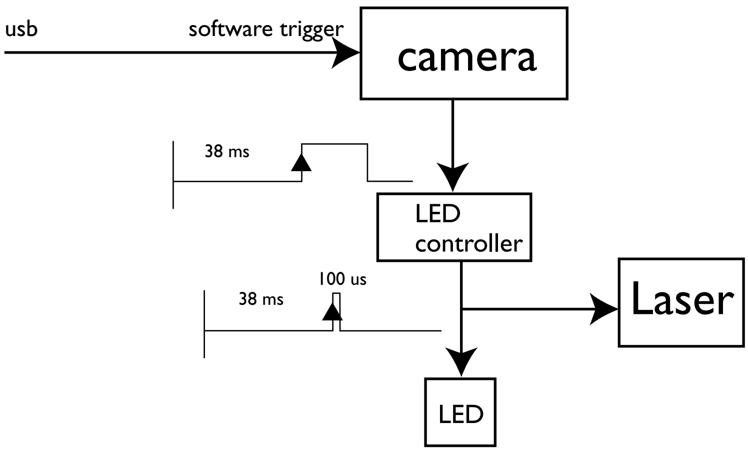

Figure 4. The synchronization of the data acquisition is critical and is initiated by a software trigger of the camera of the vision system. The camera has to prepare for acquisition and after 38 ms releases a trigger that starts the LED flash illumination and latches the momentary position information of the laser interferometer. The trade-off between acceptable image blurring and sufficient exposure of the frame has finally resulted in an optimized flash duration of 100 µs.

The vision system consists of a microscope with zooming capability [8] and a camera [9] with a resolution of 1,280 pixels x 1,024 pixels. The microscope is equipped with a quarter-wave plate to maximize the contrast of the relevant features on the line scales. The field of view at the highest magnification setting is about 0.28 x 0.35 mm^2, yielding about 270 nm per pixel. Initial image analysis is performed using a basic algorithm on-line during the measurement, in order to detect errors of the calibration process itself. A more detailed analysis with higher accuracy is performed off-line, because this is computationally too intensive.

Since the measurement takes place while the vision system is moving, the image will be blurred to some extent. Only when the camera has a very fast shutter or when the illumination time is short enough, the blurring will become acceptable. It was decided to use pulsed illumination – for an acceptable image contrast it was observed that a pulse duration of at least 100 µs is necessary. For the measurement speed of 0.2 mm/s the blurring therefore becomes 20 nm. Since the blurring should be equal for every scale marker it does not contribute directly to the measurement uncertainty. It is the fluctuations in the actual measurement speed, determined to be about 10% of the speed, which will cause different blurring for different markers. The final contribution due to image blurring to the measurement uncertainty is therefore 2 nm.

The image acquisition during the calibration process is adjusted such that the relevant information of the scale marker is close to the centre of the image, in order to minimize the influence of measurement errors due to the

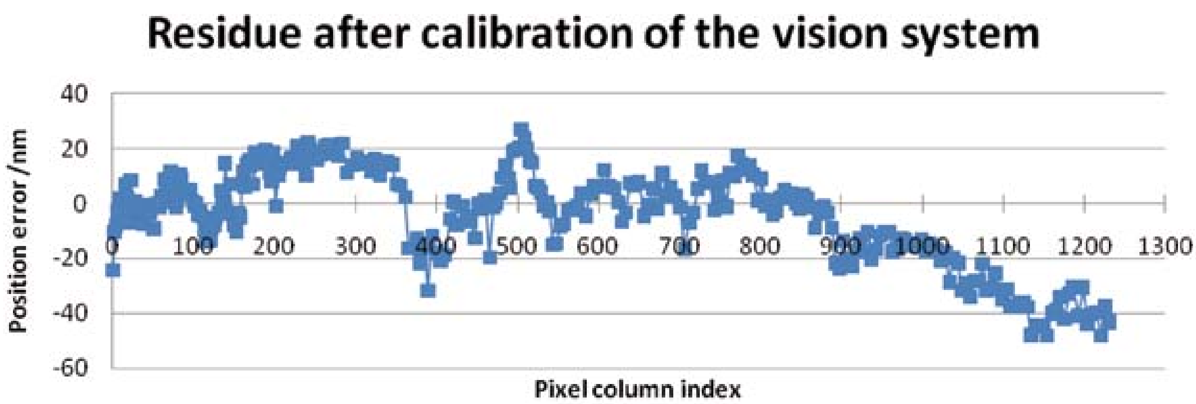

Figure 5. The residual errors of the vision system after calibration with the laser interferometer along all pixel columns. The graph shows slightly less columns than the actual 1,280 because for the first and last few columns the line-scale marker is not completely imaged. The calibration has been optimized for the central region of the vision system between pixel columns 540 and 740.

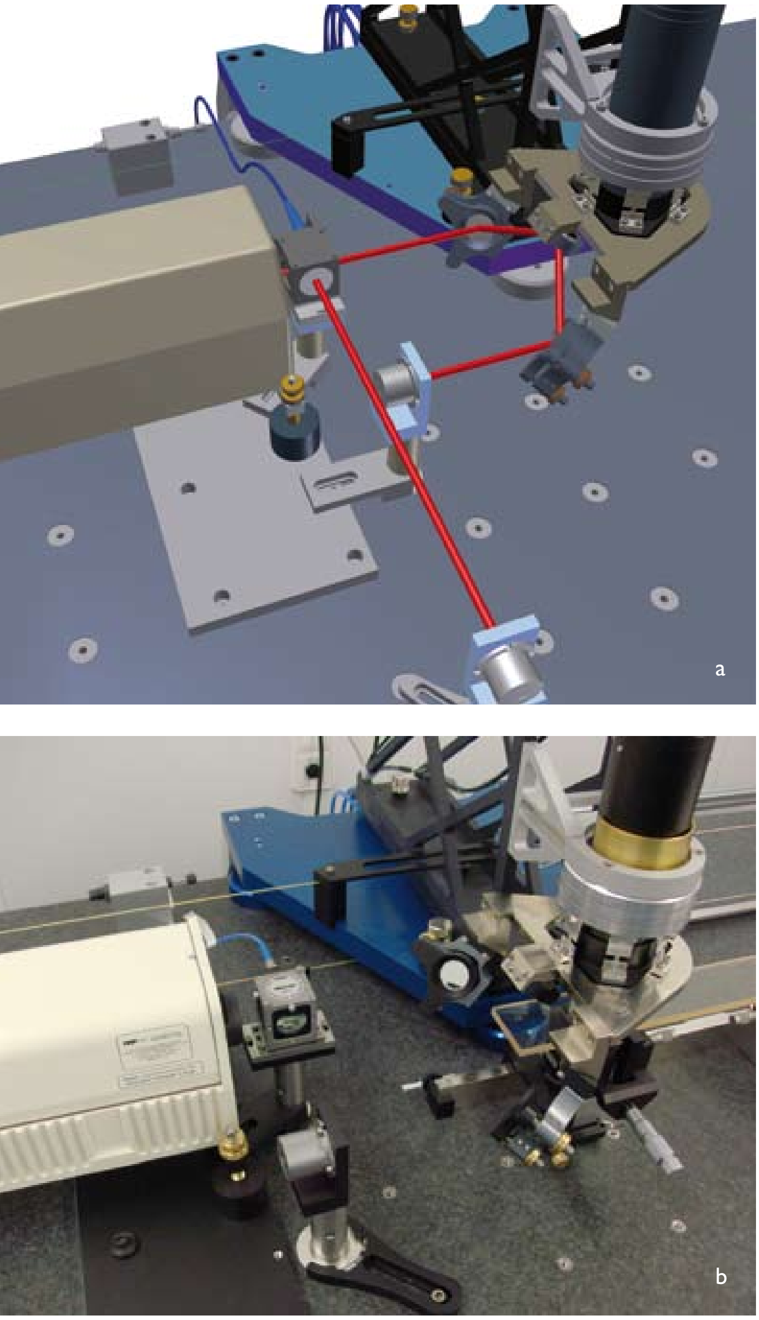

Figure 6. Design (a) and realization (b) of the measurement system. The laser beams along the measurement and reference path have been indicated in the design drawing. The effective measurement position of the laser interferometer is aligned to the field of view of the vision system in order to minimize the Abbe error.

inhomogeneous illumination and aberrations of the imaging system. In order to convert the image information, stated in pixels, to a position in meters, the vision system was calibrated by translating a marker line across the entire field of view. Figure 5 shows the residue of the position for every pixel column of the vision system that was obtained after subtracting the linear response for a scaling factor of 277.34 nm/pixel. The scaling factor was calculated for a minimum residue near the center of the image. The image acquisition is performed between the columns 540 and 740, because of the experimental observation that the relevant features of the line-scale markers are always imaged within 100 pixels from the centre position at column 640. Here the maximum position error is about 15 nm. If the measurement is repeated multiple times the contribution to the error would average out to less than 1 nm. Since the amount of repeats is limited, the fully averaged value is not realistic. In order to estimate the uncertainty contribution more realistically, the standard deviation of the errors in the centre region is taken. This value is 7 nm.

The position of the air-bearing platform with the vision system is measured with a double-pass laser interferometer [10], shown in Figure 6, for which most components are commercially available. For the speed that is used only one image can be taken with the scale marker close to the centre of the frame. To ensure sufficient signal quality the image processing uses averaging over all 1,024 image lines. The contribution to the measurement uncertainty due to the laser interferometer is given by its resolution of 0.6 nm.

The laser interferometer signal is optimized using high-quality mirrors and maximum mechanical and thermal stability of the optical components in the interferometer. Also the connection between the composite cube corner and the vision system has to be thermally stable. A temperature fluctuation of 0.1 K would result in an error in the scale calibration of at least 100 nm for a direct mount of the two components. In order to reduce this error, a symmetric invar mount was constructed with its thermal centre nominally on the symmetry axis of the microscope, reducing the contribution to the measurement uncertainty to 10 nm.

During a line-scale calibration the starting position is such that the vision system is closest to the laser interferometer optics, minimizing the amount of air in the measurement path and therefore maximizing the stability of the zero-position measurement. Additionally, the interferometer was designed to have equal lengths of the measurement path and the reference path at the starting position of the calibration (see Figure 6), such that most local fluctuations will cancel out.

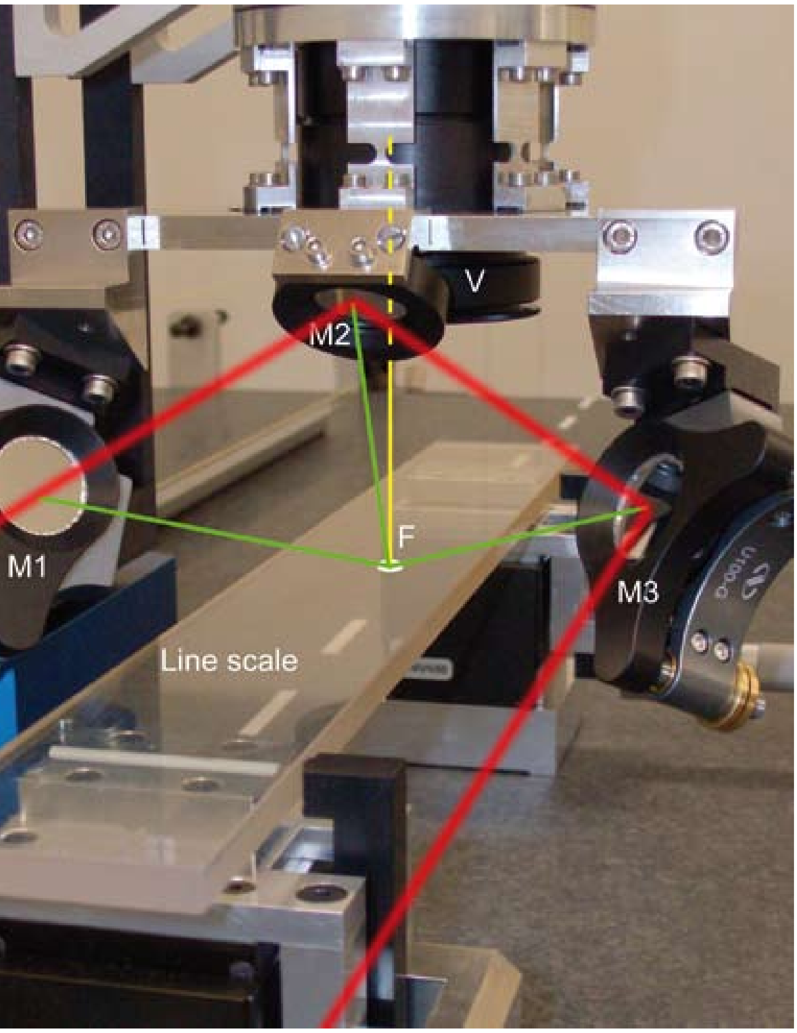

Figure 7. The composite cube corner retroreflector consisting of mirrors M1, M2 and M3 has its virtual apex aligned at the centre of the focal plane F of the vision system V. Rotational errors of the vision system during the translation result in a tilt of the field of view. The resulting errors as measured by the vision system are, however, compensated because the cube corner apex is translated over the same distance.

Abbe errors

Since the accuracy of the straight guide is limited by the residual imperfections that remain after post-processing the granite, the translation of the platform is not perfectly straight. The Abbe error that is introduced in this way is proportional to the tilt of the vision system and the distance between the vision system and the line scale. An Abbe error compensation was implemented as shown in Figure 7. The optical system is implemented as a composite cube corner retroreflector that has the apex at the effective point of measurement. In this way any common movement of this point and the cube corner can be recorded accurately, irrespective of residual rotations during the movements. The cube corner was implemented containing three separate mirrors that are mutually perpendicular and define an apex where their planes intersect. This apex is positioned at the centre of the focal plane of the vision system. In practice the positioning can be done with finite accuracy, typically 1 mm, yielding an Abbe residue of 2 nm.

Cosine errors

The line-scale facility requires several alignment steps to minimize cosine errors. First, the deviation of the three mirrors in the cube corner from mutual perpendicularity causes different directions between the exit beam and the incoming beam. The alignment of the mirrors has been optimized using VSL's angle calibration facility to less than 7 arcsec. This results ultimately in a length-dependent error of approximately $10^{-9}L$, which is nearly insignificant.

The second source of cosine errors is the misalignment of the line scale to the translation direction. The final angular accuracy of alignment is determined by the length of the scale. Given the position accuracy of 1 µm when using the vision system, the cosine error ranges from about $5 \cdot 10^{-7}L$ for small scales to less than $10^{-12}L$ for scales of 1,000 mm.

The third source of cosine errors is the alignment of the laser interferometer to the translation direction of the vision system. This alignment is inspected by tracking the position of the retroreflected laser beam with a position-sensitive detector as the platform is moving. The alignment is then optimized by changing the laser position to reduce the position shift of the returning beam to less than 50 µm, resulting in a cosine error of about $10^{-9}L$.

Repeatability

The repeatability has been established by comparing sequential data without changing the alignment and the other measurement parameters like speed and illumination. It was studied separately how the measured positions of the scale markers depend on the amount of light and on out-of-focus conditions. This dependence was found to be not significant. This is to be expected, since the conditions are the same for every line-scale marker and only the relative positions of the scale markers with respect to the zero markers are finally calculated.

In order to minimize the influence of environmental conditions during the repeatability measurements, the zero marker of the line scale for which the lengths of the interferometer paths are shortest was used. Also, at a single point the measurement could be repeated many times in contrast to the situation when the vision system is moving and only one data point can be taken with the marker image centered in the frame. The repeatability under these conditions was established to be 8.2 nm and is probably overestimated since it partly contains the calibration residue of the vision system.

Data processing

The data analysis is based on combining the position information from the laser interferometer and the image information from the vision system. For a simple line-scale marker the image is a straight vertical line of a certain width, usually imaged as a bright feature on a dark background. First, all horizontal image lines are added, obtaining a curve proportional to the average intensity of the line-scale marker image. The centre position is calculated from the average of the positions of the left and right edge. These positions in turn are defined as the interpolated positions at 50% of the height of the intensity curve. The average of the positions of the left and right edge is finally converted from pixels to meters using the calibration factor of the vision system.

The second part of the position information is generated by the laser interferometer. Here also some processing is required before this becomes a traceable value. The raw position counts as generated by the laser interferometer are converted to meters based on the calibrated wavelength, the interpolation factor of the laser controller, the correction for the momentary index of refraction and the material temperature of the line scale.

Lasers used by VSL are calibrated in-house using either a iodine-stabilized standard laser or more directly against VSL's frequency comb. These calibrations result in a very accurate knowledge of the frequency of the laser light. The vacuum wavelength is calculated using the definition of the speed of light (c = 299 792 458 m/s [11]). When the laser is used under ambient conditions, the wavelength is changed by the refractive index of air. Since direct measurement of the refractive index is difficult, the correction is usually done by calculating the index using the Edlén equation [12] while constantly measuring the required parameters, such as air pressure, air temperature, relative humidity and CO_2 content. The validity of the Edlén model to calculate the index of refraction is limited to about $1{\cdot}10^{-8}$, putting a lower limit on the accuracy. The uncertainty in the distance measurement is also determined by the uncertainty in the values of the ambient parameters, adding up to $5{\cdot}10^{-8}L$.

Besides the correction due to ambient air conditions the length of the line scale also depends on its temperature. The correction is calculated based on the coefficient of thermal expansion and the temperature deviation from 20 °C. When the thermal expansion coefficient is not explicitly calibrated, an uncertainty of 10^{-6} K^{-1} in its value is assumed. With a temperature gradient over the scale estimated to be 0.1 K, the relative contribution to the measurement uncertainty is $10^{-7}L$.

Combining the processed laser interferometer and image information finally results in an accurate position of each line-scale marker.

Uncertainty budget

The most significant uncertainty sources have been identified in the previous sections, resulting in the uncertainty budget as presented in Table 1.

Table 1. Uncertainty budget.

