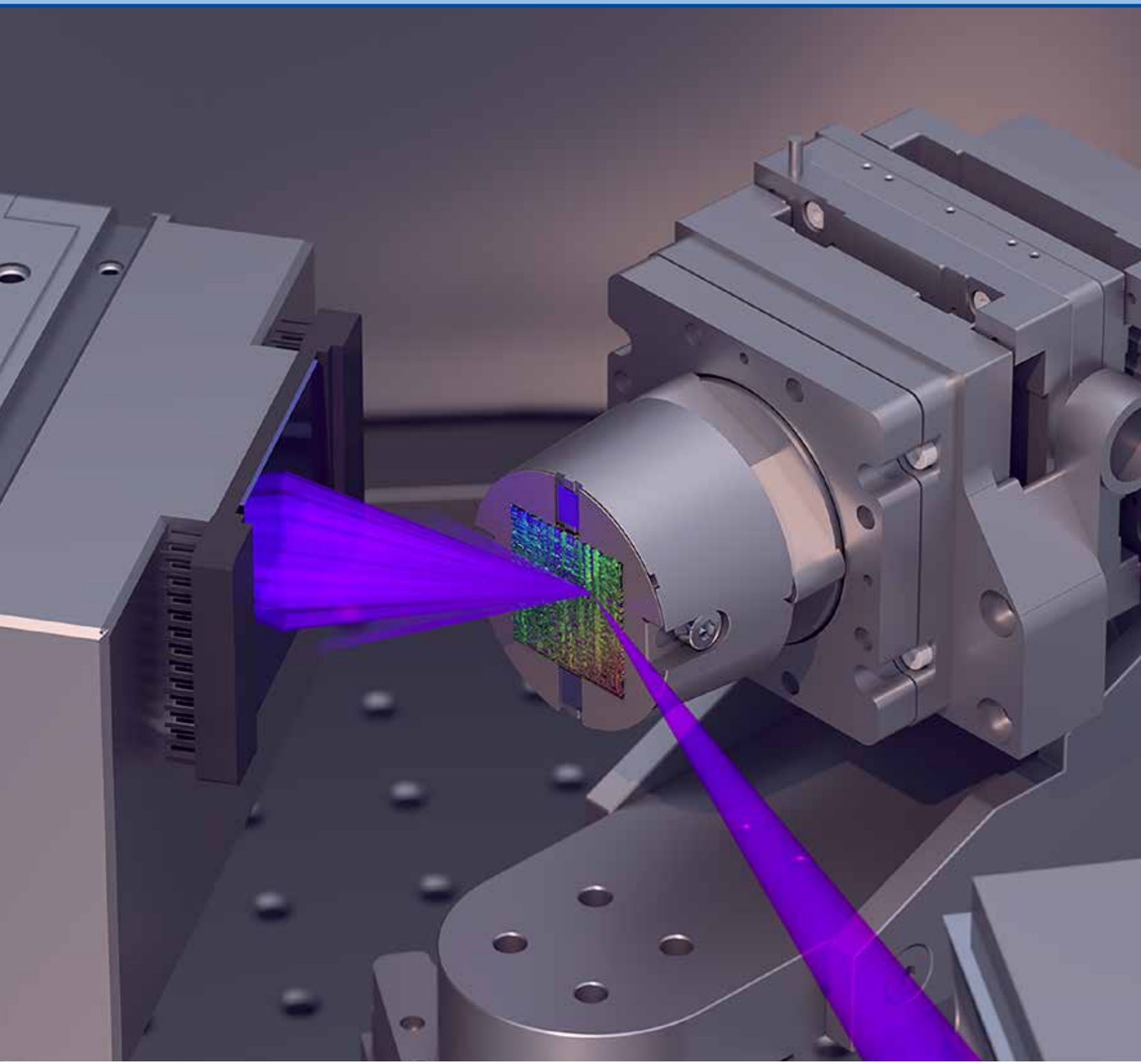
DSPE MIKRONIEK
2022 (VOL. 62) ISSUE 4
PROFESSIONAL JOURNAL ON PRECISION ENGINEERING



- THEME: METROLOGY & TIMEKEEPING
- A LENSLESS APPROACH TO EUV AND SOFT X-RAY MICROSCOPY
- A COMMUNITY REJOICING AT EUSPEN'S NON-VIRTUAL CONFERENCE
- PRECISION CLEANING OF INDUSTRIAL PARTS AND SURFACES

MIKRONIEK IS A PUBLICATION OF THE DUTCH SOCIETY FOR PRECISION ENGINEERING – WWW.DSPE.NL

PUBLICATION INFORMATION

Objective
Professional journal on precision engineering and the official organ of DSPE, the Dutch Society for Precision Engineering. Mikroniek provides current information about scientific, technical and business developments in the fields of precision engineering, mechatronics and optics. The journal is read by researchers and professionals in charge of the development and realisation of advanced precision machinery.

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Subscription
Mikroniek is for DSPE members only.
DSPE membership is open to institutes, companies, self-employed professionals and private persons, and starts at € 80.00 (excl. VAT) per year.

Mikroniek appears six times a year.

ISSN 0026-3699

The cover image (featuring the sample stage of a lensless microscope) is courtesy of Sven Weerdenburg (TU DelfT). Read the article on page 5 ff.

IN THIS ISSUE

THEME: METROLOGY & TIMEKEEPING

FEATURES

METROLOGY TRENDS IN PRECISION MANUFACTURING

(Photo: Nicole Minneboo)

It can be argued that the story of precision is an arc driven by a search for perfection and the need for interchangeable parts to drive manufacturing volumes. With that comes accuracy and tolerance needs that must be met by measurement innovations. Metrology, from the ancient Greek metron (measure) and logos (study of), is the science of measurement. As precision engineers we understand that a scientific approach to measurement is critical to assure precision outcomes.

It has been reported that there are now more transistors in the world than leaves on all the trees. As metrologists we would say this must be proven, but what is certain is that when it comes to semiconductor fabrication equipment, such as lithography machines, the hunger for precision does not stop. For integrated circuit production typical layer-to-layer accuracy (overlay) during fabrication is now at 1.5 nanometer. And the mirrors integrated in the latest generation of lithography machines require a form accuracy one hundred times smaller again.

As the targeted precision increases, so too does the skill required to control potential disturbances. Unwanted temperature gradients, for example, or unintended vibrations at extremely low levels, can have significant impacts on performance and must be managed. As each functional part of a machine becomes more complex, the measurement strategy needed to achieve precision also becomes more challenging. This strategy must take into consideration each of the parts and their interrelationships.

Printing has required precision for many decades as the human eye is very sensitive to accurate registration of colours. Today however, large cylindrical printing equipment parts must achieve sub-micron ($< 10^{-6}$ m) level accuracy over ~5 m. With advanced printing technologies, not only visuals are printed but also devices such as electronics. This requires control of the substrate during the printing process with sub-micron accuracy, whether the substrate is thin (glass) or flexible (plastic foils). In-line inspection interferometers can be applied to verify these accuracies.

Moving from 2D to 3D printing, these accuracy requirements become spatial. Here, precision motion components are key to achieve the required volumetric repeatability. The latest 3D (polymer) printers have the capability for sub-micron feature printing. For production this requires extremely accurate x-, y- and z-stages. Air bearings allow to move without friction at high speed, essential to achieve both accuracy and productivity.

In the area of machine tools, demands grow for complex shapes such as turbine blades, impellors and medical protheses. Today, 5-axis machine qualification demands sub-micron measurement of the kinematic accuracy over the full machine working volume in under a minute. Further, the trend is moving from only measurement and correction to prediction and intervention.

Precision timekeeping is inescapably linked to precision instruments. Today's official standard of time is generated by hundreds of caesium atomic clocks around the world operating at microwave frequencies. Progress with optical clocks in the last decades has reached accuracies of one part in 10^{+18}; this value corresponds to losing less than a second over the age of the Universe. This progress has been achieved through precision components and in turn feeds the precision timing needs of tomorrow's complex machines.

IBS has been part of this precision ecosystem for 30 years. We now design to the picometer. Making virtual machines has become the norm. And big data strategies have become a standard requirement as machines become more intelligent. In the field of precision engineering, the challenges never stop. Luckily, neither does the ingenuity of the engineers who love to meet these challenges.

Henny Spaan
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COHERENT DIFFRACTIVE IMAGING

Semiconductor features such as transistors used in computer chips have reached the nanometer scale, yet metrology tools still have to follow the advances in the industry to study this new generation of chips. Short-wavelength microscopy using extreme ultraviolet (EUV) light or soft X-rays could offer a solution, but it is not compatible with conventional imaging optics. Researchers from Delft University of Technology have built a lensless microscope that uses coherent EUV light to make an image at the scale of 100 nm. With further refining of this technique, they expect to drastically improve the resolution, possibly down to wavelength scales.

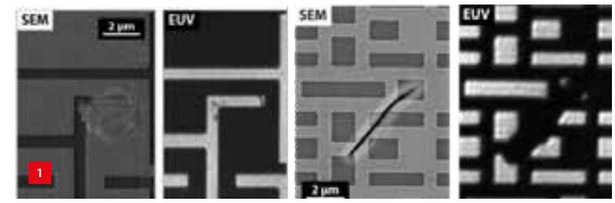
SVEN WEERDENBURG

Introduction

The quest for lensless microscopy with extreme ultraviolet (EUV) and soft X-rays (SXR) originated from the need for short-wavelength (roughly below 20 nm) microscopy. A conventional microscope uses a set of lenses, arranged in such a way that they can magnify extremely small objects. The smallest feature one can observe with such a device is typically defined by the quality of the lenses and the wavelength of the light used to illuminate the sample. This is the so-called diffraction limit or Abbe limit, which is defined as $d = \lambda/(2 \cdot NA)$, where d is the resolution, λ is the wavelength and NA (numerical aperture) indicates the quality of the optics.

Improving the resolution is obviously of interest for many applications, but in particular for optical metrology in the semiconductor industry. The continuous innovation in this industry reduces the dimensions of structures in next-gen chips and thus increases the resolution requirements for metrology tools. Consequently, this wavelength-dependent diffraction limit is obviously a good reason to use shorter wavelengths.

If resolution is the main driver, then why not use electron microscopy, as this is an already well-adopted and matured tool? Besides resolution, optical contrast is of importance, especially for lithography mask metrology, for example. The masks involved are exposed to EUV light (13.5 nm) in advanced lithography scanners and project the structures in the mask onto a wafer. If they contain defects, these are transferred via the EUV light to the wafer and could potentially ruin the product. Therefore, one would ideally like to know what the defects look like under EUV light, so-called actinic metrology, as they can look vastly different in different metrology tools; see Figure 1.



Defects in semiconductor samples can look vastly different depending on which metrology tool is used. (Image source: [1])

So, why not use the smallest wavelength possible and go all the way down to EUV, X-rays or gamma rays for high-end microscopy? Unfortunately, fabricating optics for these wavelengths is quite a challenge. Conventional refractive optics do not exist in this regime (with some exceptions [2]), so we have to resort to other types of optics. Diffractive optics, such as Fresnel zone plates, and reflective optics can be used, but are exceptionally hard to manufacture in a high-NA version.

As an indication, the advanced optical system of ASML's EUV scanners is based on a set of mirrors with an NA of 0.33 (which will be improved to 0.55 [3]). While ASML's deep-UV immersion scanner, which still works with refractive lenses, has an NA of 1.35. Although these are not metrology tools, it does demonstrate that reaching a high NA with EUV is a major challenge.

Lensless imaging, particularly ptychography (see below), can be an exciting approach to bypass this issue for next-generation metrology tools and extract the potential that EUV and SXR light can offer to the industry.

Lensless imaging

In a conventional microscope, an object of interest is illuminated with a light probe and part of the light is

AUTHOR'S NOTE

Sven Weerdenburg is a Ph.D. candidate in the Optics Research Group at Delft University of Technology. The research presented in this article is the result of a collaboration between five Dutch universities (Amsterdam (VU), Utrecht, Eindhoven, Twente, and Delft) and several industrial partners in the NWO-TTW perspective programme P16-08, LINX (Lensless Imaging of 3D Nanostructures with soft X-rays). LINX provided funding for this project.