Source	Un-certainty	Distrib-ution	Standard uncertainty
Laser interferometer	0.6 nm	rectangular	0.2 nm
Vision system	7 nm	normal	7 nm
Data synchronisation	2 nm	rectangular	1.2 nm
Abbe error static	2 nm	rectangular	1.2 nm
Abbe error dynamic	1 nm	rectangular	0.6 nm
Laser alignment	$1.2{\cdot}10^{-9}L$	rectangular	$7{\cdot}10^{-10}L$
Scale alignment	$1.2{\cdot}10^{-9}L$	rectangular	$7{\cdot}10^{-10}L$
Edlén equation	$1{\cdot}10^{-8}L$	normal	$1{\cdot}10^{-8}L$
Refractive index	$5{\cdot}10^{-8}L$	normal	$1{\cdot}10^{-8}L$
Expansion correction	$1{\cdot}10^{-7}L$	rectangular	$6{\cdot}10^{-8}L$
Deformation granite	2 nm	normal	2 nm
Retroreflector alignment	$1{\cdot}10^{-9}L$	normal	$1{\cdot}10^{-9}L$
Retroreflector stability	10 nm	rectangular	5.8 nm
Repeatability	8.2 nm	normal	8.2 nm
Combined standard uncertainty			12.5 nm + $7.9{\cdot}10^{-8}L$
Expanded uncertainty (95% coverage)			25 nm + $1.6{\cdot}10^{-7}L$

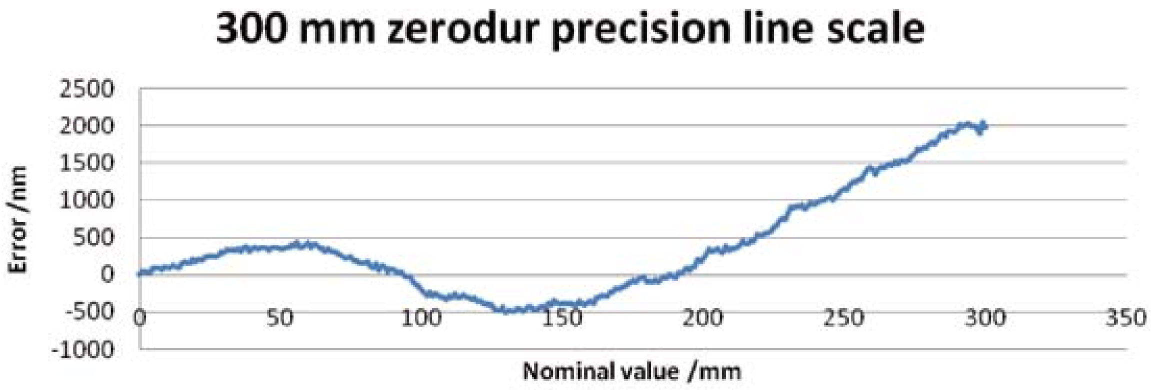

Figure 8. One of the first results obtained with the new set-up for VSL's 300 mm Zerodur precision line scale, showing the errors for every single line-scale marker along the scale. This scale has a deliberate, large deviation from nominal towards the end of the scale but was previously calibrated only at a few points.

First results

Figure 8 shows the result of one of the first fully automated measurements on VSL's 300 mm Zerodur precision line scale. The result is an average over two measurement sequences moving the vision system in opposite directions. Although from this result it had to be concluded that the alignment of the laser to the translation direction still had to be improved, the graph shows the errors for all of the 300 individual line-scale markers for the first time and reveals a regular substructure that was previously unknown and could indicate imperfections in the equipment that was used to manufacture the scale.
The new line-scale set-up will be validated completely in the coming months by comparison to results from other metrology institutes.

Conclusion

The new facility for line-scale calibrations at VSL has been described in detail and first results were demonstrated. This facility will provide internationally accepted calibration services at a much reduced uncertainty level, covering all individual markers for line scales up to 1,000 mm.

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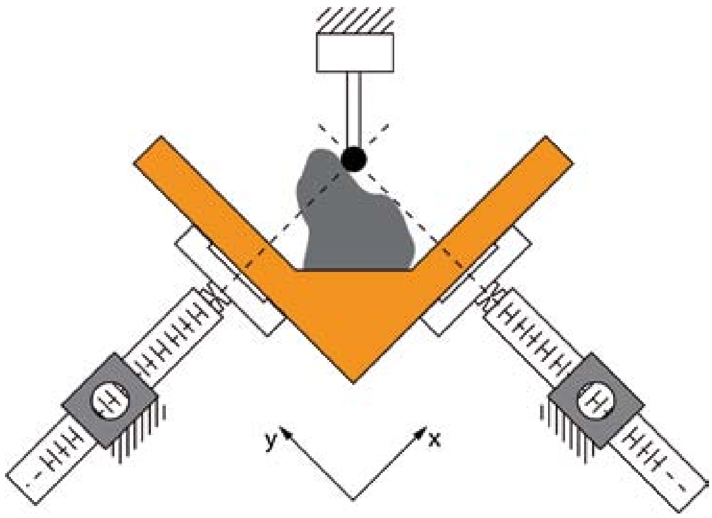
Nanometer uncertainty for a micro price

The TriNano, a new coordinate measuring machine (CMM), has been designed in line with needs from industrial and academic CMM users. Many of these users do not require a large measurement volume, but need nanometer uncertainty within a measurement volume of about 20-40 cm³. This reduction in measurement volume enables the TriNano to employ a new 3D actuation principle, resulting in a low-cost CMM with nanometer uncertainty.



• *Martijn van Riel and Ton Moers* •

Most micro CMMs available today are the result of fundamental research. In general, the real challenge is to achieve the lowest possible uncertainty over a large measurement range. Consequently, the cost price of these CMMs is often not the most important factor. This has resulted in wonderful metrology systems, but they often come at a high price. A market study conducted by the The Hague University of Applied Sciences showed that most owners of micro CMMs measure relatively small objects.

The micro manufacturing market is growing fast, with most of the products and their moulds fitting in a matchbox. The TriNano micro CMM is precisely targeted at measuring

Authors

Martijn van Riel conducted his Master's research, at Eindhoven University of Technology (TU/e), on the TriNano and is at present performing his Ph.D. research at TU/e on the design of a new measuring probe. Ton Moers recently joined the engineering team of Xpress Precision Engineering in Eindhoven, the Netherlands. His professional interests include precision engineering, medical technology and micro manufacturing.

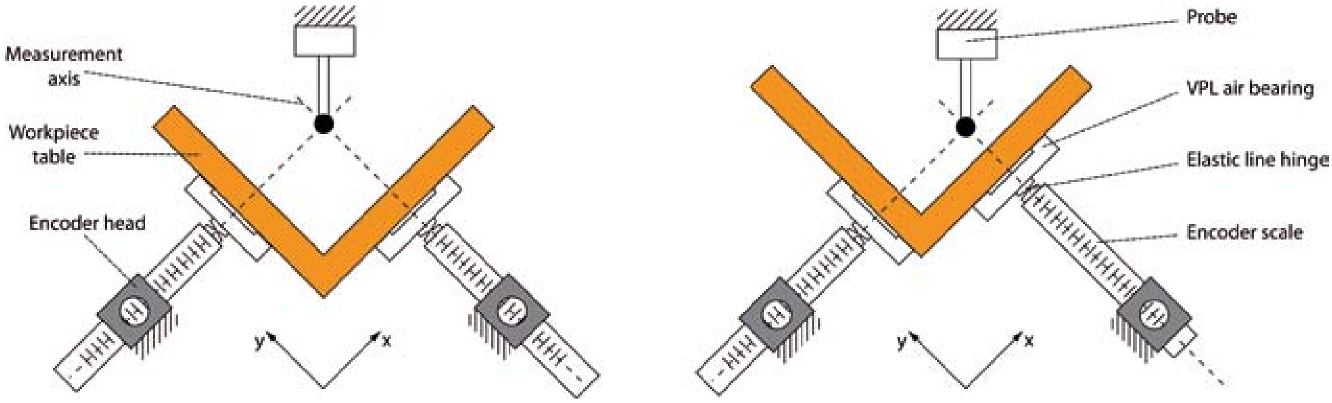


Figure 1. TriNano schematic 2D operating principle, with the workpiece table in its neutral position (left) and after making a translation in y direction (right).

those items with nanometer uncertainty. This article describes considerations for designing a high-precision metrology machine and their effect on the design of the TriNano.

Operating principle

In the TriNano, the workpiece moves in three directions with respect to the stationary probe by means of three identical linear translation stages. The stages are positioned orthogonally and in parallel, and support the workpiece table via vacuum preloaded (VPL) porous air bearings as shown schematically in two dimensions in Figure 1. From this figure the operating principle of the TriNano becomes clear. A linear translation of a stage is transferred via a VPL air bearing to the workpiece table. Translations of the workpiece table with respect to the linear stage in other directions than the translation of the stage are decoupled by the VPL air bearing. In this manner, the three stages independently determine the position of the workpiece table in three dimensions. Figure 2 shows a schematic 3D representation of the TriNano; the workpiece table, VPL air bearings and linear stages can be recognized.

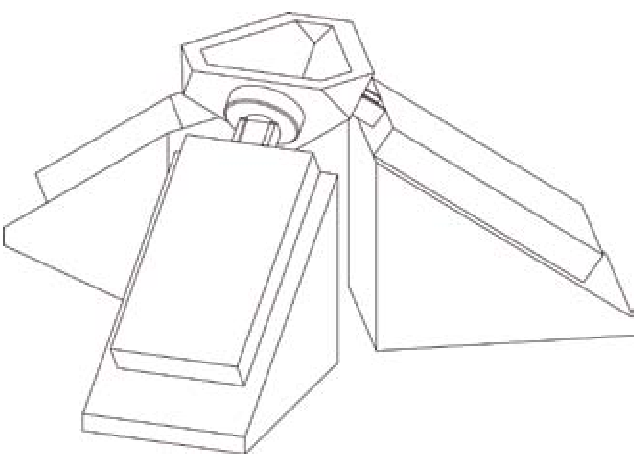


Figure 2. Schematic 3D representation of the TriNano.

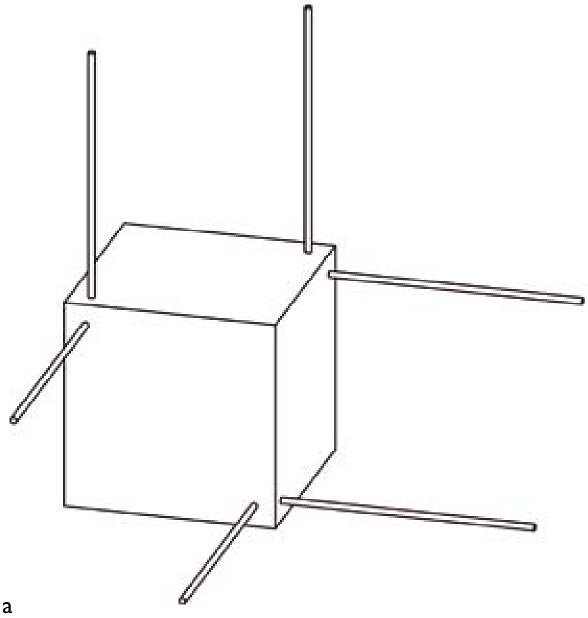
On each linear stage, the scale of an optical linear encoder is mounted. At the point of intersection of the measurement axes of these encoders the probe tip is located. As the orientation of the encoder scale does not vary with respect to the probe, as can be seen in Figure 1, the TriNano complies with the Abbe principle over its entire measurement range. As a result, rotations of the workpiece table will have little effect on the measured dimension.

Instead of a conventional orientation of the machine axes, i.e. two orthogonal axes in the horizontal plane (x and y) and a third, vertically oriented axis (z), the three axes in the TriNano are oriented such that each stage experiences an equal gravitational load. This orientation of the axes combined with the operating principle shown in Figure 1, results in identical translation stages, which can be produced at a lower cost.
The TriNano employs linear encoders to determine the position of the workpiece table. Compared to conventional ultra-precision CMMs, which often employ laser interferometer systems, this results in a considerable reduction in cost. Finally, the TriNano is designed such that the use of expensive low-thermal-expansion materials can be kept to a minimum, thus reducing cost even further. As a result, a cost reduction of up to 75% compared to available high-precision CMMs can be achieved.

Kinematic design

An unconstrained rigid body has six Degrees of Freedom (DoFs), three translations and three rotations. If all DoFs of a rigid body are fixed once, this body is said to be statically determined or exactly constrained. If more or less than six DoFs of a rigid body are constrained, it is said to be over- or underconstrained, respectively.

An important benefit of an exactly constrained design is that it will isolate critical parts or systems from the influence of manufacturing tolerances or deformations of the support frame, due to temperature variations or loading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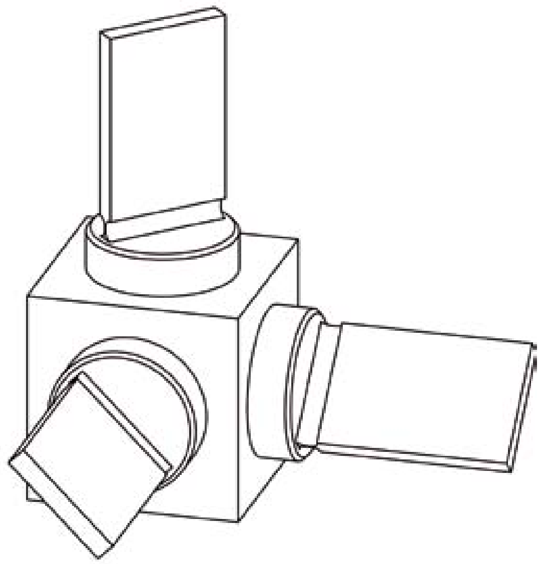
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Figure 3. Principle of an exactly constrained design.
(a) Classical.
(b) TriNano.

of the frame. An overconstrained design often suffers from backlash and requires tight tolerances in order to function properly. In order to obtain the highest measurement repeatability, an exactly constrained design is key [1]. The design of the TriNano is therefore based on well-known kinematic design principles, in order to obtain an exactly constrained design.

A classical solution of exactly constraining a body is to use six slender rods, as displayed in Figure 3a. A single (VPL) air bearing as used in the TriNano constrains three DoFs: two rotations and one translation. Applying an elastic line hinge releases one of the rotational constraints. Combining three of these air bearing-elastic line hinge combinations as shown in Figure 3b results in an exactly constrained body.

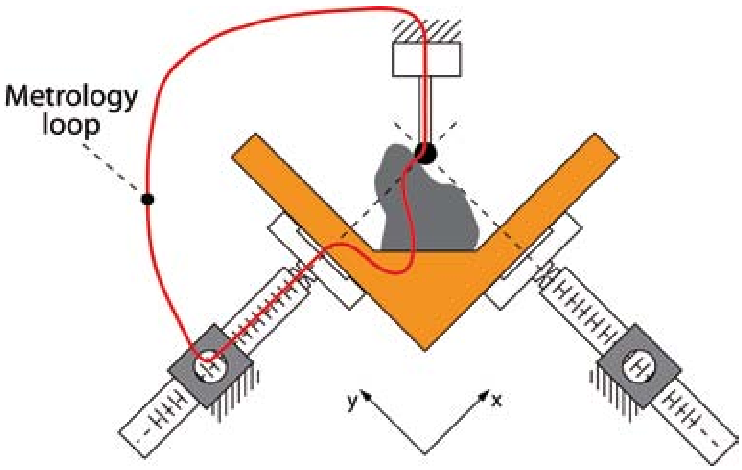

Figure 4. Metrology loop in the TriNano.

VPL air bearing

In Figure 4, the 2D schematic of the TriNano is depicted, with the metrology loop indicated. As can be seen, the loop passes through the encoder, elastic line hinge, VPL air bearing, including its air layer, workpiece table, workpiece, probe and back to the encoder via the frame. The fact that the air layer of the air bearing is a part of the metrology loop might be cause for concern, as has been indicated in several studies [2], [3]. To determine the effect of a VPL porous air bearing within the metrology loop on the performance of the TriNano, preliminary tests were performed and their results are shown in Figure 5.

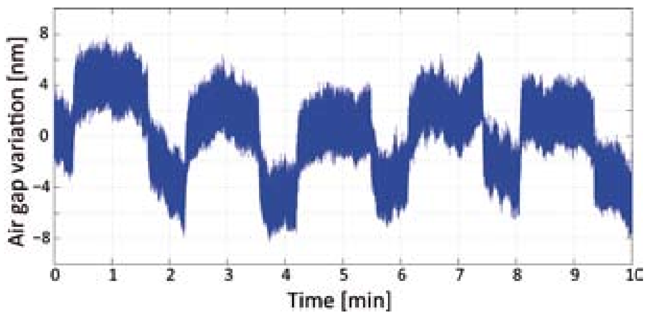

Figure 5. Air gap variation in a VPL air bearing.

The variation of the height of the air gap amounts to ± 8 nm over a period of 10 minutes, which includes sensor noise of ± 3 nm. It can be seen that the air gap variation displays a repetitive pattern with a cycle period of approximately two minutes. This cyclic behavior is due to variations in the pressure and vacuum supply. In the current test set-up, air pressure and vacuum were directly obtained from a wall outlet and no additional means were

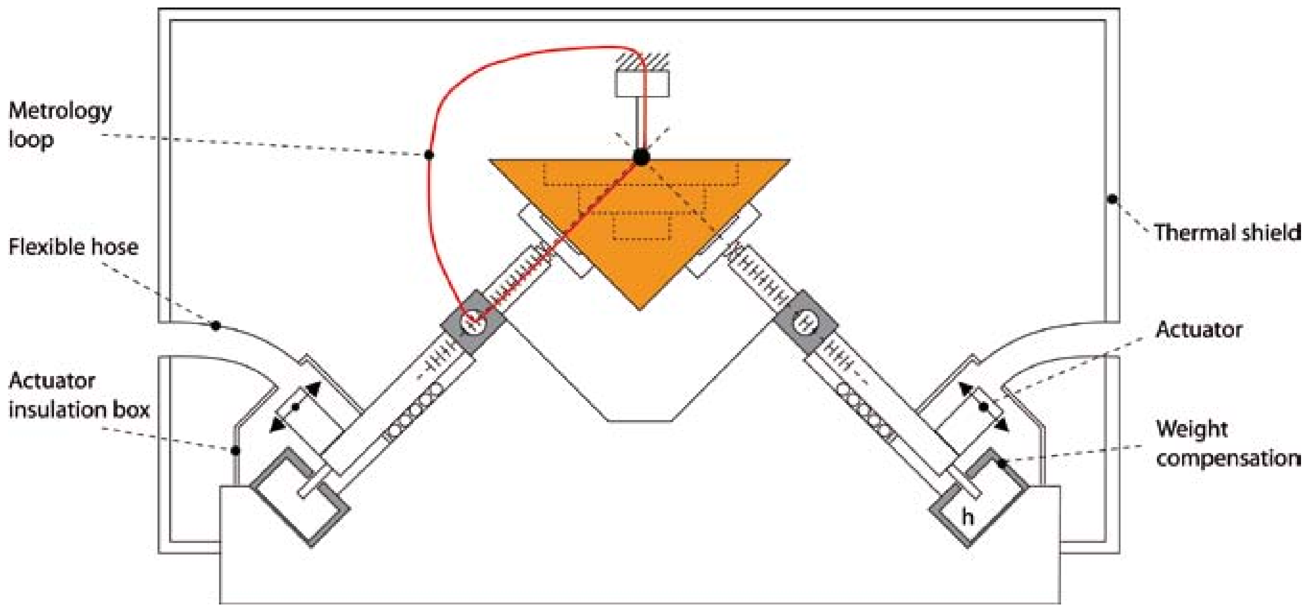

Figure 6. Schematic thermal design of the TriNano.

employed to control the vacuum and air pressure. Even without compensating for variations in air pressure and vacuum supply and for the environmental noise, the stability of the VPL air bearing is sufficient. Obviously, in the actual implementation of the VPL air bearings, pressure and vacuum monitoring and control will be applied to ensure stability.

Thermal design

Thermally induced errors are often the largest contribution to the total error budget in precision measurement equipment, despite more and more research performed on the matter [4]. However, certain straightforward measures can be taken to reduce these thermally induced errors, such as minimizing and controlling the heat flow and decreasing the thermal sensitivity of the machine.