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reflected and diffracted by the sample. This light is captured by a set of lenses (or mirrors) and transformed into an image on a camera or an observer's eye. Now if this were repeated without any lenses, the electric field E of the light beam would freely propagate towards the camera; see Figure 2. This propagation of the electric field can be described as:

$$E(x,y,z) = \iint \frac{1}{i\lambda}\frac{e^{ikr}}{r} E_0(x_0,y_0,z_0)dxdy$$

Here, E_0 refers to the electric field at the sample and r is the observation location in x,y,z space, i.e. the location of the camera:

$$r = \sqrt{(z-z_0)^2 + (x-x_0)^2 + (y-y_0)^2}$$

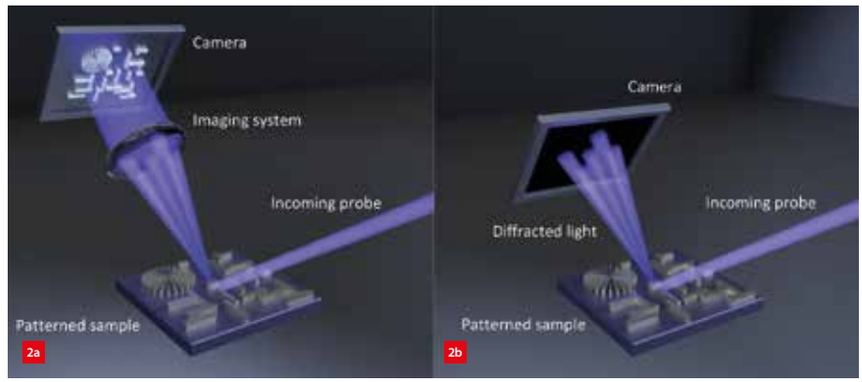
If the camera is sufficiently far away from the sample, meaning z becomes sufficiently large, these equations approach a 2D Fourier transform of the light that originated from the sample.

The diffraction patterns contain amplitude and phase information, both of which are needed to be able to perform an inverse Fourier transform and resolve the sample. However, cameras can only register intensity, so that the phase information is lost. It has been shown previously [4] that the phase can be retrieved via an iterative phase-retrieval algorithm. Loosely said, a suitable phase is found by fitting/optimising via iterations between Fourier space and real space. Imaging methods based on this concept are often referred to as coherent diffractive imaging (CDI).

CDI can be extended by scanning the probe across the sample and acquiring multiple diffraction patterns. By overlapping the probe at different scanning locations, we ensure that diffraction patterns acquired at neighbouring locations share information. This results in ambiguities, which reduce the number of solutions in the optimisation algorithm and make the reconstruction more robust. This approach is commonly known as ptychography and it has shown great potential in recent publications [5]. We have developed our own ptychography reconstruction algorithm, which is outside the scope of this article.

High harmonic generation

In order to perform ptychography and capture sets of diffraction patterns, the sample has to be illuminated with spatially and temporally coherent EUV light. Typically, researchers resort to large facilities such as synchrotrons or free-electron lasers (FELs) for obtaining laser-like EUV light. Unfortunately, this is out of reach for many research or industry applications. However, enormous advances in table-top coherent EUV sources have made them commercially available, making it a viable solution for most applications with these requirements.



Two ways of capturing diffracted light.
(a) Conventional imaging: using an optical (imaging) system to create an image on a camera.
(b) Lensless imaging: the optical system is removed and the diffracted light is captured directly.

The sources are based on high harmonic generation (HHG), which is achieved by focusing a high-power laser with pulses of a few femtoseconds (fs) on a gas jet. The electric field in the focus is sufficiently large to distort the potential well of these noble-gas atoms to such an extent that electrons can tunnel out of this well and the atom is essentially ionised. The electric field accelerates the electron away from the parent ion. Eventually, the electric field of the light pulse flips and the electron starts to decelerate and then accelerate again back towards the parent ion with considerable additional kinetic energy.

If the electron recombines with the ion, it releases this additional energy in the form of light. This light contains multiple harmonics of the fundamental drive-laser frequency, leading to a frequency-comb-like response of odd harmonics (i.e. n = 1, 3, 5, 7, etc.). By combining the individual responses of a collective of atoms, it becomes possible to generate coherent light through phase matching.

The EUV system is driven by a 1,030-nm infrared (IR) Ytterbium fibre laser (Active Fiber Systems) with an average power of 100 W running at a repetition rate of 600 kHz and a pulse length of 300 fs. These pulses are compressed to ~30 fs with an efficiency of 70% and focused onto a pressurised noble-gas jet (Figure 3). Higher harmonics are generated (depending on the drive gas) up to 140 eV (~9 nm). The wavelengths of interest for our applications are 68 eV (18 nm) and 92 eV (13.5 nm), with photon fluxes of $1{\cdot}10^{11}$ and $0.5{\cdot}10^{9}$ photons per second, respectively.

The residual high-power IR light needs to be removed after the low-power EUV and SXR light has been generated. A set of grazing-incidence plates set at the Brewster angle of the IR light help to get rid of the majority of the IR light. A few free-standing aluminium or zirconium foils with a thickness of 200 nm remove the last remainder of IR light.

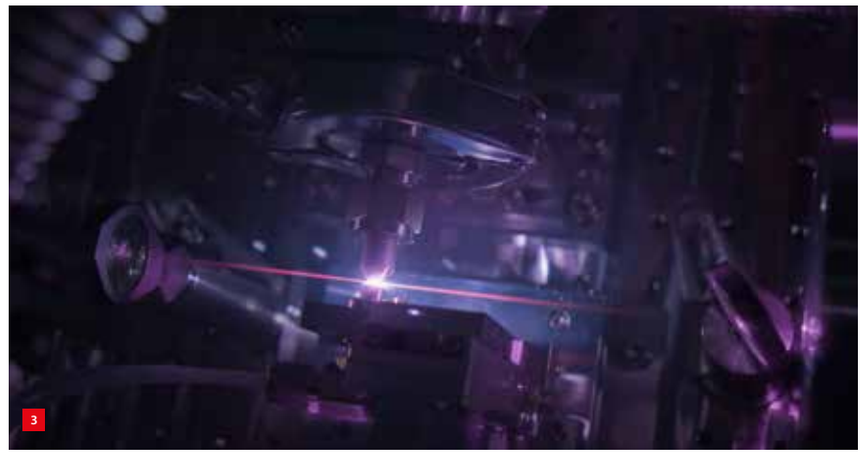
The EUV beam contains a wide range of harmonics, up to the ~110th harmonic (for 9 nm wavelength), see Figure 4. As mentioned before, preferably temporally coherent light is produced, so that a single harmonic is ideally isolated (although this is not strictly necessary). The metallic foils used as an IR filter already reduce the bandwidth down to tens of harmonics. A set of multi-layer mirrors, set at an angle of 45°, select a narrow bandwidth of 0.6 nm at 18 nm (or 13.5 nm) with a combined peak reflectivity of 20%.

Beamline realisation

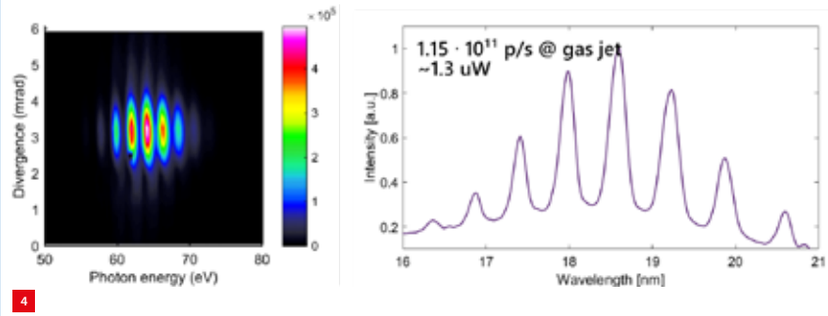
After spectral filtering, the beam is focused onto a sample via an ellipsoidal mirror. The EUV beam hits the curved mirror at a grazing incidence of 10° (relative to the surface) for sufficient reflectivity. With a rather rough alignment of the ellipsoidal mirror, a probe of 50 µm x 80 µm has been achieved. This relatively large probe size limits the expected resolution of the microscope to about 80 nm. Improving the optical alignment of the ellipsoidal mirror should yield a reduced probe size and therefore push the resolution further down, potentially to the wavelength regime.

Downstream of the ellipsoidal mirror, there is an assembly of stages containing the sample holder and the camera. A sample is mounted in a custom-built 5-DoF (degrees of freedom) stage. This allows for lateral (x,y), angle of incidence (θ), azimuth (ϕ) and depth (z) sweeps during the ptychography experiments. The large range and accuracy of slip-stick piezo stages enable the scanning of samples of 20 mm x 20 mm with a few nm positioning accuracy. A full-vacuum EUV camera (PI-MTE3 2048x2048) is mounted on a rotation stage to allow adjustments in the angle of incidence on the sample. Figure 5 shows the complete system.

With all the ingredients available, a first test run was performed. This run consisted of a 2D grid pattern with intentional perturbations on a silicon sample with gold structures ranging from 500 nm down to 10 nm at an angle of incidence of 20° relative to the surface. In total, 225 frames have been acquired with an exposure time of 200 ms per frame and a total exposed area of 70 µm x 260 µm. Thus, excluding camera read-out rates and stage movement time, an imaging rate of about 400 µm²/s is achieved.



Coherent EUV and SXR light can be generated by focusing high-power IR light into a noble-gas jet. This ionises the atoms in the gas jet leading to a beautiful plasma being displayed.



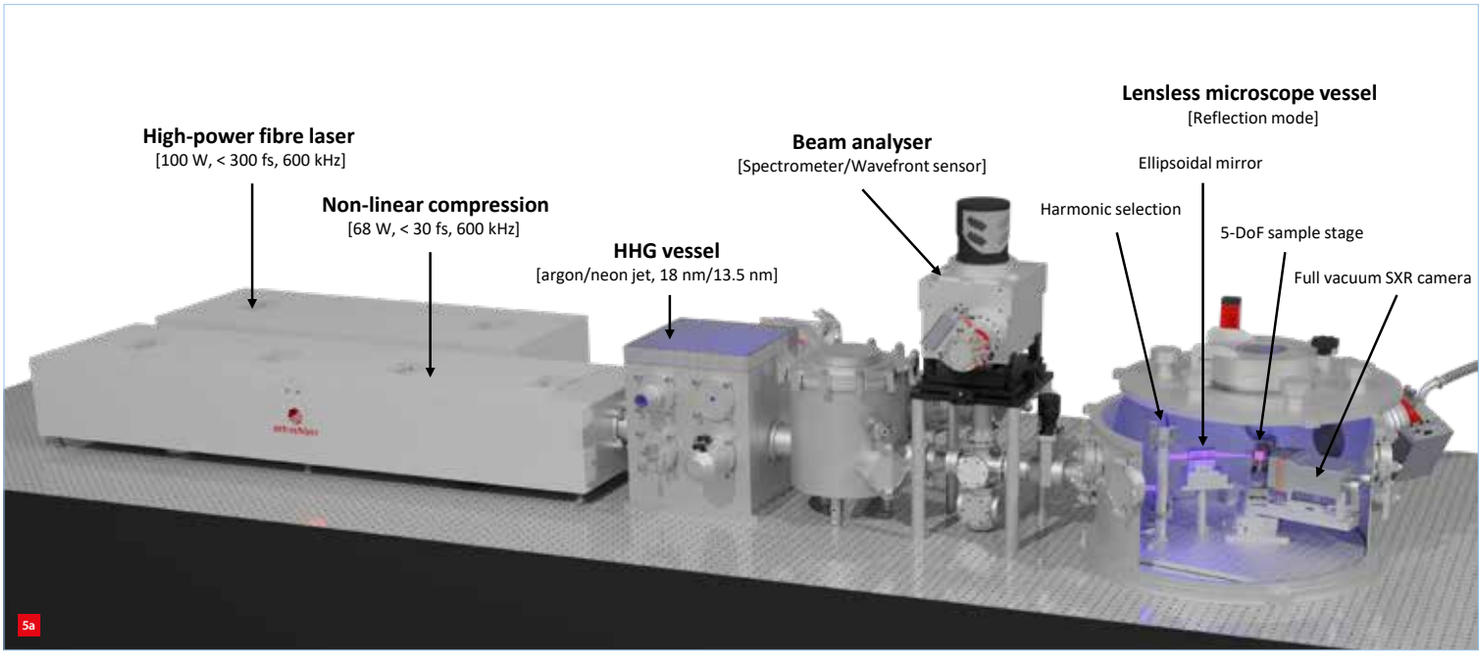
The high harmonics can be optimised in a certain bandwidth through phase matching, in this case (argon drive gas, 1.3 µW flux observed) around 18 nm.

With these 225 diffraction patterns and the advanced reconstruction algorithm, both a complex sample and probe can be resolved. Linear gratings with a pitch of 100 nm have been resolved indicating that the resolution is at least 100 nm, very close to the expected limit of 80 nm. As a complex image, i.e. reflection function and phase function, can be retrieved, it is possible to retrieve material information and height of the structures, as shown in Figure 6.