In the TriNano, a pneumatic weight compensation system is applied to minimize the heat production in the actuators. Furthermore, a thermally insulating box is placed over the actuators preventing heat produced by the actuators from affecting the measurement. The volume in which the parts of the metrology loop are located, is enclosed by a thermal insulation shield, as shown in Figure 6. A temperature control system is subsequently employed to create a 'mini-environment' inside this volume. The thermal sensitivity of the TriNano is further reduced by designing the parts of the metrology loop to have a large thermal time constant. For most parts this is achieved by adjusting their dimensions, instead of using expensive low-thermal-expansion materials. Only parts which need to be of a specific slender shape, such as the elastic line hinges, are made from a low-expansion material.

Gannen probing systems

The TriNano is designed to be used with a wide range of sensors, including 3D probing systems, AFM-tips and white-light interferometers. In the standard configuration, the TriNano will be supplied with a Gannen XM probing system, as shown in Figure 7. The Gannen XM is a 3D probing system supplied by Xpress Precision Engineering. It is suitable for measuring micrometer-sized features with nanometer uncertainty. Other ultra-precision probes by Xpress will be supported as well, including the Gannen XP and probes from the Heimen series.

The suspension of these Gannen probes consists of a silicon membrane with three slender rods. The probe tip is connected to the center platform of this chip via a stylus. When the probe tip is displaced, the three slender rods, connected to the center platform in the silicon chip, will deform. This deformation is measured using piezo-resistive strain gauges on the slender rods. The strain gauges are manufactured together with their electrical connections and the slender rods in a series of etching and deposition steps.

Figure 7. Gannen XM probing system.

Figure 8. Gannen probe chip with a selection of target products for measurement.

The resulting design has an extremely low moving mass of 25 mg including the weight of stylus and tip, as shown in Figure 8. Also, the design allows the manufacturing of rods with a thickness down to several micrometers, which as a result are very compliant. The stylus of the Gannen XP has a length of typically 6.8 mm. In this configuration, an isotropic stiffness of 480 N/m is obtained and the sensitivity of the probe is equal in each probing direction.

Since the piezo-resistive strain gauges are deposited onto the silicon membrane, hysteresis is below 0.05% and the standard deviation in repeatability is 2 nm over the whole measurement range and in any probing direction [5]. This combination of a highly compliant design with low moving mass and nanometer repeatability allows the use of micrometer-sized probe tips. Currently, tungsten probe tips with a diameter down to 42 µm have been manufactured and used with this probe, allowing 3D measurements on micrometer-sized features [6].

The Gannen probes have been integrated on several commercial CMMs as well as on different custom set-ups for the high-precision measurement of small 3D components.

Joint development

TriNano is a joint development of Eindhoven University of Technology, NTS Systence, TASS Software Professionals and Xpress Precision Engineering, all based in the Netherlands. The first TriNano will be operational at the end of this year. The market has shown great interest in TriNano, both from industry and research institutes. In collaboration with a metrology equipment manufacturer, the TriNano will be launched in 2011 on a global scale. The TriNano project was partially funded by the European Regional Development Fund, the Dutch government and the province of Noord-Brabant under the Operational Programme South Netherlands.

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Information

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One, two ...

Light interferometry has many advantages in the area of precision measurement and positioning. It offers high accuracy and resolution, long measuring range, up to hundreds of feet, ease of setup, the capability for making measurements having very low Abbe offset, and the ability to handle small angular displacements of the stage. This paper explains operation of the Michelson interferometer with single-frequency (DC interferometry) and two-frequency sources (heterodyne or AC interferometry). It discusses measurement errors when operating in air and vacuum, and an example application.

• *Greg Swan* •

The Michelson interferometer in Figure 1 takes a single-frequency (wavelength) light source and splits it into two measurement paths going to mirrors 1 and 2. Beams 1' and 2' reflect from the mirrors and combine into a single, collinear and coaxial beam at the beam splitter. The screen shows intensity changes of the combined beam caused by mixing, or interference, of beams 1' and 2'. In early times, a human observer carefully noted and counted intensity changes from maximum to minimum to maximum again as mirror1 or mirror2 changed position. Photodiode receivers, amplifiers and digital circuitry have taken over this task.

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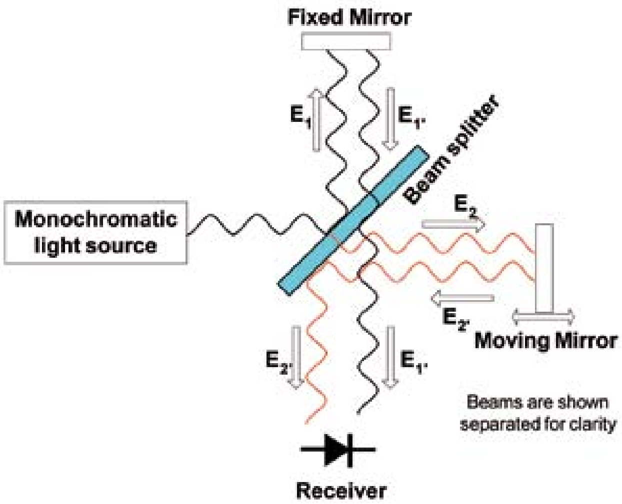


Figure 1. Michelson interferometer.

Principle

'Sine waves' shown in Figure 1 represent amplitude and phase of the electric field of a fixed-wavelength standing wave in space. Between the beam splitter and receiver, electric fields $E_{1'}$ and $E_{2'}$ add. Intensity at the screen is the magnitude of the vector sum of these fields. Assuming equal intensities of $E_{1'}$ and $E_{2'}$, a change in intensity at the screen caused by mirror motion Δd is expressed in the following equation [1]:

Michelson

$$I = 2I_0 \left[1 + \cos\left[\frac{2\pi}{\lambda}(2n\Delta d)\right]\right]$$

Ideally, $E_{1'}^2$ and $E_{2'}^2$ being constant, the intensity depends on the phase ($\theta_{1'2'}$) between the two E-fields, which is influenced by the position of the two mirrors. In Figure 1, assume the mirrors are positioned so the receiver sees the maximum intensity, meaning the two electric fields are in phase. Then we move mirror 2 to the right a distance of $\lambda/4$ or one quarter wave. This changes the phase of $E_{2'}$ by 180° because the round trip distance to mirror 2 from the beam splitter increases by $2 \cdot \lambda/4$ or one half wavelength total. The net effect is that beams $E_{1'}$ and $E_{2'}$ are 180° out of phase and when added together, they cancel each other, reducing the intensity at the receiver to zero (assuming $E_{1'} = E_{2'}$). One would say this interferometer has an Optical Fold Factor of 2, or it is a 'single-pass' interferometer configuration.

Directional uncertainty

While the mirror position is stable, the intensity at the receiver is constant. Eventually, normal use of the stage will position the mirror so light intensity at the receiver is maximum or minimum, making it difficult to know at the next sample which direction the mirror is moving, since intensity would decrease or increase respectively regardless of the direction the mirror moves. Practical DC interferometers add optics to create additional signals with different phase delays to overcome this uncertainty. The AC or heterodyne interferometer gets around this issue and will be described next.

Heterodyne

In the heterodyne interferometer, the measurement is made using two light frequencies, spaced closely together (a few MHz) relative to the light frequency ($4.7 \cdot 10^8$ MHz). Operating a helium-neon laser with an axial magnetic field splits its output into two oppositely circularly polarized frequencies (call them *f1* and *f2*) typically spaced between 1 and 7 MHz apart. This is referred to as the split frequency or Zeeman split. Optical components convert the output beam into two linear, orthogonal polarizations. Using linearly polarized light facilitates separation in the interferometer using a polarizing beam splitter. Figure 2 shows the single-pass design for conducting heterodyne interferometry.

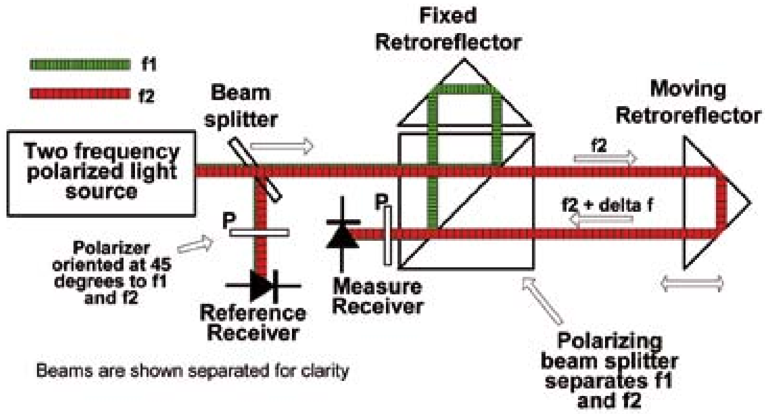


Figure 2. Heterodyne interferometer.

Replacing the beam splitter with a *polarizing* beam splitter (PBS) changes the Michelson interferometer into a modified Michelson, but it works the same way as previously described. The PBS separates and directs light from the source to two arms, but this time the light frequencies in the arms are different. Another change is replacing the mirrors with retroreflectors (which might be corner cubes). These components reflect incident light directly back toward the source, on a parallel path.

This substitution makes two improvements, helping us recover the measurement signal (a combination of *f1* and *f2*) because the retroreflector offsets the beam as shown in Figure 2, and maintains optical alignment should the stage pitch or roll. This design requires two receivers, one observes the two-frequency beam before it enters the interferometer (called the 'reference beam') and the other picks up the beam when it leaves (called the 'measure beam'). Inside each receiver, a polarizer oriented at 45° to *f1* and *f2* allows the component of *f1* and *f2* that is aligned with the polarizer axis to exit. Exiting the polarizer, the beam is linearly polarized, with the electric fields of *f1* and *f2* parallel. They interfere, and their sum is a low-frequency amplitude modulated beam at a frequency of $|f1 - f2|$ that is detected by a photodiode. Referring back to Figure 2, the reference receiver sees $|f1 - f2|$ and the measure receiver sees $|f1 - (f2 + \Delta f)|$, where Δf is a Doppler shift in frequency caused by movement of the retroreflector. The laser axis board electronics compares the measure and reference frequencies, basically measuring to high accuracy the phase difference between them. For example, a phase change of 270° corresponds to a change in position of 270°·(λ/2)/360° = 0.375λ = 237.3 nm (λ = 632.8 nm, in air).

Error sources

Can we believe it when the interferometer reports position x.xxxxxx? Yes, when the machine, interferometer and compensation work well together. Machine design is a science and art; here we will only introduce key accuracy limitations for heterodyne interferometry.

Index of refraction in the measurement path

Assuming we are working in air, the vacuum wavelength of the source is multiplied by a 'Total Compensation Number' (*TCN*), where $TCN = (\eta_{air}/\eta_{vacuum})^{-1}$ plus an adjustment for thermal expansion of the part (for discussion later). This is a variable error proportional to the measurement distance. For example, a 10 ppb wavelength error produces a 10 nm error with the interferometer and mirror separated by one meter ($1\ m \cdot 10 \cdot 10^{-9}$ m/m). η_{air} is either measured directly or computed with the well-known Edlén equation [2]. Table 1 presents rules of thumb for estimating errors due to air temperature, pressure and humidity changes.

Table 1. Rules of thumb for error estimation.

Environmental change	Effect on TCN*
1°C increase in temperature	~1 ppm decrease
3 mm Hg increase in air pressure	~1 ppm increase
25% increase in relative humidity	~0.22 ppm decrease

* Values computed with the aid of "Refractive Index of Air Calculator Based on Modified Edlén Equation" [3].

Unlike temperature, pressure and humidity vary slowly. It is advisable to minimize temperature variation along the measurement path by managing air flow using baffles and air showers. Place heat-generating components away from the measurement beams whenever possible and make accommodations for heat removal. Temperature especially has a large effect on the measurement and stringent control is necessary.

Deadpath error

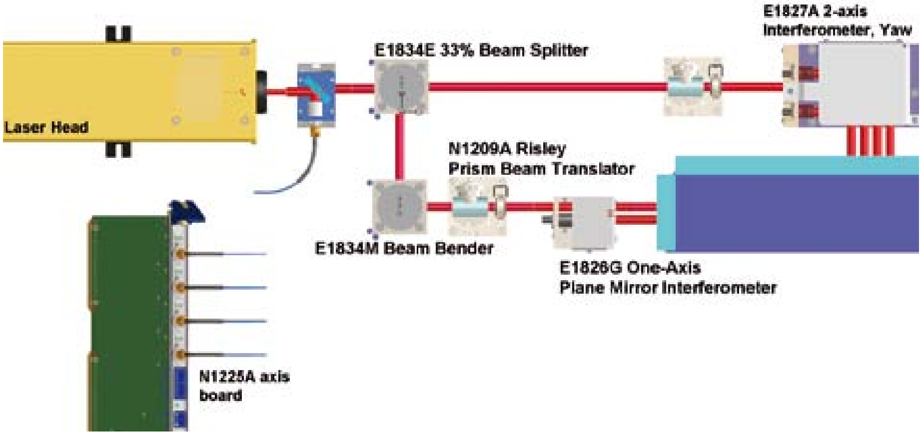
The laser system makes a relative measurement from an arbitrary zero point chosen by the designer. Referring to Figure 2, it is clear that the laser wavelength in both the reference and measurement paths is affected by index of refraction changes in the air. Referring to Figure 2, imagine putting the measurement corner cube the same distance away from the PBS as the reference corner cube, and calling this 'zero position'. Now assume the air temperature increases by 1°C causing a -1 ppm change in wavelength in both paths. Since the path lengths are equal, there is no net phase change at the measurement receiver and deadpath is zero in this case. As an example, assume 5 mm of deadpath in the reference arm and air temperature increase by 1°C. This causes a 1 ppm reduction in *TCN*, effectively 'shortening' the reference path and adding a +5 nm error to the measurement. Zero deadpath is the exception, even when operating in a vacuum, since the chamber thermal coefficient of expansion and the thermal coefficient of expansion of the interferometers themselves can affect the measurement and reference paths unequally. Deadpath only matters if the environmental conditions are changing between the time you reset position to zero and finish taking the measurement.

Laser source

The laser source is the heart of the system, and contributes a few error terms. Vacuum wavelength and wavelength stability show up as variable errors. Beam direction changes introduce a cosine error into the measurement. This is a lesser effect, caused for example by changes in the laser mounting due to thermal effects, and the mounting locations for all beam-bending and -splitting optics along the path, as well as the splitting and bending components themselves. Ellipticity and non-orthogonality of the two polarizations will add a cyclic error to the measurement, which is not proportional to the separation between the interferometer and retroreflector. This has been described in numerous papers [4].

Interferometer

Imperfect separation of *f1* and *f2* by the polarizing beam splitter causes a small amount of unintended mixing of the two polarizations that has been described and modeled in numerous papers on optical non-linearity, also called cyclic error. This is primarily a sinusoidal error having the same period as the fringes themselves. For example, a single-pass interferometer will have a fringe period of λ/2, a plane mirror (two-pass) unit has a period of λ/4.



Application type: XY stage position measurement/control
Maximum stage velocity: 500 mm/s
Maximum stage travel: 200 mm in X, 50 mm in Y
Resolution: 0.15 nm
Environment: vacuum, 10^{-9} torr
Operating temperature: 22 ± 0.1°C
System materials: Invar (coefficient of thermal expansion = $1.5 \cdot 10^{-6}$ °C^{-1})
Position interface: VME
Measurement time: 20 minutes

Figure 3. Three-axis application example.

Mirrors

Mirrors contribute a fixed amount of reproducible error coming from their manufacturing process. A flatness specification of $\lambda/10$ measured at 635 nm implies 64 nanometers from peak to trough over the mirror surface that contributes a fixed error. The error can be reduced by mapping the mirror.

Example application

A sample configuration is shown in Figure 3. The XY stage operates in vacuum and is monitored for X and Y position. Interferometer E1827A measures mirror position at two points to track yaw. Hence, Z rotation is also monitored. Main components are the Agilent E1826EV and E1826FV interferometers, N1209A Risley prism translators, N1225A axis board, E1706C remote sensors and 5517DL laser head. Not shown in the figure: vacuum window, ST-ST fiber feedthrough, VME rack, power supplies and cables. The strain-free vacuum window with S-D 60-40 or better surface quality should provide transmitted wavefront distortion of < $\lambda/10$.

This application has three degrees of freedom and will use stage mirrors. Looking at error sources may give a rough idea of the best-case accuracy to expect; see Table 2.

Choosing the laser source

The Doppler shift from mirror motion in both directions has to be below the laser head split frequency and within the laser axis board frequency range. A two-pass interferometer produces one fringe per $\lambda/4$ travel distance. At 0.5 m/s, the Doppler shift from fringe motion is (0.5 m/s)/(λ/4) = 3.16 MHz. The minimum input frequency for the laser axis board is 0.5 MHz, so the absolute minimum split frequency for the laser head is 3.66 MHz. The Agilent 5517DL split frequency is > 4.4 MHz, and this fits the velocity requirement. Assuming a 4.4 MHz split, the axis board will see from 1.24 to 7.6 MHz which fits well with its 0.5 to 30 MHz input frequency range.

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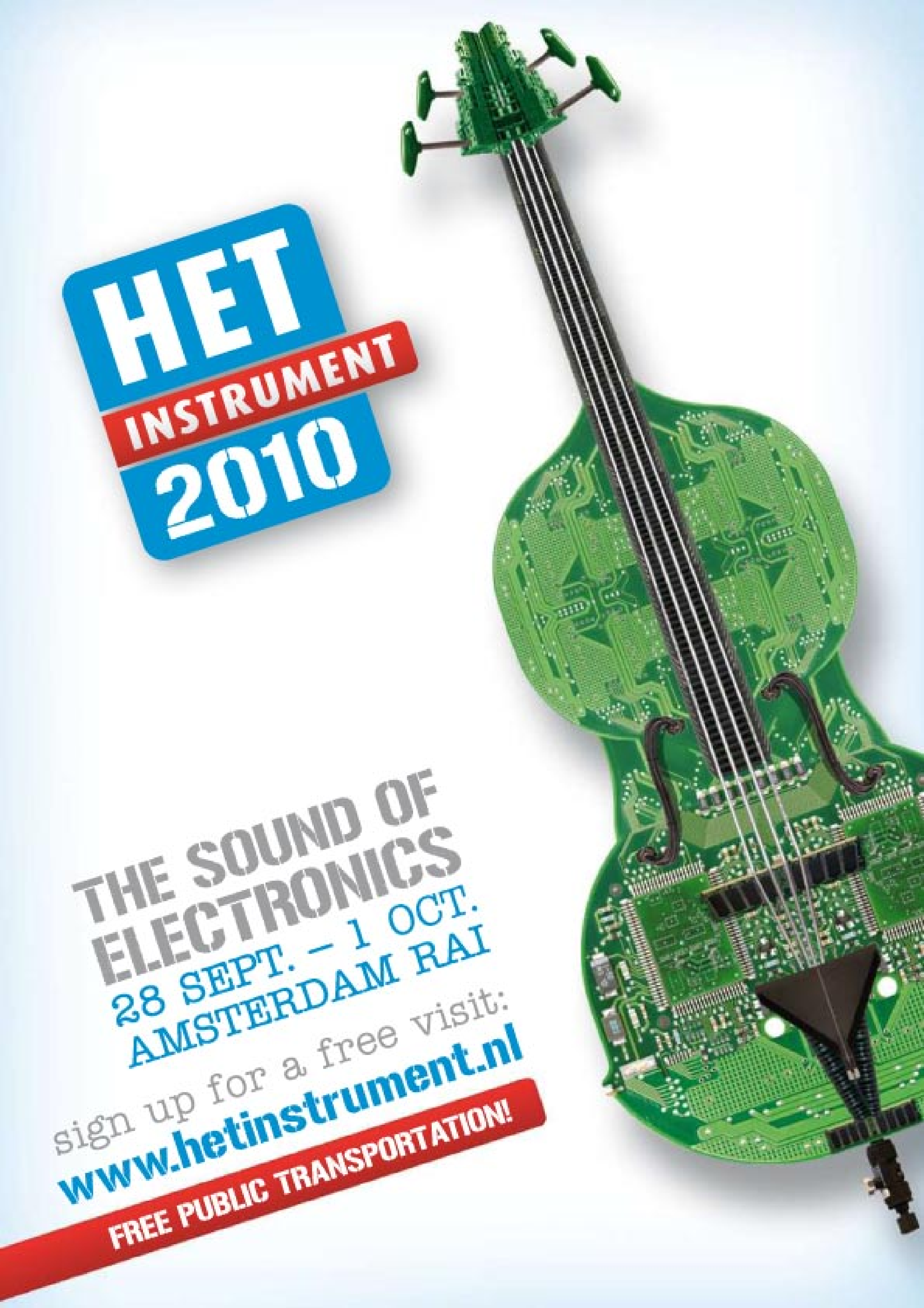
Table 2. Error sources and magnitude.