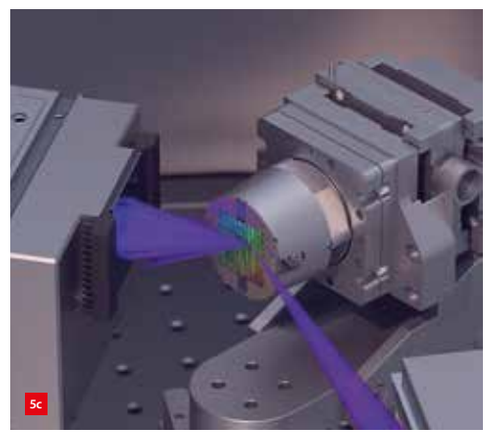
Outlook

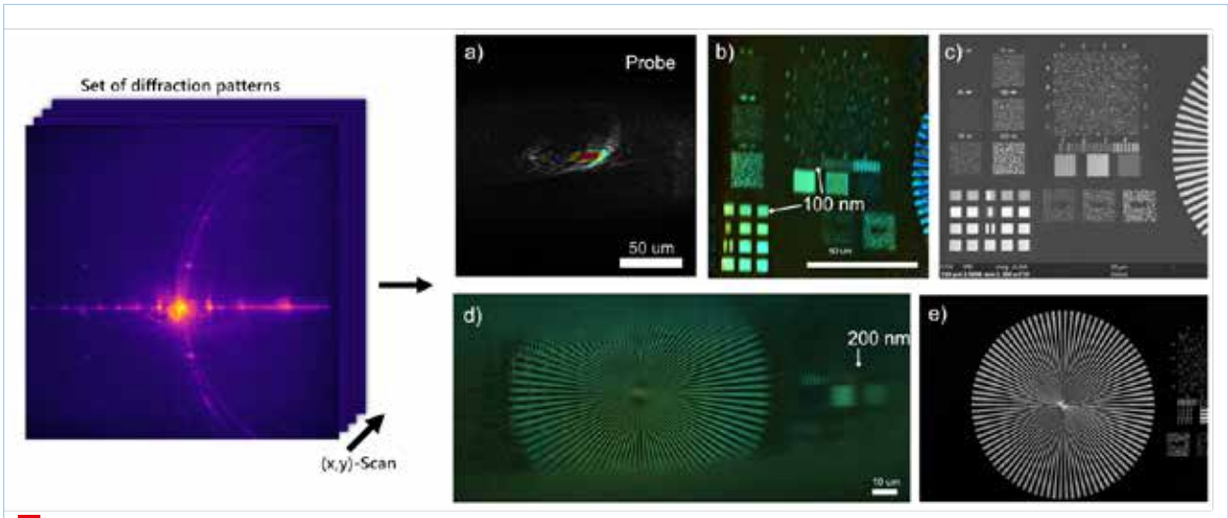
This article presents the creation of a high-resolution imaging beamline using coherent EUV light in Delft, allowing for non-destructive imaging with a high resolution. With an achieved resolution of about 100 nm, close to the expected limit in the current system settings, great potential for future computational imaging applications has been demonstrated.

Future improvements of alignment of the ellipsoidal mirror should drastically improve the resolution, possibly down to wavelength scales. Additionally, adding a-priori knowledge could help to go even beyond those scales and move to 3D imaging.



Overview of the table-top EUV SXR beamline with a lensless microscope as the end-station. The entire system fits on a 5-m optical table.
(a) Schematic.
(b) Lab set-up.
(c) Close-up of the sample stage.





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A set of diffraction patterns is acquired and a complex probe a) and object b) can be reconstructed using the algorithm. The rather large, aberrated probe indicates that further alignment and optimisation needs to be performed.
The first reconstruction b) was able to retrieve linear gratings, with a 100 nm pitch. SEM image c) of the sample presents a reference. Another scan d) focused onto a Siemens Star (spoke target), with SEM image e) as a reference.
Note that in a), b) and d), the intensity and the colour represent the reflectivity and the phase, respectively.

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THE TIMES THEY ARE CHANGING

What time is it? What is time? Time keeps running, but how can you keep up? Although the position of the earth with respect to the sun or other celestial objects is still a useful indicator for the time of day, modern timekeeping with the highest accuracy can only be done by using atomic clocks. This article discusses the past, present and future of accurate timekeeping and some of its applications.

ERIK DIERIKX

Past

In 1967, the international organisation coordinating the use of all measurement units, the *Bureau International des Poids et Mesures* (BIPM), proposed the definition of the unit of time interval, the second, based on the cesium atom. The definition of the second (after the last revision in 2020) is as follows:

> The unit resulting from the fixed numerical value of the cesium frequency $\Delta\nu_{Cs}$, the frequency of the undisturbed hyperfine transition of the cesium-133 atom in the ground state, which is fixed at 9 192 631 770, expressed in the unit Hz, which is equal to s^{-1}.

In addition to this definition of the second, a common internationally accepted time scale is also important for many practical matters. By means of radio transmissions of time signals, coordinated by the International Telecom Union (ITU), the first international comparisons of atomic clocks (see the text box on the next page) were carried out about 52 years ago. Based on this, BIPM started calculating the International Atomic Timescale (TAI).

The TAI is much more accurate than the former universal time (UT1) based on the rotation of the earth. However, over time it was seen that the TAI and the UT1 were starting to diverge. Therefore, the ITU proposed a universal coordinated time (UTC) running at the same pace as TAI and in which a step of 1 second is introduced occasionally to remain close to UT1. We call these correction steps 'leap seconds'. At first this seemed like a good compromise, but because practical implementation proves difficult in time-critical systems, the leap second has been under discussion for quite some time.

Present

Currently, there are about 90 time laboratories around the world that together have more than 400 atomic clocks. These clocks are compared with each other continuously, day and night, mostly by means of microwave measurement techniques using satellites. All measurement data from these laboratories is collected at BIPM and once a month, based on this data, the official UTC from the previous month is computed. Since this delay of more than a month is undesirable for certain applications, an unofficial "UTC rapid" (UTCr) was introduced several years ago, which is computed every week. In the monthly "Circular T", BIPM reports to all time laboratories in 5-day intervals how much the timescale realisation of laboratory *k*, denoted by UTC(*k*), deviated from the computed UTC. And similarly, a weekly report is published that shows the differences between the UTC(*k*) and UTCr at 1-day intervals.

In the computation of the UTC, there is a distinction in the types of atomic clocks. Most of the clocks included in the UTC calculation are first-generation atomic clocks, which have already been commercially available for a long time. These are cesium-beam clocks and hydrogen masers. They generate a very stable (precision) frequency, but because the atoms are not completely brought into their ground state first, they still have a small deviation from the definition of the second (accuracy). In addition, there are several dozen second-generation atomic clocks worldwide; cesium or rubidium fountain clocks (in which atoms are launched upwards; while weightless, they are measured to set the frequency). In these clocks, the atoms are first brought to their ground state by means of laser cooling. As a result, the frequency coming from these clocks is not only extremely precise, but also accurate to the definition of the second.

For the computation of International Atomic Time (TAI), the clocks of the first generation are like a large flywheel of frequency standards, each of which has a stable deviation from the group mean. This group mean is a weighted mean in which the weight of each clock is determined by the stability of the individual clock relative to the mean of the

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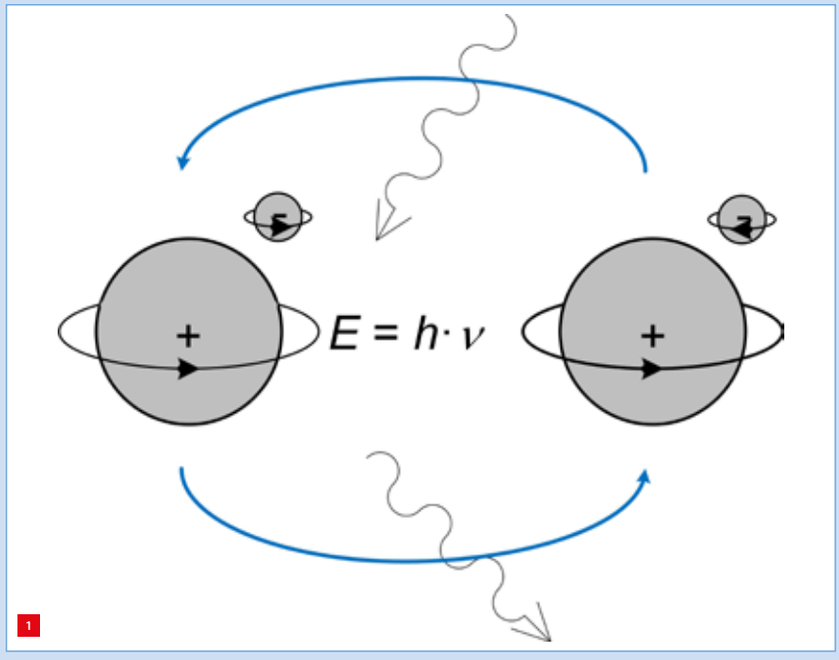
Principle of an atomic clock

Atomic clocks often work with atoms that have just one electron in the outer valence band. ^{1}H, ^{85}Rb and ^{133}Cs atoms are the most well-known elements used in microwave atomic clocks. The atom can be in two energy states. In one case (low energy), the electron spin is opposite to the nuclear spin, and in the other case (high energy), the electron spin is in the same direction as the nuclear spin. To get from the low state to the high state, the atom must absorb energy, and when the atom falls back from the high state, energy is released (Figure 1). The difference in energy can be directly linked via Planck's constant, h, to the frequency, ν, of the electromagnetic (EM) radiation that is released when the atom falls back to its low-energy state. Conversely, radiation of the same frequency must be added to return the atom to its high-energy state.

In a Cs-tube clock, the atoms in the low-energy state are separated from the atoms in the high-energy state by means of a magnetic field. The atoms in the low-energy state are exposed to an EM-field, with a frequency that is as close as possible to a frequency to which the atom is sensitive. This field is generated with a very stable crystal oscillator, the frequency of which can be adjusted. The atoms coming out of the EM-field are separated again into low- and high-energy-state atoms. The ratio of high- to low-energy-state atoms shows how close the generator is to the optimal frequency – the higher the ratio, the closer.



Transition of an atom between two hyperfine levels, in which electromagnetic radiation is absorbed or emitted. On the left, the high-energy state (nucleus and electron have the same spin direction); on the right, the low-energy state (opposite spins).

The generator is automatically adjusted to the optimum point via a feedback mechanism. The output frequency of the generator in a Cs clock is 9 192 631 770 Hz. Since this is not a useful value for many practical applications, this signal is converted via frequency dividers to signals of 10 MHz and 1 pulse per second. These signals are used as frequency and time references.

rest of the group. We call this weighted average of first-generation atomic clocks the "free atomic timescale" (*Échelle Atomique Libre*, EAL). Daily, the mean frequency deviation of this EAL is determined with respect to the second generation of atomic clocks.

Due to the complexity of second-generation clocks, it is difficult to keep them running continuously, but because of the stability of the EAL's flywheel, a continuous comparison of individual second-generation clocks with respect to the flywheel is not necessary, as long as there is sufficient data to monitor the average frequency of the EAL. The TAI calculation is based on the EAL corrected with the integrated frequency offset with respect to the second-generation atomic clocks. Finally, the TAI is corrected with leap seconds to get the coordinated universal time, UTC.

The Dutch national timescale

In the Netherlands, the National Metrology Institute, VSL, has been appointed by the government for the centralised maintenance of national measurement standards, including the standard for absolute time, time interval and frequency. VSL is one of about 90 time laboratories in the world with atomic clocks contributing to the computation of UTC. For this purpose, VSL has four first-generation atomic clocks that contribute to the EAL flywheel. From the monthly Circular T produced by BIPM, VSL knows the small deviations of its clocks and corrects for this deviation with a frequency offset generator. We call this corrected frequency and time UTC(VSL) – it is the physical realisation of Dutch time.

Comparing atomic clocks over large distances

For determining the difference between the calculated UTC and the realisation of UTC(VSL) as accurately as possible, VSL has always been at the forefront in developing measurement methods for comparing clocks over long distances. Two techniques are currently used at VSL for (semi-)continuous international clock comparisons.

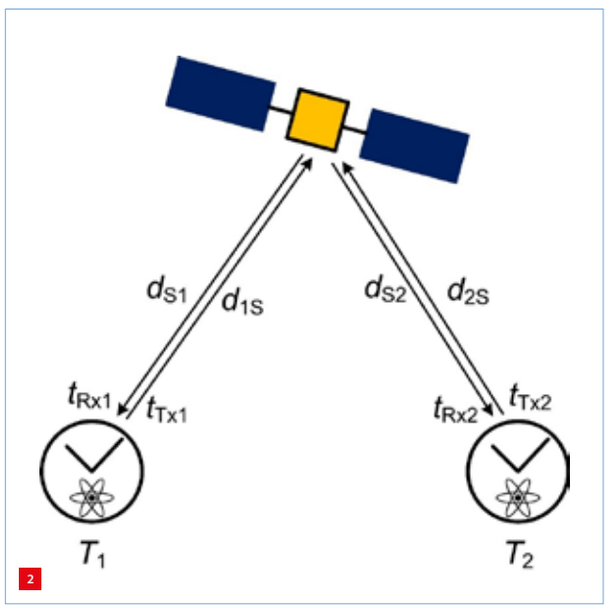
The first method uses geostationary communication satellites and is called "Two-way satellite time and frequency transfer (TWSTFT)". The second method uses global navigation satellite systems (GNSS) such as GPS, Galileo, GLONASS and BeiDou; it is called "GNSS common view (GNSS CV)".