Error source	Worst-case impact on X-axis measurement	Worst-case impact on Y-axis measurement
Laser head, 0.02 ppm wavelength accuracy with special calibration	± 4 nm error @ 200 mm	± 1 nm @ 50 mm
Laser head, 1 hour short-term wavelength stability 0.002 ppm	± 0.4 nm error @ 200 mm	± 0.1 nm @ 50 mm
Non-linearity error from interferometers	± 1 nm	± 1 nm
± 1 count error from digital electronics	± 0.15 nm	± 0.15 nm
Mirror quality (λ/20)*	± 16 nm	± 16 nm
Thermal coefficient of expansion for system materials	± 30 nm (over ± 0.1°C)	± 7.5 nm (over ± 0.1°C)
Interferometer thermal drift due to glass path imbalance	< 1 nm	< 1 nm

* Addition of redundant axes and mirror mapping can reduce this error.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Ensuring the quality of micro-parts

Both the manufacture and quality inspection of micro-parts present special challenges. With the F25, Carl Zeiss has developed a solution that unites optical and tactile measuring technology. Launched in 2006, the F25 is now used in industrial and university environments.

• ***Marc Wagener, Ferdinand Bader and Karl Seitz*** •

An increasing number of applications require micro-components. Micro-parts are essential to miniaturized systems such as pressure sensors, micro-motors, switches, drives, pumps, ball bearings and bioreactors, which are used in medical and metrology equipment, as well as in motor vehicles. For example, micro-parts ensure that a dentist's high-speed drill works properly. They ensure the required performance in the injection regulator of a turbo diesel engine. Thanks to their surface qualities and exact dimensions, these tiny parts ensure smooth operation despite often extreme demands.

For the production of these micro-parts, manufacturing processes had to be enhanced in step with new application possibilities. While the use of traditional manufacturing technologies such as turning, milling, grinding and forming is to a certain extent limited for micro-parts, new technologies such as laser machining, galvanic forming or chemical etching are emerging. These tooling processes can create fine and complex structures with tolerances of approx. 1 µm.

Until recently, the quality inspection of these parts was realized by comparing parts, making comparative measurements with master workpieces or conducting functional tests, etc. Needless to say, the critical applications described above require much more advanced quality inspection. Geometric product-characteristic defects or the results of defects which endanger success can only be avoided through steady quality inspection. Furthermore, the efficiency of micromechanical parts production can only be increased through efficient, fast and reliable quality inspection.

Multi-sensor CMMs

As with the production method, measuring technology had to be enhanced to meet the needs of micro-parts. The preferred solution for the quality inspection of micro-parts is multi-sensor coordinate measuring technology that combines the benefits of optical and tactile measuring in one system. Special attention is given here to contact measurements because the vertical walls of micro-parts cannot be captured optically, for example. In these cases, contact coordinate measuring technology is often the only technically suitable and economical solution.

Authors

The authors are working or have been working with Carl Zeiss Industrial Metrology in Oberkochen, Germany. Dr Marc Wagener is in the Division of Marketing and Business Strategy, and Ferdinand Bader is in the Division of Bridge Type Measuring Machines. Karl Seitz was involved in developing the F25.

www.zeiss.de/imt

Figure 1. F25 coordinate measurement machine from Carl Zeiss.

However, extremely small dimensions and different forces exist here; other principles apply. Consequently, the requirements on a measuring machine for micro-system technology are completely different from those on its 'colleagues' in automobile production or tool making.

Positioning and fixing micro-parts requires highly precise equipment. At the same time, the holding force must be very low to ensure that a micro-part is not deformed or damaged during the measurement. This necessitates a miniaturized sensor system with very a small probe diameter that works with extremely low measuring forces, thus guaranteeing that the micro-part is not deformed or moved by the machine when it is measured with contact sensors.

CAD-based software is essential for multi-dimensional measuring tasks on micro-parts. As the features on micro-parts are practically invisible to the naked eye, the control data and measuring program should be directly programmed in the CAD module and remotely tested for interfering contours and travel paths before the measurement. This ensures that all features can be reached by the minute stylus without a collision. Feature-guided and object-oriented software enables selecting and running any number of features from the entire measurement program – a decisive advantage with detailed measurements on micro-parts.

Additional requirements on the measurement system for micro-parts include scales with very high resolution, kinematics with high stiffness, visualization of the workpiece and details, and new mathematical evaluation methods.

Figure 2. F25 SSP contact sensor.

F25

The F25 3D coordinate measuring machine from Carl Zeiss featuring CALYPSO measuring software fulfills the above-mentioned requirements; see Figure 1. The measuring volume of the F25 is one cubic decimeter – a drop in the bucket compared to its 'big brothers' in process control and tool manufacturing for example. Measuring uncertainty for this volume is 250 nm at a resolution of 0.25 nm. Using minimal probe forces, this resolution, along with optimum control of the linear drives, enables contact measurements even in bores less than one millimeter in diameter. The basic precision kinematics were developed in cooperation with the Dutch metrology institute NMi (now VSL) and Eindhoven University of Technology, the Netherlands.

The contact, passive scanning sensor consists essentially of a silicon chip membrane with integrated piezoresistive elements; see Figure 2. Developed in a joint effort with the Physikalisch-Technische Bundesanstalt (PTB) and the Institute of Microtechnology (IMT), both in Braunschweig, Germany, it works with a resolution of one thousandth of a micron and is designed as a flexible changer. Single-point measuring and scanning are both possible. The sensor is designed for stylus diameters of 20 to 500 microns at a free shaft length of up to 4 millimeters. Stylus tips can have a diameter between 50 and 700 microns. A 50 mm long match with a 5 mm diameter head is a giant in comparison. The probing forces were also reduced, to less than 0.5 milliNewtons per micron. The contact accuracy according to DIN EN ISO 10360-2 is $MP_{EE} = 0.25 + L/666$ μm (L in mm) and $MP_{EP} = 0.3$ μm.

To measure soft materials, analyze extremely fine structures or to conduct 2D evaluations, the system uses an optical sensor, whose optics have been optimized and adjusted based on proven Carl Zeiss microscope lenses; see Figure 3. The optical sensor can be selected with 10x or 20x magnification; its measuring accuracy is $MPE_{PF} =$ 0.6 μm. An additional camera aids visualization when probing the miniaturized features, thus simplifying learn programming.

Figure 3. Contact sensor, visualization camera, optical sensor.

Accuracy test

The F25 demonstrated its measuring capabilities in an accuracy test involving a Zerodur ball plate that exhibits practically no thermal expansion; see Figure 4. Nine half balls (hemispheres) are positioned on the ball plate, the distances between the hemispheres, which have to be measured, are between 13 and 100 mm. For the test, normals were used that were calibrated by the Carl Zeiss IMT Measuring and Calibration Center and are traceable to the gauge blocks calibrated by the PTB.

To verify accuracy, a 2D test was conducted on a flat plate. This was followed by a 3D test in which the plate was tilted 30 degrees; see Figure 4. The results of the accuracy check demonstrate that the system delivers measuring accuracy clearly better than the specified MP_{EE} = 0.25 + L/666 μm (L in mm). In the specific 2D measurement, the measuring accuracy, even for lengths up to 100 mm, was E_{max} = 0.05 μm; for the 3D measurement E_{max} = 0.18 μm.

Outlook

Launched in 2006, the F25 is now used in industrial and university environments. In 2009, Carl Zeiss introduced an additional system, the F40. This system features a VAST XXT sensor, and optics with 10x magnification. The contact accuracy according to DIN EN ISO 10360-2 of the F40 is MP_{EE} = 0.4 + L/666 μm (L in mm) and MP_{EP} = 0.5 μm.

Furthermore, a joint project with the PTB is examining the use of a T-stylus on the F25. Initial results indicate that the T-stylus easily meets the specifications during calibration, single-point measuring and scanning. The use of this T-stylus will further simplify measurements for the user and open up new fields of application.

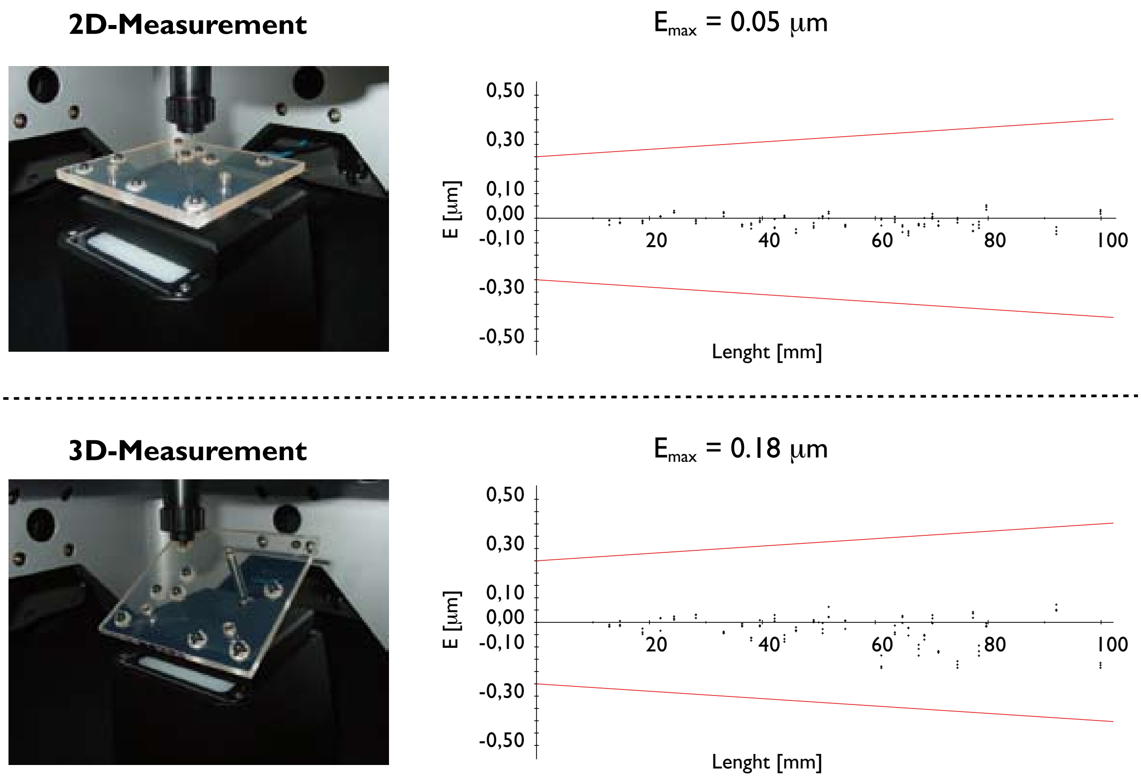

Figure 4. Accuracy test with ball plate.

Innovation

Mitutoyo, which is still the biggest manufacturer of measuring instruments worldwide, looks back on turbulent times. The banking crisis resulted in a poor global economic climate, which also affected the organisation. "Recently, we were able to put this tiresome period behind us", says Henk Slotboom, Sales Manager of Mitutoyo Nederland. Together with Marketing Manager Ron Meijer, he explains, exclusively for Mikroniek, the state of the affairs within the company. It is worth noting, so they claim, that Mitutoyo's role as global metrology innovator has remained untouched. In addition, service – from general metrology training to calibration of measuring instruments – is becoming ever more important.

• ***Hans Koopmans*** •

In recent years, Mitutoyo has put a great deal of effort into preparing its organisation for the future. For instance, on 1 January 2010, a new European headquarters was established in Neuss, near Düsseldorf, Germany, in order to stimulate the further growth of the European sites. In addition, as of July, the warehouses of the European companies, including the one in Veenendaal, the Netherlands, were centralised in a new European Distribution Centre. The national warehouses, among them the one in Veenendaal, have subsequently been closed. "Both decisions result from the huge value that Mitutoyo attaches to customer satisfaction", Slotboom explains. "Sales activities are coordinated efficiently from the European headquarters, from where technical support is

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Figure 1. Sales Manager Henk Slotboom (left) and Marketing Manager Ron Meijer of Mitutoyo Nederland.

and service

also provided. By centralising the stocks, we want to increase supply reliability and reduce delivery times. A practical target is that, by the end of 2010, we must be able to supply handheld measuring instruments within 24 hours. CNC measuring machines can now be supplied from stock as well, which is why they can be delivered considerably faster than in the past."

Distribution model

An important policy change in the Netherlands is that the distribution model with hundreds of partners carrying brands including Mitutoyo in their sales programme has been abandoned. Instead, a select group of technical wholesale companies has been chosen to take care of retail activities. These companies are expected to provide a considerable specialised contribution such that they can offer adequate advice to their customers in the measuring sector.

Dual-use goods

Meijer: "It may be clear that the worldwide economic crisis had a significant impact on the sale of capital goods such as CMMs. As a result, Mitutoyo centralised the production of CMMs to Japan, which meant, for instance, that the CMM production facility in the Netherlands was forced to close at the end of 2009. Given that CMMs are what are known as dual-use goods, Mitutoyo has worked hard in recent years to set up a foolproof system in accordance with the so-called Wassenaar Arrangement."
This Arrangement, the rules of which were tightened in 2008, addresses the export of dual-use goods – goods that can have a civilian as well as a military application. Every customer with whom Mitutoyo is doing business is screened on their use of the machine. The customer must show a 'Letter of Assurance' in which they guarantee that they will not resell the machine without consultation or use it for dubious purposes. Some customers see this as an awkward issue because the competitors – they say – do not ask for such a guarantee. However, under the Wassenaar Arrangement, this is compulsory for all manufacturers of dual-use products.

Market expansion

Slotboom and Meijer do not beat about the bush: as a result of the banking crisis, 2009 was, from an economic point of view, one of the worst years in the history of the Japanese concern.
While they are gradually recovering, this situation is not helped by the current auctioning off of investment goods, including measuring equipment, at extremely low prices. However, the global trend is moving upwards, in Asia even more so than in Europe. A frustrating aspect of this change for the better is that all suppliers of measuring instruments, including Mitutoyo, have to deal with increasing delivery times due to fast-growing demand.

Slotboom: "The crisis has taught us not to concentrate excessively on measuring machines, but also to give manual equipment and other precision tools the attention they deserve. In addition, we have also broadened our market by penetrating new areas. The Medicare sector, for example, turns out to have a need for vision measuring systems as well, and we have developed a dedicated brochure for this marketing segment. Other new market segments are also emerging, such as manufacturers of solar cell panels. At the same time, we have to appreciate that our traditional market – the metal-processing industry – declined in 2009, while the number of suppliers of measuring instruments stays constant. As a result, we are fishing in a smaller pond with the same group of manufacturers. Another phenomenon that Mitutoyo has to deal with is the rapid growth in handheld tools launched with their own trademark or under private labels. While cheaper, of course, their quality is dubious – for the time being at least. However, quality is not a top priority for every customer."

Automation

In the measuring instruments market, there is an undeniable trend towards automation. This not only applies to the machines – measuring processing is already to a large extent automatic – but especially to product handling. Several Dutch companies are carrying out projects in which (equal or unequal) products are transported from a warehouse over a pallet change system to the measuring machine for an automated good/fault indication. When such projects are completed, Mitutoyo can benefit fully from the expertise and products of Komeg, a specialist in clamping technology that became a member of the Mitutoyo concern several years ago; see Figure 2.

Figure 2. Clamping of a double-curved object with Komeg elements.

In the wake of the ongoing automation in the manufacturing industry, the supply programme was recently extended to include the Mach-3A 653 high-speed coordinate measuring machine, which can be integrated into a production line; see Figure 3. The machine has an integrated index table and because it is completely encapsulated it can work without any problems in rough production environments and in a wide temperature range from 5 to 40°C. Despite the high dynamics – a velocity of up to 1,212 mm/s and acceleration of 12,000 mm/s^2 – the length measurement deviation stays within 2.5 µm.

Figure 3. The Mach-3A 653 high-speed coordinate measuring machine can be integrated into a production line.

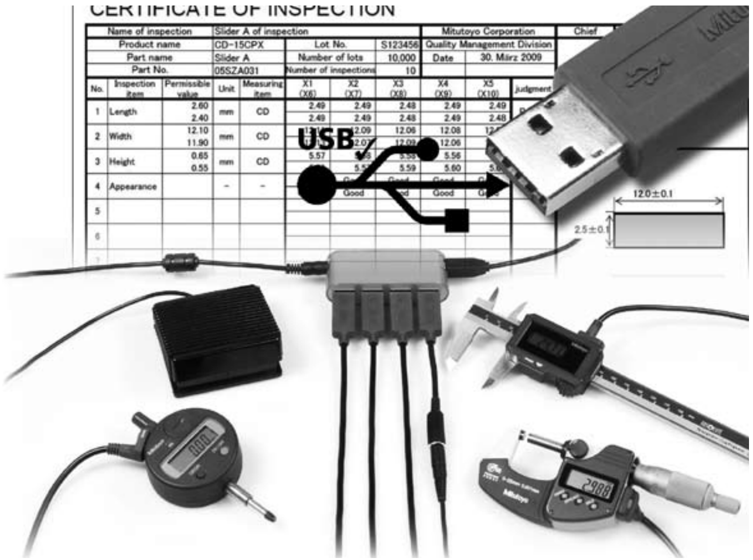

Figure 4. Every measuring instrument with a USB connection can be linked to a MeasurLink network.

Database system for measurement data

There also seems to be renewed interest in Statistical Process Control (SPC). Meijer: "After a period of popularity some ten years ago, interest in SPC has been waning for some time, but interest in statistics-based quality control is now growing again. You want to judge the process as well as the machine by means of only one parameter. In technical terms this means that there is a need for real-time data acquisition systems that produce the CP, process capability, and CM, machine capability, automatically."

Adapting to this demand, Mitutoyo developed MeasurLink, a database system for measurement data. Every measuring instrument with a data connection, from caliper to measuring machine, can be connected; see Figure 4. MeasurLink, which was originally developed by Mitutoyo American Corporation, includes no fewer than seven types of package software (process monitoring, process analysis, inspection report creation, data acquisition in the inspection room, data acquisition on the shop floor, etc.). The user selects the most suitable combination based on budget and situation. It is also possible to start with one program and gradually extend it into a network.
As indicated, input of measurement data in MeasurLink is possible via cable connections, but also wireless. Last year, Mitutoyo introduced a radiographic transmission system for the reliable transmission of measuring data from manual measuring instruments to the computer, under the name U-Wave.

'Painting without paint'

The third trend Meijer mentions is laser scan technology, which is emerging because systems based on it are becoming more affordable and accurate. Laser scan equipment is often used in sectors like the automotive and the aircraft industries that use a lot of double-curved panels. Mitutoyo has introduced a mobile hand scanner in this field called the SpinArm M-series (Figure 5), which is a portable 3D coordinate measuring machine for easy inspection of small or large, possibly complex shaped objects. The series is available in three precision classes; every class has been released in four sizes. Handling of the device looks like 'painting without paint'. The resulting points cloud can be used in Quality Control for comparison with a CAD model. An interesting side application is in the design area: a CAD model can be derived from existing objects without a drawing by means of reverse engineering. Research and development in this field is ongoing, meaning that you can expect Mitutoyo to develop and market more laser scan products in the future.

Increasing precision

"Throughout the metrology industry, you can see the limits moving upwards to a higher level of precision, from the micron to the submicron area", Meijer continues. "Space technology, among others, is an important booster. We supply, for instance, roundness measurement instruments that work primarily in nanometers." Slotboom adds: "The precision of our equipment is growing gradually. Some years ago the accuracy of a standard CMM such as the Crysta Apex C was 2.5 µm, now it is 1.7 µm. A non-contacting 3D measuring machine nowadays is more accurate than a CMM from a few years ago. This also applies to roughness and roundness instruments, which has consequences for the inspection and acceptance test of the machines: while gauge blocks, etc., were sufficient in the past, it is now necessary to use a laser interferometer. This makes higher demands on the skill and knowledge level of our Technical Support employees, which means that we constantly need to improve our know-how by means of additional training at national, European and global levels."

In the Mitutoyo programme, a typical novelty that fits this picture perfectly is the UMAP-CMM (see Figure 6). This is an exchangeable, swivelling microprobe for 3D coordinate measurements, provided with a stylus with a diameter of only 100 µm. The microprobe is stimulated in such a way that it will oscillate in ultrasound resonance frequency. The oscillation is dampened when the probe touches the workpiece, which causes the deflection or amplitude of the oscillation to change. The detection of this

Figure 5. The SpinArm M 3D coordinate measuring machine for measurements based on laser scanning.

Figure 6. The UMAP-CMM swivelling microprobe may work with probe forces of only 1 µN.

Figure 7. The Quick Vision ULTRA 404 is twice as accurate as its predecessor.

change in oscillation ultimately results in the recording of the position coordinates as a measuring point. This functional 'touch trigger' principle allows for contact measurement of even the very finest details with an unbelievable degree of sensitivity. The contact forces may reach a level of 1 μN, which is scarcely measurable. Standard measuring heads apply gram-range forces to the workpiece.

Another example of increasing precision in equipment is offered by the Quick Vision ULTRA 404 (Figure 7), heralded by Mitutoyo as their flagship in image processing. Compared to the previous model the inaccuracy in Z-direction has been reduced by half: from 3.0 to 1.5 μm; in XY-direction, the inaccuracy is a mere 0.25 μm.

Service

Mitutoyo's primary activities are and will be the development and sale of measuring equipment. However, service is also becoming ever more important. The Mitutoyo Institute of Metrology (MIM) acts as a knowledge and training centre in the field of geometric measuring technology in the Netherlands and Belgium. There is significant interest in the courses on offer, which include drawing interpretation, product assessment, measuring technology and product quality, form and position tolerances for production employees, etc. (a Dutch language brochure is available). "Course registration is going well", states Slotboom. Apart from these general courses and seminars, Mitutoyo also organises product training sessions, where users learn how to operate a coordinate measuring machine, for example.

Calibration

Another successful part of the range of services provided is the calibration service. The ISO/IEC 17025 standard describes the general demands for the competence of calibration laboratories. Mitutoyo Nederland carries out all calibration according to this standard, meaning that it has the right organisation and skills at its disposal to carry out sophisticated calibrations. In the meantime, Mitutoyo has been authorised to calibrate a steadily growing number of measuring tools and to provide them with an RvA certificate (Dutch Council for Accreditation, www.rva.nl). At present, Dutch customers are not the only ones to be issued with RvA-accredited calibrations, with all Mitutoyo's European sales companies sending their inspection gauges to the Veenendaal laboratory for an internationally accredited calibration as well.
Slotboom: "Everything we sell we can calibrate in-house. This is important because companies that work according to ISO standards must be able to show an RvA certificate for the measuring instruments they use to inspect their products. Look at it like this: the Council for Accreditation has so much faith in us that they let us issue those certificates for almost all common measuring tools. While we carry out those calibrations in-house, we also do so on location at the customer's site. After all, it is not always possible to transport a huge measuring machine or heavy surface plate."

Information

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Double-Beam and four-point

Principles of electrical and mechanical characterization of piezoelectric thin films are discussed. Both large- and small-signal measurements are presented for AlN (aluminum nitride) and PZT (lead zirconate titanate) films. Additionally, precision aspects and tolerances are addressed for typical measurement set-ups such as in Double-Beam Laser Interferometry and four-point bending test methods. To conclude, the authors discuss possibilities of wafer level vs. single test structure characterization.

• *Klaus Prume, Stephan Tiedke and Thorsten Schmitz-Kempen* •

Knowledge of the piezoelectric properties of thin-film structures on substrates is crucial for the development and design of e.g. micro-electromechanical systems (MEMS). But, test set-ups that have been established for bulk materials, can not be used for thin-film structures. Obstacles for these measurements on the one hand are very small thin-film deformations in the picometer range. On the other hand, it is a challenge to get well-defined mechanical boundary conditions for stress and strain.
For actuator and sensor applications two different ways of film excitation can be distinguished:

1. Electrical excitation of a structure to induce a deformation or vibration of the device when it is used as an actuator.
2. Mechanical excitation due to pressure or force and measurement of the electrical charge response of the device in sensor applications.

In both cases, the polarization direction and therefore the ‘relevant’ piezoelectric coefficient (longitudinal or transversal) needs to be taken into consideration. The transversal piezoelectric coefficient perpendicular to the polarization direction is typically used in the cantilever and membrane structures of piezoelectric MEMS devices.

Authors

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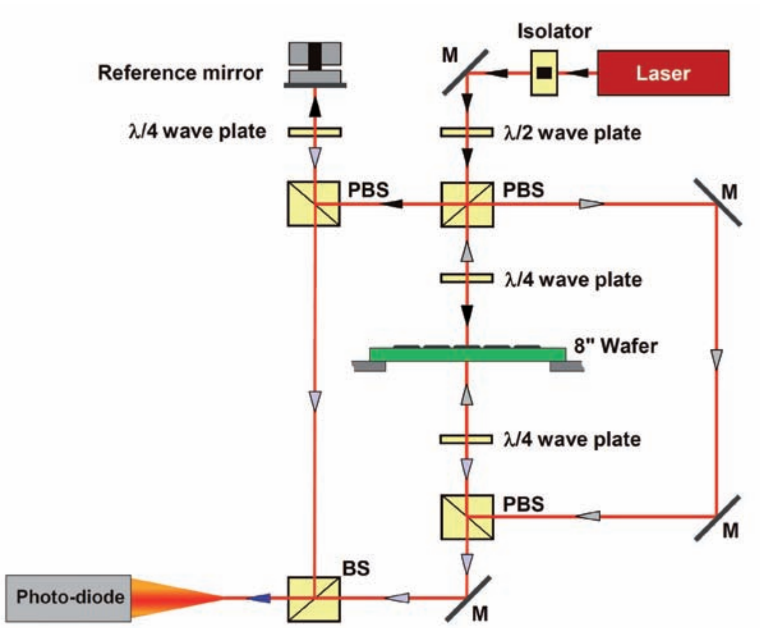

Figure 1. DBLI principle as it is used in the aixDBLI system from aixACCT.

Over the last years, new measurement methods have been developed to extract characteristics like the longitudinal $d_{33,f}$ and transversal $e_{31,f}$ piezoelectric coefficients. The suffix '33' is a reduced tensor notation and indicates that the coefficient $d_{33,f}$ correlates an electrical excitation in the polarization direction with a mechanical deformation response in the same direction. In contrast, the $e_{31,f}$ coefficient couples the generated electric charge when a film is deformed perpendicular to the polarization direction. The suffix 'f' indicates an effective value of the coefficient involved, as influenced by the properties of the substrate and electrode layers. Usually the measured effective thin-film parameters are smaller than reported bulk values due to clamping of the underlying substrate. Known measurement methods are the following:

- Measurement of the piezoelectric effect in parallel to the polarization direction (d_{33}) with a Double-Beam Laser Interferometer by applying an electrical excitation signal to the sample [1], [2].
- Measurement of the direct piezoelectric coefficients by applying a pressure on the sample and integrating the charge on the electrodes [3]. But, it has been shown by [4] that the observed high piezoelectric response is mainly influenced by substrate bending.
- Measurement of d_{31} from the bending of a cantilever structure by applying an electrical excitation signal to the film or by mechanically bending the cantilever and measuring the current response [5].

Two established measurement methods will be described in more detail. One to derive the longitudinal and the other for the transversal piezoelectric response.

Thin-film measurement principles

Measurements using Double-Beam Laser Interferometry (DBLI)

Typically the high resolution of laser interferometry is used for precise measurements of very small mechanical deformations of thin-film structures. But, unavoidable sample or wafer bending effects lead to large measurement errors. These can be extinguished by the differential measurement method used in DBLI, which is shown in principle in Figure 1. With this method thin-film expansions can be measured under electrical excitation with a resolution much better than 1 pm. This has been proven by measurements of the linear expansion of an x-cut Quartz single-crystal sample with known piezoelectric response.

Figure 2 shows example measurements of the large- and small-signal response of a 1 µm thick PZT film. One great advantage of this measurement principle is that it can be

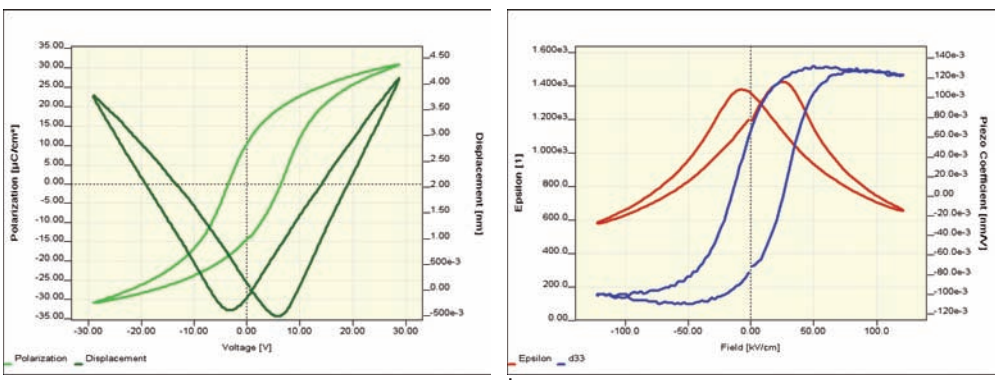

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Figure 2. PZT thin-film characterization.
(a) Large-signal polarization and displacement response.
(b) Small-signal dielectric and piezoelectric $d_{33,f}$ response vs. applied dc bias voltage.

Figure 3. The aixDBLI system for automated wafer level measurements on wafer sizes up to 200 mm.

used not only for measurements on small wafer pieces but also on whole wafers. So piezoelectric film property distributions can be measured at an early stage of the processing of the MEMS devices.

The effective piezoelectric coefficient $d_{33,f}$ describes the film response on an ideally clamping substrate. It is defined, as introduced in [4] and [6], by:

$$d_{33,f} = \frac{S_3}{E_3} = d_{33} - 2d_{31} \cdot \frac{s_{11}^E}{s_{11}^E + s_{12}^E}$$

where E_3 is the electrical field in 3-direction, S_3 the mechanical strain in 3-direction, and s_{11}, s_{12} and s_{13} are elements of the mechanical compliance matrix of the piezoelectric film; the superscript E denotes that the values are measured at constant electrical field.

Additional effects like a top-electrode-size dependency of the piezo response, [7] and [8], or changes of the coefficient across the top electrode can be investigated with DBLI and reveal important information for layout and design of applications.
Figure 3 shows the DBLI system that was constructed by aixACCT Systems, Table 1 lists technical data.

Table 1. Technical data of the aixDBLI system.

Resolution	≤ 1 pm tested by x-cut Quartz
Measurement range	5 pm to approx. 25 nm
Laser wavelength	632.8 nm

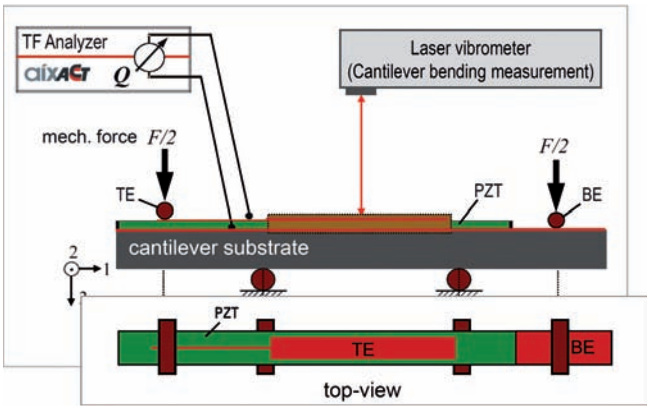

Figure 4. Measurement set-up to measure the transversal piezoelectric coefficient by the four-point bending configuration.

Four-point bending measurements

In contrast to the electrical excitation of the DBLI system, the four-point bending set-up uses a mechanical sample excitation and the electrical response is measured. Furthermore, the transversal piezoelectric response perpendicular to the film polarization direction is measured. This effect is exploited in many MEMS devices based on cantilever or membrane structures. Figures 4 and 5 show the measurement set-up and the sample holder itself, which is used to stress the cantilever bending samples. The aspect ratio of cantilever length to width should not be smaller than 8 to fulfil the requirements of a homogeneous stress distribution. This has been verified by finite-element simulations in [9]. The piezoelectric film thickness needs to be much smaller than the substrate thickness.

Figure 5. The aix4PB measurement system: four-point bending sample holder with connected single-beam laser interferometer.

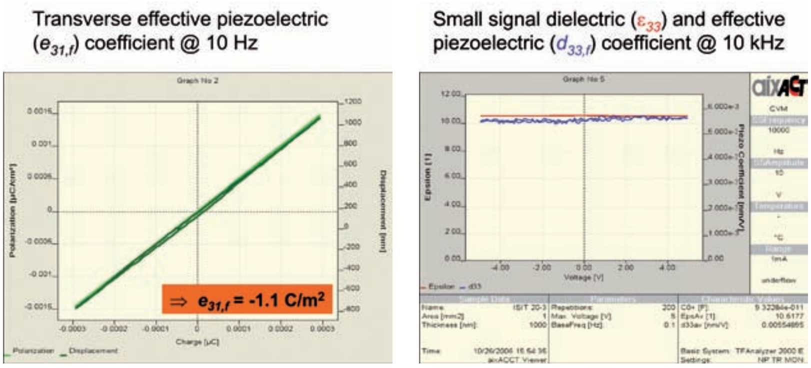

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Figure 6: Piezoelectric response of an AlN thin film of 1 μm thickness.
(a) Transversal (by using the aix4PB measurement system).
(b) Longitudinal.

Under these conditions this four-point bending configuration guarantees a very homogeneous and well-defined tensile stress distribution in the piezoelectric thin film. These well-defined mechanical boundary conditions are most important for precise measurements and a drawback for many other measurement methods for $e_{31,f}$. The effective transversal piezoelectric coefficient $e_{31,f}$ is defined, according to [5] and [6], as:

$$e_{31,f} = e_{31} + e_{33} \cdot \frac{s_{13}^E}{s_{11}^E + s_{12}^E} = \frac{d_{31}}{s_{11}^E + s_{12}^E}$$

Between the inner two supports of the four-point bending set-up the sample is exposed to a constant bending moment and therefore the thin film is exposed to a constant mechanical strain. This strain induces electrical charges on the electrodes proportional to the direct piezoelectric effect. An equation for $e_{31,f}$ can be derived that is only dependent on the bending of the cantilever (which is measured with the laser interferometer), the measured charge, and material coefficients and geometrical dimensions of the cantilever. A measurement repeatability of less than one percent can be achieved. More details on this measurement method can be found in [9].

Figure 6 shows the transversal and longitudinal piezoelectric response of an AlN thin film. The transversal response was measured using the four-point bending (4PB) configuration, the longitudinal response was derived using DBLI.

Device characterization on wafer level

It is most desirable in the production of piezoelectric MEMS devices to fully determine the electromechanical properties of the piezoelectric film at an early processing stage after the deposition of the film. So that only wafers with good film quality are further processed with cost- and time-consuming steps like backside etching.

For MEMS devices based on the longitudinal piezoelectric coefficient all relevant data can be directly measured on wafer level with the aixDBLI system. This can be done right after deposition and structuring of the piezoelectric film and the electrodes. Information like the values of $d_{33,f}$, the dielectric coefficient and loss tangent, the maximum obtainable strain, and the leakage current through the film

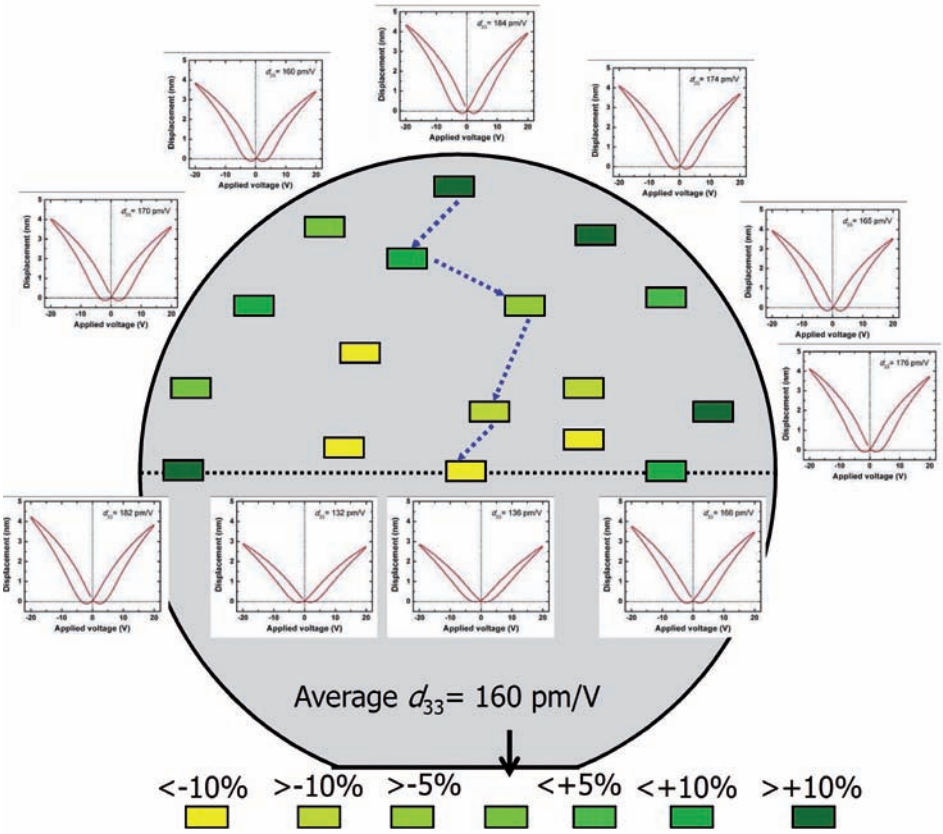

Figure 7. Wafer distribution of the large-signal displacement and derived average effective longitudinal piezo response of a PZT thin film (by courtesy of SolMateS).