TWSTFT

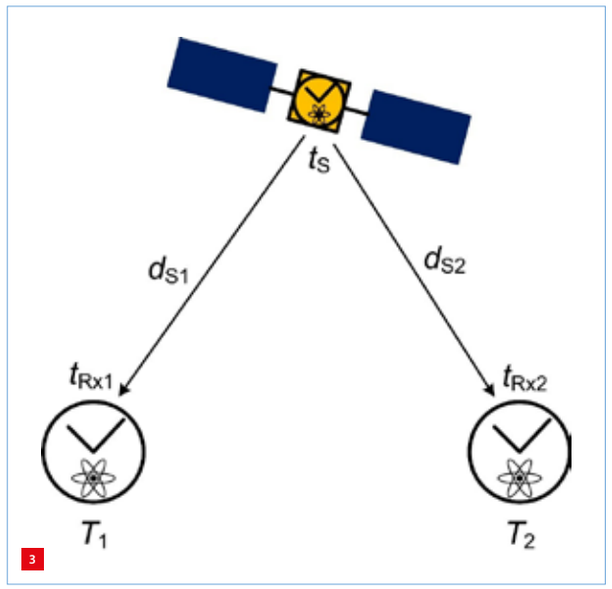
In TWSTFT, two time laboratories send a time signal simultaneously to a communication satellite (Figure 2). This communication satellite sends the signals back to earth so that the laboratories can receive each other's time signal. Each laboratory measures the time interval between the time of transmit of its own time signal, t_{Txi} (where Tx stands for transmit), and the time of receipt of the other time signal, t_{Rxi} (where Rx stands for receipt). By combining the two measurements, the difference between the two timescales T_1 and T_2 can be calculated. The accuracy of this measurement method is within approximately 5 ns.

GPS/GNSS CV

In the GNSS CV measurement method, time signals transmitted by navigation satellites (Figure 3) are used to determine clock differences. Each navigation satellite broadcasts navigation signals of which the time and frequency properties are derived from an atomic clock on board the satellite. Further, the satellite also broadcasts information on its position and orbit. When two time laboratories simultaneously 'listen' to the time signals from the same satellite and, based on their location relative to the satellite, correct for the transfer time of the signal from the satellite to the receiver, the combination of the two measurements determines the difference between the two timescales T_1 and T_2. The total uncertainty in this measurement method is approximately 7 ns.



Schematic representation of a TWSTFT measurement in which the difference between the time scales T_1 and T_2 is measured via a communication satellite. The delays of the signals d_{1S} and d_{Si} (where S stands for satellite and i stands for clock 1 or 2) are almost completely eliminated from the calculation because the two signals follow exactly the same path nearly simultaneously, only in opposite directions.



Schematic representation of a GNSS common view measurement method in which the difference between the timescales T_1 and T_2 is determined by simultaneous measurements of time signals transmitted by a GNSS satellite. Based on the known position of the laboratories and the known orbit of the satellite, the measurements are corrected for the delay of the signal from the satellite to the laboratories.

Optical fibre

In addition to clock comparisons via satellites, a lot of research has also been done in recent years on clock comparison and time distribution via fibre-optic networks. Optical fibre has the advantage of being a very stable medium in which access can be strictly regulated. As a result, the chance of intended or unintended disruption of the time signals is very small.

However, a disadvantage of this technique is that it is difficult to realise long-distance connections. Although the attenuation of the signal can be compensated for by amplifiers, the biggest challenge is often in linking connections from different operators. A European or global fibre-optic network for international comparisons of atomic clocks is therefore still a challenge for the future. Nevertheless, on a national scale, both in the Netherlands and in other countries, significant progress has been achieved on time distribution networks via optical fibres for distributing accurate time from the atomic clocks to end users.

Synchronisation techniques via networks, such as the network time protocol (NTP), are almost as old as the internet but are limited in accuracy to approximately 5 ms. The improved version, the precision time protocol (PTP),

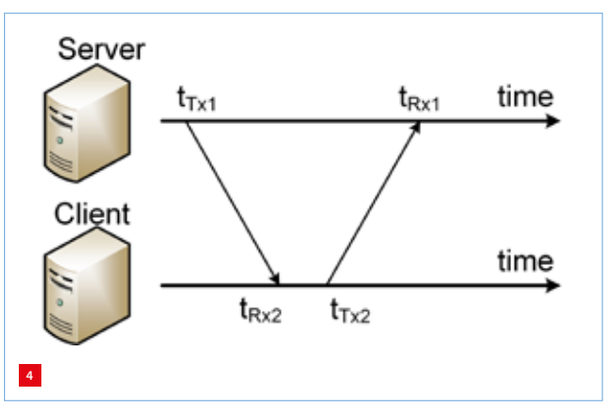
was developed about 20 years ago and achieves an accuracy of about 1 µs. About 10 years ago, the European research organisation CERN started to develop an improved version of the PTP that performs extremely well on fibre-optic networks. This variant is called the "White Rabbit (WR) protocol" or "PTP high accuracy profile". Research by VSL, among others, has shown that uncertainties of less than 1 ns can be achieved over distances of several hundred kilometers.

Like TWSTFT over communication satellites, NTP, PTP and WR are also two-way synchronisation techniques, thus (largely) eliminating the delay due to signal transit time, assuming that the forward signal propagation delay is as long as the reverse delay (Figure 4). The degree to which the assumption of equal forward and reverse delays is satisfied and the accuracy with which the times are measured, ultimately determine the total uncertainty in the synchronisation. An uncertainty of less than 1 ns is achievable with WR.

Which time?

Via satellite and network techniques, 'time' is made available for all kinds of applications, but which time is this actually? The UTC is the common universal timescale, but it essentially exists only on paper or in a text file. Time signals broadcast from satellites or via network time servers are from a physical realisation of UTC that corresponds approximately to the calculated UTC.