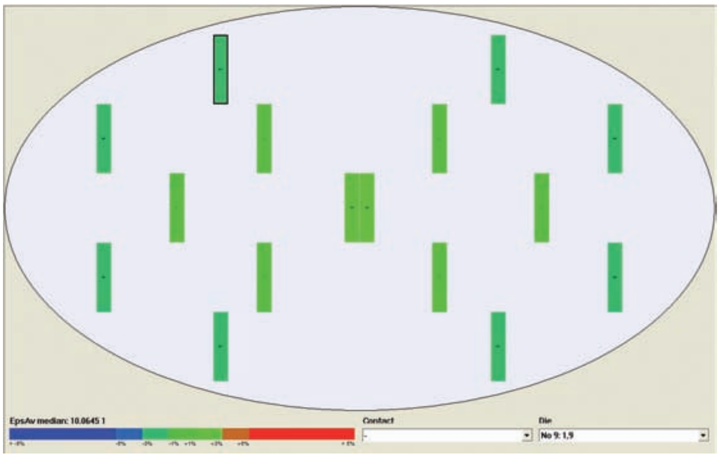

Figure 8. Wafer distribution of the dielectric constant of an AlN thin film deposited on a 150 mm wafer.

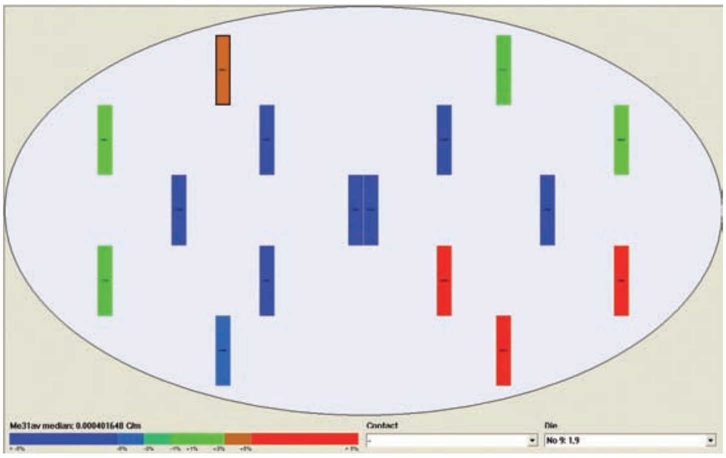

Figure 9. Wafer distribution of the transversal piezoelectric response of an AlN thin film deposited on a 150 mm wafer. Measured on bending structures cut from different positions on the wafer.

(extracted from the polarization loop) provide criteria to decide to further process the wafer. Furthermore, fatigue tests on selected devices or test structures help to optimize the processing. An example of such a wafer map distribution of the large-signal displacement on a 150 mm PZT wafer is given in Figure 7.

As discussed before, measurements of the transversal piezoelectric coefficient $e_{31,f}$ can not be done directly on wafer level. But, for dense and homogeneous films there exists a direct correlation between $d_{33,f}$ and $e_{31,f}$. So, a process control for MEMS devices based on this effect is as follows: during material qualification the cantilever test structure is part of the wafer design and will be fully characterized after the wafer has been cut. Wafer map distributions of the dielectric constant and the transversal piezoelectric response of an AlN thin film (provided by Fraunhofer ISIT, Itzehoe, Germany) are shown in Figures 8 and 9. Criteria can now be fixed for $d_{33,f}$, dielectric constant, and loss tangent that correlate to a minimum specified $e_{31,f}$ value. During production these values are used for the wafer level test with the aixDBLI system as described above, which does not require this special cantilever test structure and the cutting of the wafer.

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From AO to EUVL

From 31 May to 4 June 2010, the euspen 10th International Conference was held at Delft University of Technology, the Netherlands. The conference attracted over 400 participants and some 45 exhibitors from Europe, America and Asia. Keynotes were concerned with Extreme Ultra Violet Lithography (EUVL) and Adaptive Optics (AO). Besides, a large number of oral and poster presentations was delivered on the latest advances and market developments in precision processes and manufacturing, as well as fabrication, metrology, sensing applications and cutting-edge materials. The programme also included pre-conference tutorials, an international football match, a commercial session and exhibition, a conference dinner, and technical tours.

• *Raymond Knaapen and Hans van Eerden* •

The euspen 10th International Conference in the Aula congress centre (Figure 1) in Delft, the Netherlands, attracted over 400 participants. Naturally, the Dutch showed a strong performance with over 100 registrated participants, but Japan scored a remarkable second place with nearly 50 attendants. Euspen's strong links with industry were underlined by the number of 45 exhibitors, the majority comprising companies in the fields of precision engineering and nanotechnology.

Figure 1. The Aula congress centre on the Delft University of Technology campus.

Figure 1. Euspen president Dr Henny Spaan opened the euspen 10th International Conference in Delft. (Photo: Nicole Minneboo)

After pre-conference tutorials and a welcome barbeque in Delft Botanical Gardens on Monday, the conference was officially opened on Tuesday 1 June by euspen president Dr Henny Spaan, who elaborated on the history of Delft, the (scientific) 'Golden Age' of the Netherlands (Huygens, Van Leeuwenhoek, etc.), and 400 years of Dutch relations with Japan and with (the US of) America; see Figure 2. Following Dr Spaan's opening words, the participants were officially welcomed by vice president Karel Luyben of Delft University of Technology, a university with some 16,000 students and 4,500 employees and host of this year's euspen conference.

First keynote: EUVL

On conference day 1, the first keynote was delivered by Dr Jos Benschop, vice president Research of ASML, the world market leader in lithography machines, based in Veldhoven, the Netherlands. In his keynote on "Extreme Ultra Violet Lithography", Benschop discussed the EUVL roadmap, status and future. EUVL, using 13.5 nm wavelength, all-reflective optics and a vacuum environment, is a leading candidate to succeed immersion 193-nm lithography to print features of 22 nm and below. Several major programmes worldwide have matured this technology since the late 1980s. In 2006, ASML shipped its first two alpha demo tools, to Imec in Leuven (Belgium) and CSNE in Albany (New York, USA), respectively. Currently, early production tools are being assembled.

Benschop explained why EUVL is used to enable Moore's Law in a cost-effective way, presented some results obtained with the alpha demo tools, as well as an update of critical tool-related issues, including the EUV source, and the status of early production tool integration; see Figure 3. The EUVL roadmap, according to ASML's vice president

Euspen

Euspen is a European network organization devoted to promoting contacts between industry and research institutes in the areas of precision engineering and nanotechnology. Euspen was founded in 1999 with support from the European Commission's 'Competitive and Sustainable Growth'-programme. Now, euspen is an independent, not-for-profit organization counting over 550 individual members and 90 corporate members. Euspen collaborates with fellow organisations ASPE in the USA and JSPE in Japan; jointly they publish the Precision Engineering journal. Euspen headquarters is at the Cranfield University campus in the UK. Euspen's focus is on ultra/nano-precision manufacturing; design and build of ultra-precision machine systems; and characterization (metrology systems, instruments and techniques).
One of the highlights of euspen's activities is the annual conference, which was held this year in Delft.
Previous conferences were in Bremen (1999), Kopenhagen (2000), Eindhoven (2002), Glasgow (2004), Montpellier (2005), Baden (2006), Bremen (2007), Zürich (2008) and San Sebastian (2009). The next, eleventh euspen conference will be held on 23-26 May 2011 in Cernobbio, near Lake Como, Italy.

www.delft2010.euspen.eu
www.euspen.eu

Figure 3. The NXE 3100, ASML's EUVL pre-production tool.

Research, includes higher numerical aperture lenses, more powerful sources, and improved transmission and mechatronics, to achieve a resolution of 18 nm or better and a 150 wafers per hour productivity in 2013 – this productivity being comparable to state-of-the-art immersion lithography.

Patterning

Following the keynote, the first session of the day was devoted to "Emerging Patterning Technologies & Methods". S.V. Sreenivasan of Molecular Imprints (Austin, Texas, USA) talked about "UV Nanoimprint Lithography". Nanoimprint lithography techniques, he stated, possess remarkable replication capability with a resolution below 5 nm. In recent years, a form of UV imprint lithography knows as Jet and Flash Imprint Lithography (J-FIL) has seen significant progress in mask infrastructure, materials, critical dimension control, defect reduction, overlay, and throughput. This progress has opened up emerging nanomanufacturing applications for J-FIL, such as patterned media for hard disk drives, and as a complement to photolithography at sub-25nm half-pitch nodes for semiconductor ICs.

Sreenivasan presented the current state of J-FIL technology in applications such as terabit-density magnetic storage and advanced solid-state memory. He discussed both stepper tools as well as whole-substrate patterning tools developed using the J-FIL technology. Finally, he touched upon emerging applications in the biomedical and energy sectors.

Next, J.S. Faber of FEI Company (Eindhoven, the Netherlands) discussed "Novel FIB-SEM Based Methods for Nano-Patterning and Nano-Prototyping". Nano-patterning with a focussed ion or electron beam offers local deposition or removal of material in a process that is relatively slow, but has high spatial resolution, at the nanometer scale. Another advantage, as compared to optical lithography, is that no expensive masks are needed and that instanteneous changes to the design are allowed, giving a high turnover speed and offering a promising 3D nano-prototyping solution. Faber elaborated on the use of dual-beam FIB/SEM systems (Focussed Ion Beam/ Scanning Electron Microscope) for creating 3D nano-structures. Applications include, for example, photonics structures.

Figure 4. Snapshot of the audience attending one of the sessions. (Photo: Nicole Minneboo)

The final presentation in the "Patterning" session was delivered by P. Möller of RepliSaurus (Kista, Sweden), on "A High Precision System for Aligned Metal Printing on Wafers Using ECPR – Electro Chemical Pattern Replication". This new wafer metallization method, ECPR, is capable of printing patterned metal layers on 200- and 300-mm wafers. It combines the precision and resolution of advanced lithography with the efficiency of electrochemical deposition, by integrating the entire metallization sequence for top metal layers used in IC applications into one single electrochemical metal printing step, so Möller claimed. He presented a novel system architecture for a high-precision tool designed to perform aligned metal printing using the ECPR method. The alignment performance was shown to be better than 250 nm, as measured on 200-mm wafers.

Commercial session

The first conference day also comprised sessions on "Nano & Micro Metrology" and on "Ultra Precision Machines & Control". As an intermezzo, a commercial session was held in which some twenty companies seized the opportunity to present themselves and their product(s). Among the presenters were Moore Nanotech, IBS Precision Engineering, SIOS, MI-Partners, Klocke Nanotechnik, Cedrat, Attocube, Innophysics and Cranfield Precision. The day was concluded with a sporting event, a football match between a Dutch team and the International All Stars. In the game, the competitors lacked their professional precision, but they compensated with enthusiasm.

Second keynote: AO

The second conference day was opened by Prof. Rob Munnig Schmidt from Delft University of Technology with a keynote on "Adaptive Optics – Current International Status". In optics, shape and index of refraction of optical elements determine system properties, and disturbances in shape and index can therefore deteriorate optical performance. Well-known disturbances are thermal effects within optical components as well as atmospheric index variations. These disturbances can be corrected for by adapting shape or index of refraction of optical elements, the process of which is called Adaptive Optics (AO). The increasing demand for precision requires improvements in both hardware and software algorithms. In the keynote, some examples were presented with an explanation of the principles, as well as challenges and possible solutions.

The first example concerned terrestrial telescopes, the size of which is increasing for improved light-gathering capability as well as improved resolution. The European Extremely Large Telescope (E-ELT) of ESO (European Southern Observatory), which is planned to become operational in 2018, will have a main mirror diameter of 42 meters, which can only be realized by dividing it in 1,000 segments. Each segment is individually mounted and controlled to obtain the desired shape of the combined mirror. Additional to this shape correction, corrections must be made to compensate for atmospheric disturbance. Due to variations of atmospheric composition and density, the 'wavefront' of the incoming light is disturbed. This wavefront disturbance can be compensated for using feedback control of the mirror segments using, for example, a Shack-Hartmann wavefront sensor.

The number of actuators to be controlled in the E-ELT will be much more than 5,000, which poses an enormous constraint on control hardware and algorithms. A nice example of a very fast hardware configuration that can be stacked to large correctable mirrors had been presented on conference day 1 by R.F.M.M. Hamelinck (TNO Science and Industry): "Real-time Compensation of Dynamic Thermally Induced Optical Aberrations by a Deformable Mirror Based on Reluctance Actuators"; see Figure 5.

Another AO application can be found in lithographic projection systems for IC manufacturing with imaging resolution below 30 nm and image conformity better than

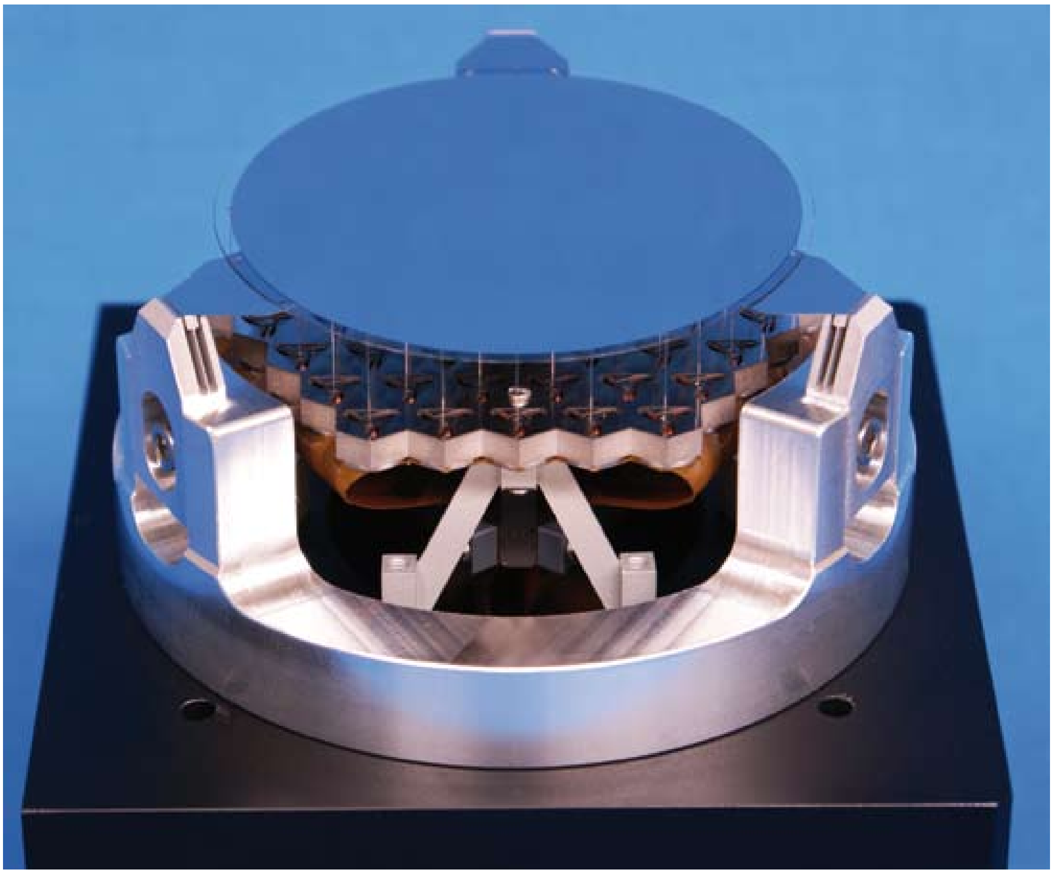

Figure 5. A deformable mirror comprising 61 actuators.

10 nm, although there is no long air path in lithography as compared to astronomy. In this case, the optical elements themselves are causing problems due to energy that is absorbed from incoming light. Additionally, other dissipative sources such as electronics and actuators impact optical performance. In EUVL, where the optical system operates in vacuum, similar AO approaches as used in telescopes are expected to be introduced. However, requirements on speed and accuracy are very different. Thermal effects are generally not as fast as atmospheric fluctuations, but accuracy levels in EUVL systems require surface accuracies down to 100 pm, which is a factor of 30 better than for the telescope example described above. This will provide the basis for a very interesting field of future research.

High Precision Mechatronics

Following this interesting keynote, J. Wesselingh, also from Delft University of Technology, opened the "High Precision Mechatronics" session with his presentation on "Contactless 6 DoF Planar Positioning System Utilizing an Active Air Film". A thin air film is used to directly position flat substrates, which can be used for production of, for example, integrated circuits, flat-panel displays and solar cells. Since no positioning stage is needed, the moving mass is reduced by two or three orders of magnitude compared to conventional positioning systems. Furthermore, the absence of mechanical contact reduces the chance of contamination and damage.

Then, S. Spiewak (University of Calgary, Canada) presented a paper on "Acceleration Based Evaluation of Motion Errors in a High Performance Translational Exciter". Position measurement errors that occur by double integration of acceleration are reduced by filtering of non-linear acceleration errors before integration. S.L. Paalvast (Delft University of Technology) talked about "Thermal Hard Disk Drive Micro Actuator for Improved Tracking Performance". His fine-stage thermal actuator enables increase in storage capacity of future drives by improving tracking accuracy. The design, fabrication and characterization of a thermal micro actuator for a hard disk drive were discussed by Paalvast.

The last presentation in this session was given by S. Henein (CSEM Centre Suisse d'Electronique et de Microtechnique, Neuchâtel, Switzerland): "Flexure-based Pointing Mechanism with Sub-microradian Resolution for the Laser Interferometer Space Antenna". Henein showed how a mirror mounted using flexures is actuated by two redundant linear piezo actuators in steps of 0.14 μrad up to a maximum stroke of 412 μrad. The mirror will compensate an out-of-plane point-ahead angle between three satellites flying 5 million kilometers apart.

Conference dinner
Other sessions on day 2 were on "Ultra-precision Manufacturing & Assembly Processes" and "Nano and Micro Metrology". The conference programme of this day was concluded by euspen presentations on the Co-Nanomet research programme activities, the forthcoming 11th conference, and the euspen Review by Prof. Pat McKeown. In the evening, the conference dinner was held in the Netherlands' smallest city, Madurodam. First, the conference participants could visit famous Dutch (architectural) highlights on a scale of 1:25. Then, they could seize the opportunity to make new business and social contacts and strengthen existing ones, while enjoying a delicious dinner.

Japan
The morning of the third conference day was dedicated to state-of-the-art developments in precision engineering & nanotechnology in Japan and the USA. The first session focused on Japan and was started by N. Moronuki (Tokyo Metropolitan University) on "Fabrication of Micro/nano-structures by Using Self Organizing Process". He explained about a self-organizing process of fine particles to produce micro- and nano-structures at lower costs compared to traditional top-down processes. Self-organizing behaviour is achieved by phenomena like surface tension in fluids, capillary forces and fluid evaporation.

W. Gao (Tohoku University, Sendai) presented a paper on "Micro and Nano Measurement Instruments". He described innovative optical sensors such as a grating-based encoder that can measure displacement along the encoder scale as well as perpendicular to the same encoder scale, by using positive and negative first diffraction orders in combination with a reference grating. Gao also reported about the same concept as used to perform 3D measurements.

The third and final Japanese presentation was by H. Yoshioka (Tokyo University of Technology), about "A Newly Developed Ultraprecision Machine Tool 'ANGEL'". ANGEL is a nano-pattern generator with a work area of 180 x 180 x 70 mm^3. The tool mechanism is fully suspended by air bearings and voice-coil actuator to prevent non-linear effects such as friction. Machining resolution of better than 50 nm has been shown in tests.

USA
The second morning session was about state-of-the-art developments in the USA. The first paper in this session, "Precision Equipment and Tools that Enable Practical Probe-based Nanomanufacturing" was presented by S.K. Saha (MIT, Cambridge, Massachusetts). He discussed process modeling for designing probe-based nanomanufacturing stations. Additionally, he addressed the design of a pilot probe-based manufacturing station which has a 6-axis nanopositioner moving the tool, kinematic couplings for workpiece alignment and a transfer line enabling sealed enclosure and work handling.

J.S. Taylor (Lawrence Livermore National Laboratory, Livermore, California) talked about "Precision Engineering within the National Ignition Campaign". He discussed several key precision engineering applications within the National Ignition Facility (NIF) at LLNL. This facility, which contains the world's largest and most energetic laser experimental system, contains a 192-beam, 1.8-MegaJoule, 500-TeraWatt, ultraviolet laser system that is used for ignition experiments. As Taylor explained, there are many precision engineering challenges in the constructing and manufacturing of the NIF system with its 75,000 optical elements.

The last presentation in the 'USA session' was given by V.K Badami of Zygo Corporation, Middlefield, Connecticut, on "High-accuracy short range displacement metrology". He gave an overview of precision measurement technologies of sub-millimeter displacement. Subsequently, he focused on a fiber-based, multi-channel interferometric sensor system that combines high-accuracy displacement measurement capability with absolute distance measurement over a range of 500 µm, with a displacement measurement uncertainty of 4 ppm.

Last session
In the afternoon, after a session on "Important / Novel Advances in Precision Engineering & Nanotechnologies", the last conference session was started. This second session on "Ultra-precision Manufacturing & Assembly Processes" was opened by G.P.H. Gubbels (TNO Science & Industry; see Figure 6) with a presentation on "Fabrication of Strongly Curved Aspheric Silicon Carbide Mirrors". His application was concerned with the GAIA spacecraft, which includes a Basic Angle Monitoring Opto-mechanical

Figure 6. TNO Science and Industry was one of the 45 (commercial) exhibitors at the euspen conference in Delft. TNO also contributed several presentations.

Assembly. In this assembly, two telescopes will measure the position of the stars with accuracy much higher than ever done before. This performance requires, as discussed by Gubbels, that the two telescopes have sub-µrad stability with respect to each other, and the telescope's off-axis parabolic mirrors have to be polished to a high shape accuracy of better than 25 nm rms.

In his presentation on "Lessons from Two Years of Building Fusion Ignition Targets with the Precision Robotic Assembly Machine", R.C. Montesanti of LLNL gave an overview of the design and function of a precision robotic assembly machine that is to manufacture the small and intricate laser-driven fusion ignition targets, which are to be used in the NIF (see above).

The last presentation, "Laser Cutting of Thin Gold Foils", was given by R. Meess (Physikalisch-Technische Bundesanstalt PTB, Braunschweig, Germany). He discussed a method for fabrication of gold foil absorber arrays of 50 um thickness by laser ablation. These foils are used in a device for the in-situ measurement of kinetic energy of micrometer-sized particles in space. Production challenges were found in thermal distortion, contamination and fixation, and handling of the gold foils.

Technical tours

The euspen 2010 International Conference was officially closed by Prof. Paul Shore of Cranfield University, UK. Prof. Shore is euspen's vice president and will succeed Dr Henny Spaan of IBS Precision Engineering as euspen president in 2011. On Friday, conference participants were offered the choice between two interesting technical tours in the Delft area. One option was the European Space Research and Technology Centre (ESTEC) in Noordwijk, the largest site and technical heart of the European Space Agency (ESA). The other tour was to the independent research organization, TNO Science and Industry, and to the Dutch metrology institute, VSL, both in Delft.

Authors' note

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X-rays measure

X-ray computer tomography has become an indispensable medical examination aid. Three years ago, Dr. Martin Simon started Volumetrik GmbH in Singen, Germany, with the intention to apply the CT X-ray technology for industrial inspections. Much older is the family-owned Wenzel Metrology Group in Wiesthal, Germany, a well-known supplier of high-precision coordinate and gear measurement machines. The Wenzel management had the brilliant brainwave to acquire Simon's Volumetrik to expand their measuring machine programme with instruments that are not only able to look into, but also inspect and measure the – often hidden – interior of industrial objects. Combining the disciplines of these two firms proved to be a perfect and fruitful marriage, which led to the birth of two sophisticated measuring machines: the exaCT® M for large objects and the exaCT S for smaller ones.

• *Frans Zuurveen* •

For the exaCT range, see Figures 1 and 2, Wenzel contribute their skills in accurately machining granite and metal base plates and parts including precision slides and position measurement systems, whereas Volumetrik contribute their knowledge of computer tomography including X-ray detector and source technology. This not only applies for the hardware but also for the indispensable software, without which X-ray tomography would be absolutely impossible. Here an essential difference between medical and industrial applications must be emphasized: the human body remains stationary, whereas the industrial object rotates, with the X-ray detector and source remaining stationary.

Figure 1. The exaCT M measuring machine from Wenzel Volumetrik.

Industrial X-ray CT technology, as applied in Wenzel exaCT contactless measuring machines, makes it possible to look into the interior of objects. Thus faults in castings

inside objects

Figure 2. The Wenzel Volumetrik exaCT S.

and forgings can be revealed non-destructively, including cracks, pores, pinholes, inclusions and other inhomogeneities. Such faults not only are made visible but also their quantity, dimensions and positions can be displayed. Other important application areas are wall thickness analysis, tool and plastic component optimization and joining technology testing. The exaCT machines also are highly valuable in designing and prototyping components, and in reverse engineering, where CAD data easily can be obtained from an existing product. Moreover it is possible to measure products in terms of deviations from CAD data, and deviations from a master model, thanks to user-friendly software.

Objects of most kinds of material can be measured, including metals and plastics. But the walls of steel parts should not be too thick and objects from heavy metals like lead are excluded, of course.

How industrial CT works

Computer tomography visualizes the interior of an object by scanning it with an extremely small X-ray source. A complete CT image is being built up from the sum of a series of images on a flat X-ray detector, where each image corresponds to a certain angle of rotation of the object around an exactly defined axis. The detector consists of millions of X-ray sensitive elements, to some extent comparable with the elements in a TV LCD or plasma screen. The object can be thought to consist of a great number of volume elements, called voxels. Each voxel contributes to the attenuation of an X-ray beam that ultimately hits one detector element. This attenuation can be translated in a grey level that corresponds with the X-ray dose on that element. The available number of grey levels depends on the bit rate of the analog-digital converter connected to each detector element. A powerful computer uses specialized algorithms to reconstruct the volume being imaged by attributing a grey level to each voxel. Another software programme calculates sharp transitions in the object by interpolation between voxels, thus creating a higher resolution than purely defined by the size of each voxel. They include transitions from material to air or from one material to another.

For real measurements in objects, the CT process requires precise knowledge of many geometrical parameters, such as the distances between source, detector and the axes of object rotation. The overall accuracy is – among many other factors – a function of the geometric resolution, which is the ratio of the sample diameter and the number of pixels in a detector row. The X-ray spot size also plays an important part when measuring small objects and can be almost as small as 1 µm. Often air bearings are applied for the linear slides and the rotation table.

Configuration and safety

The differences between the M- and S-type exaCT machines firstly concern the minimum and maximum object dimensions: for M 100 to 250 mm, for S 35 to 75 mm. They also differ in the basic configuration. In the exaCT M the rotation table has a fixed place between X-ray source and surface detector and a vertical slide is used for positioning the object with respect to the detector. In the S version the object table is able to move between source and detector, and therefore has been mounted on a Wenzel precision slide with measuring scale. An integrated video camera and marking laser facilitate object positioning.

Of course, working with X-rays demands extra safety requirements. That is why CT measuring instruments are provided with a rather heavy casing and a safety door with X-ray shielding material, i.e. steel of sufficient thickness. Switching on the X-ray tube can only be done when the safety door has been closed. In addition to these and other

Figure 3. Working with the Nikon XT H 225 CT measuring machine.

Figure 4. The Nikon Metrology 225 kV Ultrafocus X-ray source (left) and the silicon flat panel-detector Varian 2520 (right) with a piston as the object to be inspected.

safety provisions, the machines have to conform to DIN 54113.

Essential components

As pointed out before, CT would be absolutely impossible without powerful software. This article, however, deals with the hardware rather than with this essential 'virtual' component. The most important hardware components are the X-ray source, the X-ray detector and the object table with precision bearing and rotation-angle measurement device.

Most industrial CT machine manufacturers source their X-ray tubes. They typically absorb up to 1,500 W electrical power at a maximum anode-cathode voltage of 225 kV. It is very important to concentrate the X-ray emission in a very small spot, with a diameter of a few micrometers. From the electrical power absorption of the tube only a very small part is converted into X-ray energy; the rest is transformed to heat in the anode. This tube part therefore must have a high melting point and thus consists of tungsten, cooled by – mostly – water or by air. Needless to say that the realization of a stable, small and powerful X-ray spot is quite challenging.

At the other end of the X-ray optical system the detector constitutes the second essential component. Wenzel Volumetrik produces this component in-house. Such detectors used to convert X-ray energy into electrical energy via an intermediate conversion step into visible light. But it is not unlikely to presume (company secret!) that modern detectors directly convert the X-ray energy on a detector pixel into electrical energy. A detector typically may have a maximum of $4 \cdot 10^6$ pixels with a minimal size of 20 µm. The depth of the analog-digital conversion for each pixel mostly amounts to 16 bits, which means that every pixel can be read with a resolution of 65,536 grey levels.

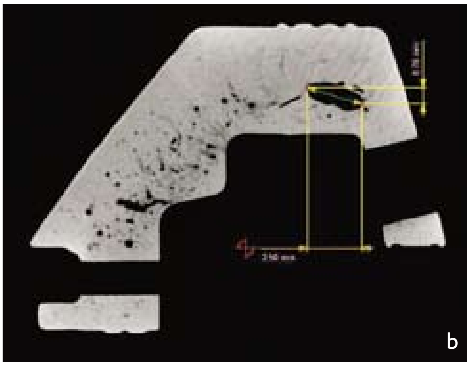
The third essential element in the imaging chain is the table on which the object to be measured turns. The Wenzel mother company shows its skills by providing the exaCT machines with a high-precision table with air bearings or – in cheaper versions – with roller bearings. Optical measuring scales allow rotation of the object with high incremental angle accuracy.

Accuracy

Wenzel Volumetrik makes a bit of a mystery of the overall accuracy of their exaCT machines. This CT manufacturer states that there still does not exist company-wide agreement about the exact definition of the accuracy of CT measuring machines.

With a detector pixel size of 20 µm and a resolution that equals the ratio of object diameter and pixel quantity in one row it seems reasonable to assume that the accuracy of CT measuring machines is positioned in the µm range, obviously not in the nm range.

Figure 5. The Werth Tomoscope HV Compact CT measuring machine.



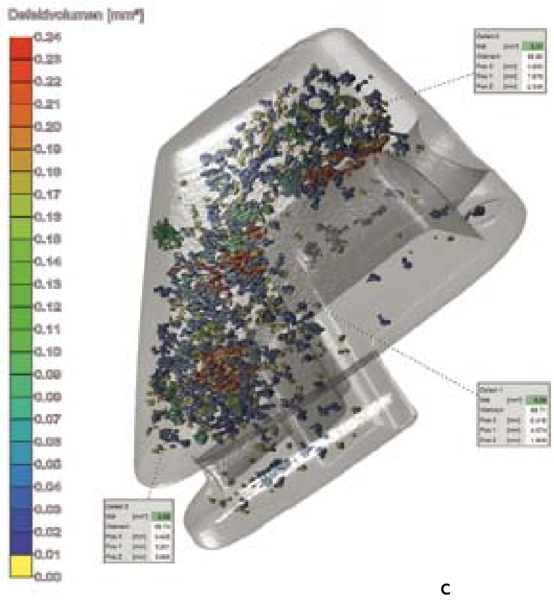


Figure 6. exaCT measuring of a cast-aluminum part.
(a) A seemingly perfect part.
(b) A virtual section of the product, showing porosity.
(c) Presentation showing all flaws in colour; on the left a colour code for pore volume.

Nevertheless, Nikon Metrology (originally X-Tek and an important provider of X-ray and CT systems) states that the accuracy of their XT H 225 industrial CT scanning machine, see Figures 3 and 4, although depending on many factors, has an extreme value of 1 µm with a feature recognition size of 500 nm.

Werth in Giessen, Germany, delivers its TomoScope, see Figure 5, and TomoCheck measuring machines with so-called multi-sensor technology (‘Multisensorik’), including a micro-fibre touching sensor with a minimum ball-probe radius of only 10 µm. These complementary measuring devices make the calibration of Werth CT measuring systems relatively easy. For measuring plastic prototype parts, Werth claims an accuracy of a few micrometers. A Werth Tomoscope reduced the release process time for a complicated plastic tool from several days to some hours, compared to measuring with a conventional coordinate measuring machine.

Anyhow, apart from the foregoing discussions about accuracy, industrial CT machines offer many innovative advantages, as discussed below.

Application examples

A fine application example is the measurement of the seemingly perfect cast-aluminum part of Figure 6a. Figure 6b shows a virtual section of the product, provided by an exaCT machine, without really cutting the object. It shows many porosities, with their dimensions, if required. Figure 6c shows one of the presentation options of the exaCT: all flaws are visible and colour coded for pore volume.

Another application example is the measurement of a hydraulic hose with different material compositions in- and outside. Even the reinforcing mesh of the hose can be displayed in a different colour. Industrial CT tomography is also valuable to check the assembly of components. Individual parts can be displayed in different colours. Also the correct assembly can be proved and gap widths can be measured.

To conclude

Industrial computer tomography is a relatively new measuring technology. Looking inside objects combined with precision measuring provides new opportunities for product-quality improvement programmes. When generally accepted accuracy definitions come into being, mutual comparison of the products of various suppliers becomes easier. One can imagine that it will not last long before CT measuring equipment becomes an indispensable part of advanced measuring rooms.

Author’s note

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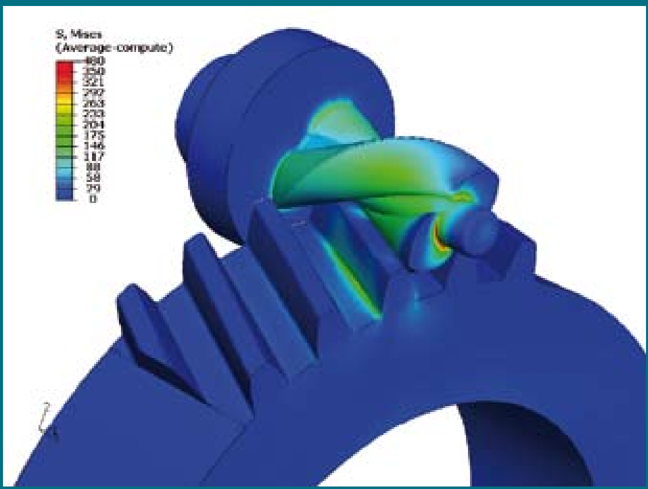
Information

www.wenzel-cmm.com
www.nikonmetrology.com
www.werth.de

Seminars, from finite elements to micro and precision machining

The Finite-Element Method (FEM) is a useful analytical tool that, when applied correctly, can save companies a lot of money. Currently, many SMEs lack the knowledge of this method or are unaware of its function. Mikrocentrum in Eindhoven, the Netherlands, organizes a special seminar on the applications and implications of finite-element simulations within product development at SMEs. "FEM a versatile technique to replace the laboratory?" will be the central question at the FEM seminar on 30 September.



Result of a FEM simulation of a gear transmission.
(Graphic: Reden)

Another forthcoming Mikrocentrum seminar that is of interest to the precision engineering community features micro and precision machining. Many of today's products (inclusing personal computers, data storage systems, mobile phones and printer heads) rely heavily on microsystems technology (MST). Microsystems are composed of extremely accurate parts that need to be fabricated (machined) and measured. New developments are not restricted to information and communication technology, but can also be expected within disciplines such as biotechnology, control engineering, sensor technology, robotics, automotive, energy and domestic appliances. During the seminar on micro and precision machining the state of the art, future possibilities and applications will be addressed. The seminar will be held on 14 October, at the Mechanics department of K.U.Leuven university in Leuven, Belgium.

www.mikrocentrum.nl

2010 Precision Fair

This year, the Precision Fair will be held on 1 and 2 December, once again in the NH Conference Centre Koningshof in Veldhoven, near Eindhoven, the Netherlands. The tenth edition of this fair will include over 200 exhibitors, a highly relevant lecture programme and the Technology Hotspot, featuring some twenty knowledge institutes from the Netherlands, Germany and Belgium.

www.precisiebeurs.nl

Cluster to cluster

With the Eindhoven region as hub, the Netherlands boasts a leading cluster in the field of precision engineering and mechatronics. Concentrations of high-tech businesses are also found elsewhere in the world, which, with their own particular focus, provide the required points of contact for business partnerships with Dutch high-tech companies. Led by innovation network Syntens, four of these companies visited the technology region of Thuringia in the eastern part of Germany at the end of June.

The mechatronics mission was a return visit after participation of the Elmug cluster (Elektronische Mess- und Gerätetechnik Thüringen) in the International Brokerage Event during the Precision Fair in Veldhoven, the Netherlands, in early December 2009. The June programme included company visits, a brokerage event and participation in the elmug4future Technology Conference. The local organisation fell on the shoulders of the Stiftung für Technologie, Innovation und Forschung Thüringen (STIFT) and the Elmug cluster. STIFT and the Dutch innovation network Syntens work together in the Enterprise Europe Network.

Resourcefulness and cooperation

Embodied in Elmug, the high-tech cluster in Thuringia originated in the period of prosperity after the fall of the Berlin Wall in 1989. Many university researchers latched onto the 'Wende' to start up their own businesses. Since then, the area around the city of Ilmenau with its university of technology is distinguished by highly specialised companies in such fields as direct-drive technologies, power electronics, sensor technologies, electronic systems and analytical devices. In the former GDR, behind the Iron Curtain, companies and researchers were heavily reliant on one another. Certain parts were hard to come by, and companies and universities had to work together closely developing and manufacturing these parts themselves. The resourcefulness that grew out of this and the collaboration that ensued between small and medium-sized enterprises and universities still characterises this region, says 'mission leader' Rim Stroeks, advisor to Syntens and Enterprise Europe Network consultant.

Interesting regions

Stroek goes on to say that companies in Thuringia have identified Eindhoven as a region that provides interesting opportunities for collaboration. "That's why – at my invitation, incidentally – various German companies decided to take part in the Precision Fair in Veldhoven, like they did last year. For their part, they asked me to combine this with an incoming mission. So in early December I will

Company visit at IMMS in Ilmenau. The system shown is the modularly designed and scalable demonstrator MKDA with a movement range of 400 mm x 400 mm and a path and position accuracy of 1 micron. With it, the concepts of distributed control and feedback of modular multi-axial systems with distributed intelligence can be verified.

be organising visits for the Thuringia businesses to companies relevant to them in the Eindhoven area." Also interesting for Dutch companies visiting Thuringia is its proximity to Jena ('Optical Valley', e.g. Carl Zeiss).

Sensor technology

The company visits to Thuringia in late June were certainly relevant and interesting, especially for commercial director and business developer Marc Schoenmakers of Maastricht Instruments. This Maastricht University spin-off develops innovative equipment for medical research and life sciences applications. This concerns equipment to support specific medical research at universities as well as manufacturing patient-specific implants for head and face surgery, for instance. An example of a medical device is an activity monitor for stimulating movement (activity) in patients with chronic illnesses such as COPD and heart failure. This device is used for examining and treating patients. A respiration chamber for measuring the metabolism in patients and test subjects has been developed in close cooperation between researchers at Maastricht University and industrial partner DSM Resolve.
In Thuringia, Schoenmakers was on the lookout for new sensors to add to his own measuring platform, which enables the concurrent measurement of physiological and non-physiological signals in various practical applications. He is also interested in sensors for measuring minute concentrations of substances in gases such as inhaled air. "We are continually exploring the boundaries of what is possible." Schoenmakers has made several new business contacts: with UST Umweltsensortechnik, a company that develops and manufactures ceramic sensor technology, to find out about developing new sensors, and with IMMS, an institute that develops micro-electronic and mechatronic systems for specific drives. Conversely, Schoenmakers was put in touch with a company that was interested in Maastricht Instruments' expertise in the field of measuring systems.

'Family'

There was also 'two-way traffic' for Huub Janssen, director and proprietor of Janssen Precision Engineering (JPE) at Maastricht-Airport. He made contact with companies he can help to mechanise the handling of biomedical samples under cryogenic circumstances. JPE has expertise in this field for astronomic and other applications. Vice versa, Janssen has invited offers for measurement electronics from companies in Thuringia. He also found it worthwhile to see how high-tech companies in Thuringia ("a sort of miniature Eindhoven") operate. "This was a good opportunity for reflection. The standard is comparable. Many of the companies were established after the fall of the Wall, which makes them a bit like a family, and it's good to see that they can work together so well as complementary companies."

Outsourcing

Ernst Treffers, business development director of Xpress Precision Engineering in Eindhoven and developer of probes and metrology (sub)modules, was mainly looking for outsourcing opportunities in Thuringia. "There are companies there that you won't find in Eindhoven, with very specific technologies in which they excel." Among the companies Treffers visited were a firm manufacturing machines for laser cutting, a mechatronics company and a sensor supplier.
Erwin Schrijver, innovation manager for equipment development at ALSI International in Nijmegen, was also in Thuringia looking for partners. ALSI develops

Information

www.syntens.nl/thuringen
www.elmug.de
www.stift-thueringen.de

equipment for laser dicing wafers, focusing on process development (laser optics). It outsources the development of the equipment and manufacturing wherever possible and has had contacts in Thuringia, with suppliers for motion, sensorics and measuring systems, since its inception as spin-off of what was then Philips Semiconductors in 2001. Schrijver established several more contacts during this trip. He was also pleasantly surprised to discover that EtherCAT, an open source I/O protocol that ALSI had adopted early on, is also very popular in Thuringia. "Maybe that rang a few bells with other Dutch participants. And if that leads to an increase in the use of EtherCAT, that can only be to our advantage."

Extensive network

Erwin Schrijver of ALSI thinks it commendable that Syntens organises trips such as that to Thuringia. "As a relatively small company with a staff of 26, we use an extensive network to build up a strong market position by being smart, lean and mean. These trips help us to identify and comprehend unique expertise within other companies and to align our developments with those of other companies, with the support of Dutch and European subsidies. We depend on a strong network and can only applaud these kind of initiatives. In this way, we break out of the 'not invented here' syndrome."

Holland@CERN

At CERN – the European particle acceleration laboratory – Dutch firms will expose themselves to the community of technicians and scientists of CERN and ESRF, the laboratory of X-ray physics. Swiss and French firms around CERN will also be invited to visit this exclusively Dutch high-tech manifestation, Holland@CERN, in Geneva from 8 to 11 November 2010. During the exposition there will be a programme with matchmaking; talks about future plans of both laboratories; general talks from technicians, scientists and firms; excursions to the experimental areas; and an All Dutch Night with all the Dutch people working at CERN.

Holland@CERN is supported by the EVD Internationaal agency from the Dutch Ministry of Economic Affairs. There are still opportunities for Dutch firms to join Holland@CERN.

www.bigscience4business.com (registration)
klopping@nikhef.nl (Rob Klöpping, Industrial Liaison Officer, Nikhef)

Parts made for the post-LHC Compact Linear Collider. This future accelerator offers opportunities for Dutch, and other, companies specialised in ultra-precise dynamic positioning and high-precision parts.

Ultra-high resolution SEMs

FEI Company recently announced their new Nova™ NanoSEM 50 Series of ultra-high resolution scanning electron microscopes (UHR SEMs). It is designed to provide industry-leading, nanometer-scale resolution and ultra-precise analysis on the widest range of samples. "In one instrument, you get imaging down to the nanometer level, high beam current for fast and precise analysis, and low-vacuum capability to extend the range of sample types and minimize preparation requirements", according to an FEI spokesman. In low vacuum, the Nova NanoSEM can examine highly insulating samples, up to nearly the same resolution that can be achieved in high vacuum, with little or no preparation, eliminating artifacts and saving time.

The Nova NanoSEM 50 Series builds on previous Nova NanoSEM instruments, and adds technological innovations from FEI's other product families:

- beam deceleration and low-vacuum capabilities (including the Helix detector for high-contrast, low-noise imaging);
- integrated sample & chamber cleaning solutions, critical for low-kV high-resolution imaging, and advanced and intuitive sample navigation and user interface;
- a universal large chamber, 16-bit scan engine and latest scanning strategies, as well as a high-precision stage;
- a new suite of detectors, retractable and in-lens, for optimized secondary electron (SE), backscattered electron (BSE), and scanning transmission electron microscopy (STEM) signal collection and filtering.

The new series comprises the Nova NanoSEM 450, targeted at advanced material science applications, and the Nova NanoSEM 650, for fast, precise navigation and 100-percent coverage of six-inch wafers. Both instruments provide 1 nm resolution at 15 kV, 1.4 nm at 1 kV, and beam currents up to 200 nA.

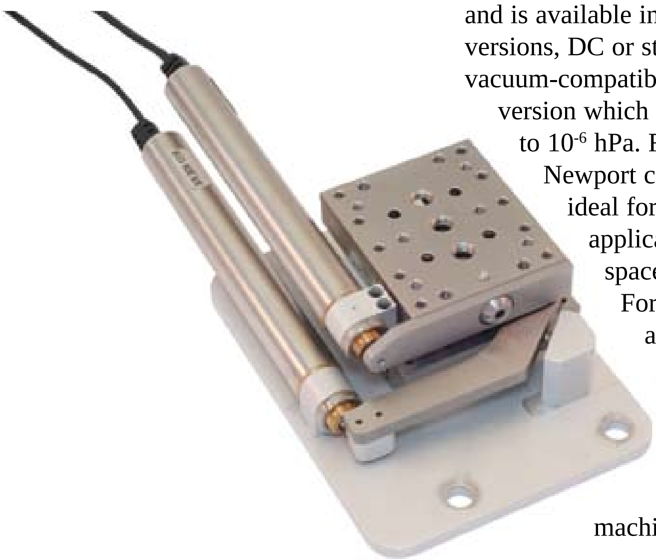
www.fei.com/nova-nanosem-50

The Nova NanoSEM 650 offers a high-precision 150-mm piezo-electric stage for fast, precise navigation, providing 100-percent coverage of six-inch wafers or masks, and substantial coverage of eight-inch samples.

Integrated XY stages

Newport Corporation recently announced the UMR-TRA XY stages. The new line of integrated XY stages are built from Newport's reliable, industry-standard UMR linear stages and TRA actuators. Affordable and compact, the small footprint measures only 90 mm wide and 38 mm high, including the base plate. The UMR-TRA-XY stages are specially designed for applications in confined spaces, according to a Newport press release, making them an excellent choice for a wide range of motion control tasks in research and industry.

The UMR-TRA has 12.5 mm travel and is available in English or metric versions, DC or stepper motor, and a vacuum-compatible stepper-motor version which is compatible down to 10^{-6} hPa. For research, Newport claims, the stage is ideal for use in vacuum applications and other space-restricted setups. For industrial applications, the robust stage is qualified for laser-beam positioning and can withstand high machine accelerations.



www.newport.com/umr-tra

The UMR-TRA-XY stages are specially designed for applications in confined spaces.

The rise of holistic lithography

This summer, ASML announced broad customer adoption of holistic lithography products which optimize semiconductor scanner performance and provide a faster start to chip production. Semiconductor manufacturers face increasingly smaller margins of error as they shrink chip features. Holistic lithography provides a way to shrink within these margins to continue Moore's Law, according to ASML, the world market leader in lithography machines.

Holistic lithography integrates computational lithography, wafer lithography and process control to optimize production tolerances and reduce 'time to money' for chip makers. During the chip design phase, ASML's holistic lithography uses actual scanner profiles and tuning capabilities to create a design with the maximum process window for a given node and application.

www.asml.com

Bringing 5-axis capability to smaller CMMs

Renishaw has introduced a new measurement product that is to transform inspection performance on a wide range of coordinate measuring machines (CMMs). Utilising technology developed for the REVO® measurement system, the new PH20 probe head offers so-called 'head touches' for rapid touch-trigger measurement, and fast infinite 5-axis positioning to guarantee optimal feature access. Its compact design makes it suitable for new CMM purchases and as a retrofit to the vast majority of existing CMM touch-trigger installations, so Renishaw claims.

The new PH20 probe head also promises to benefit CMM users with adaptive positioning to accommodate part misalignment, fast calibration routines, and an integral TP20 probe mount that optimises the working volume of the CMM, bringing 5-axis capability to smaller machines for the first time.

Renishaw's new PH20 probe head.

By incorporating the industry standard TP20 touch-trigger probe, users of the PH20 probe head will immediately have access to a range of proven probe modules, providing a wide selection of trigger forces, directional sensing options and extensions to meet application requirements. The detachable modules provide crash protection and can be automatically changed using the MCR20 change rack. Companies with existing TP20 systems will be able to upgrade to PH20 and utilise their existing modules (excepting the extended force module).

For many CMM users probe calibration can be a long and laborious process. According to Renishaw, the new PH20 head will offer dramatic time savings with a unique rapid 'inferred calibration' technique which determines head orientation and probe position in a single operation, allowing subsequent measurement at any head angle.

www.renishaw.com

Prototypes for E-ELT

In July, VDL ETG Projects and TNO have delivered three prototypes to the European Southern Observatory (ESO) to support the main mirror of what will be the largest telescope in the world, the European Extremely Large Telescope (E-ELT). With E-ELT, ESO hopes to obtain more information about the formation of galaxies, stars and dark matter. E-ELT will be built in the Chilean Atacama Desert, with completion planned in 2018.

The main mirror of the telescope will comprise of nearly 1,000 hexagonal mirror segments, each positioned with nanometer accuracy, that will work together to form a 42-meter parabolic whole. Each mirror segment is supported by a frame. The first prototypes for this frame were developed by TNO and manufactured by VDL ETG Projects.

The frame consists of a stiff interface to carry the load of the mirror of about 1.4 meters in width and 50 mm thick, and motors to compensate for image errors due to gravity and environmental disturbances. From using this huge mirror with pinpoint precision, scientists expect spectacular results.

Rectification

In the “High performance and reconfigurable design at moderate cost – An open 300mm Cassegrain telescope for the amateur astronomer” article in the June issue of Mikroniek, we neglected to mention that the project benefited significantly from the problem definition by and input of Herman ten Haaf, amateur astronomer and CEO of Astro Systems Holland. We apologise for this omission.

Raimondo Cau, Nick Rosielle and Maarten Steinbuch
Eindhoven University of Technology

Call for Prof. M.P. Koster award nominations

Every two years, DSPE presents the Prof. M.P. Koster award to a (mechatronics) designer for outstanding (lifetime) achievements in the field of precision engineering and mechatronics. Prof. M.P. Koster worked as a group leader at Philips Applied Technologies in Eindhoven, the Netherlands, and was Professor of Mechatronics at the University of Twente, Enschede, the Netherlands. He also wrote the standard Dutch textbook on design principles for accurate movement and positioning. The fifth prize-giving ceremony for this award will take place at the 2010 Precision Fair, which is being held on 1 and 2 December in Veldhoven, the Netherlands. The DSPE board now accepts nominations for the award.

info@dspe.nl

At the 2008 Precision Fair, Prof. M.P. Koster (right) handed over 'his' award, created by Philips Applied Technologies, to Jan Nijenhuis, systems engineer at TNO Science and Industry in Delft, the Netherlands. (Photo: Mikrocentrum/Sylvia van der Nol)

Precision-in-Business day: IBS Precision Engineering

One of DSPE's goals is to facilitate the exchange of knowledge and experience between members. Therefore, the society's activities include so-called Precision-in-Business (PiB) days, offering DSPE members the opportunity to be introduced to applied precision engineering at OEMs, (system) suppliers and research institutes. In June, the second PiB day of this year was held at IBS Precision Engineering in Eindhoven, the Netherlands.

Managing director Henny Spaan presented his company as 'Centre of Excellence in Metrology' and gave an overview of IBS's four product groups: special machines, machine tool calibration, non-contact sensors, and air bearings. Lex Uittenbogaard of Agilent Technologies Netherlands gave a presentation on laser interferometry; see also the article elsewhere in this issue. This spring, IBS was appointed Agilent European distributor.

Chief engineer Rilpho Donker discussed the design of the Isara 400, IBS's new ultra-precision coordinate measuring machine with an unprecedented ratio of measurement volume vs. measurement accuracy. The highly interesting PiB day at IBS also comprised a tour of the workshop, including the clean room in which the Isara 400 was demonstrated.

The Isara 400, a showpiece of precision engineering at IBS.

Successful third edition of Summer school Opto-Mechatronics

The last few sentences, as so often, were the most important ones. “In summary, although I didn’t explain before, the most important thing to remember is this. Design and build your optics as good as you can. Do the same with the mechanics and use a simple control system for fine tuning. In this way, you will build a reliable opto-mechatronic system with optimal performance.” These words by Rob Munnig Schmidt, professor of mechatronic design at Delft University of Technology, by no means were the only wise lesson during the third international Summer school Opto-Mechatronics, organised by DSPE and TNO Science and Industry. But these words did stress that all of the elements taught in the summer school were of great relevance for anyone constructing or managing the construction of a system that combines optical and mechanical elements.

The five-day summer school in the beginning of July in Eindhoven, the Netherlands, was filled to the brim with relevant subjects. Ranging from a good overview on system engineering by Friso Klinkhamer, TNO, an interesting overview of optics by Stephan Baümer, Philips Applied Technologies, and a rather dazzling lecture on control engineering by professor Maarten Steinbuch from Eindhoven University of Technology, to a thorough overview of opto-mechanics by Jan Nijenhuis and others from TNO. Finally, on Friday, Rob Munnig Schmidt and Adrian Rankers, Philips, summarized and integrated all the lessons of the days before. The evening programme was also well filled, in particular with an informative talk by Frank de Lange on system engineering in practice at ASML.

The Summer school Opto-Mechatronics is becoming an international phenomenon, with participants from Germany, Spain and Taiwan apart from the majority of Dutch participants. This added some spice to the already lively group process, as the summer school was held during the final stages of the 2010 FIFA World Cup. Supported by an excellent local organisation, ample and good food and drinks, the best possible Dutch summer weather and an inspiring environment, this summer school was a very good experience.

www.summer-school.nl

(*by Anton Duisterwinkel, TNO Science and Industry*)

The third Summer school Opto-mechatronics attracted participants from the Netherlands, Germany, Spain and Taiwan.

The House of Technology, source of technological expertise

The House of Technology is a network of technology experts and specialised engineering agencies supporting the high-tech industry to find the right technological expertise at the right time.

Development projects in the high-tech industry are very complex and almost always multi-disciplinary. Only by maximising cooperation between the different disciplines is it possible to find innovative solutions to the problems arising within these projects. It is important, therefore, that each discipline is represented by an expert with extensive experience in their field. This expert is not always available within an organisation because they are working on other projects or there is no appointed person because there is very little need for specialisation in that specific area.

Participants

It is always good to know an organisation with which experts are affiliated, experts who have proven themselves in their field and have many years of experience within the high-tech industry. The House of Technology's participants are known for their broad experience in R&D projects for the high-tech industry. Together, they cover virtually all product development disciplines (see table). Their experience enables them to get to the core of the problem quickly and instantly contribute to a project.

The House of Technology also organises meetings with presentations by high-tech companies.

Table. Overview of all fields of expertise within The House of Technology.

- Thermo & Fluid Mechanics
- Material Technology
- Production & Process Engineering
- Mechanical Analysis & Design, Mechatronics
- Lasers, Vision & Physics
- Hardware & (Embedded) Software
- Engine Design & Magnetic Applications
- System Architecture, Project Management & Construction Engineering
- CE Standards
- Industrial Packaging
- Industrial Design & Engineering
- Non-Destructive Testing

Procedure

If you need specific expertise for a project, you can contact The House of Technology. We will identify the issue and see which of our participants can tackle the question best. We will put you in touch with the expert so that your question is immediately in the hands of the right person. The expert will provide a quotation and any assignments can be given directly to them. As the participant has made arrangements with us, you owe The House of Technology nothing.

References

Many successful matches have already been made. For example, FEI Company wanted to improve the resolution of their Titan electron microscope, which required a reduction of the vibration level in the column. The House of Technology provided an expert in the field of precision mechanics, who examined the mechanics and identified the cause. Another example is Goudsmit Magnetic Systems' vibrating gutter that showed fatigue cracks. A specialist in the field of dynamic simulations analysed the cause and improved the design.

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www.thehouseoftechnology.nl

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