A time signal transmitted from a navigation satellite is derived from an atomic clock on board the satellite. This atomic clock is approximately equal to the GNSS system time realised with atomic clocks on earth. The atomic clocks that realise the GNSS system time run at approximately the same pace as UTC. However, no leap seconds are inserted into the GNSS system time. As a result, from the start of the American GPS, the difference between the GPS system time and UTC has increased to 18 s. In the signal transmitted by a navigation satellite, a message is included that provides a prediction of the difference between the clock in satellite and the UTC. This allows the user to correct the received time for synchronising as closely as possible to UTC.



Schematic representation of synchronisation via network protocols such as NTP, PTP and WR. A time server sends a time signal at time t_{Tx1}. The time client receives this signal at time t_{Rx2} and immediately returns a time signal to the time server, which receives this message at time t_{Rx1}. If the assumption of equal forward and reverse path delays is correct, then the path delay t_p of the signal and the difference between the clock of the client and the clock of the server ($T_2 - T_1$) can be calculated from the four timestamps. With this information the client can adjust its clock to synchronise with the server.

In addition, the user must also correct for the path delay of the signal from the satellite to the receiver. Navigation satellites fly in an orbit of about 20,000 km above the earth's surface. The signal therefore takes approximately 70 ms to travel from the satellite to the receiver. The satellite transmits data about its orbit, and the receiver's position can be determined from the navigation signals from four satellites. This allows the receiver to correct for the path delay of the signal.

The time being sent via network protocols can come from a GNSS receiver or can be linked directly to an atomic clock in a time lab that contributes to the realisation of UTC. Network time servers using the NTP send signals approximately equal to UTC. This signal already contains leap seconds and can also announce when another leap second is about to be inserted.

Network time servers using the PTP or White Rabbit send a signal that is approximately equal to the TAI and has therefore yet to be corrected for leap seconds. The time server or the user must keep track of the integer number seconds of difference between TAI and UTC.

As NTP, PTP and White Rabbit are all two-way protocols, the path delay of the signal can be estimated to a certain level of accuracy and the client (receiver) can correct for this.

Applications

All kinds of applications – the clock on the church tower, the train station clock, the computer network, the stock exchange, the electric power grid, the telephone network, navigation systems, scientific experiments – need a more or less accurate time that can be traced back to UTC in one way or another.

- When the clock on the church tower is delayed or advanced by 5 minutes, there is a risk that we will arrive at our appointment too early or too late.
- When the station's clock is running 1 minute ahead, there is a risk that the train will leave too early and that passengers don't catch the train.
- When computers on a network fail to synchronise within 1 s, there is a risk that the user can no longer

log in to the corporate network, or that encrypted messages can no longer be decrypted by the recipient.
- When the computers in the stock exchange are not synchronised within 1 ms, the order in which purchases and sales of shares have been made cannot be traced properly, and therefore the price of the share cannot be fixed at the time of the transaction.
- When measuring equipment in the electricity network is not is synchronised within 50 µs, it is more difficult to determine whether the supply and demand of electricity are still balanced, resulting in the risk that the electricity supply is shut down as a precaution to avoid larger grid instabilities.
- When phones in a mobile phone network are not synchronised within 1 µs, there is a risk that a phone call drops out because the digitised conversation does not run smoothly over the connection.
- When the clocks of a satellite navigation system are out of sync by more than 100 ns, navigation for vehicles within cities or for ships in a harbour is much more difficult because the position of the receiver has become too inaccurate.
- When the clocks in a scientific experiment to determine the speed of particles are not synchronised with each other within a nanosecond, there is a risk that a wrong conclusion is drawn about particles moving faster than the speed of light...

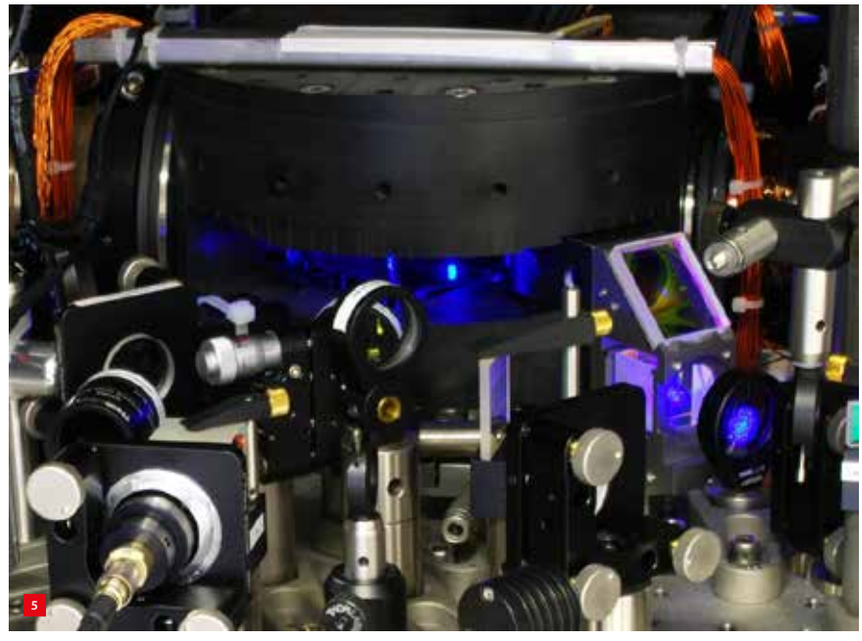
All in all, there are countless reasons why it is important that all clocks are properly synchronised with the UTC.

Future

New clocks

Since the invention of the atomic clock, 'time' has progressed. With advances in microwave and optical techniques, it was found that atoms other than cesium would be better candidates for the definition of the SI-second. New clocks have been developed that are based on atoms like strontium (Sr) and ytterbium (Yt), producing frequencies in the terahertz range. These are optical frequencies, and therefore these clocks are called optical clocks (see Figure 5). Simply speaking, these signals are more accurate for timekeeping because they include more vibrations per second, which increases the resolution for determining time intervals.

The technology of optical clocks has now come to the point where about 15 laboratories worldwide have them operational. Not yet continuously operational, but with sufficient operating time that they can be used to better determine the stability of the EAL timescale, which is the basis of UTC. The discussion on redefining the SI-second began several years ago, and the roadmap towards this redefinition is now becoming steadily clearer. Although there is still a lot of work to be done, a new definition of the SI-second is expected between 2030 and 2040. This definition will then be based on energy transitions of atoms or ions that produce electromagnetic radiation in the optical range.



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An optical clock based on Sr atoms is under development at the University of Amsterdam. (Source: www.strontiumbec.com, courtesy of University of Amsterdam)

New UTC

Initially, it seemed to make sense to keep the atomic timescale (UTC) quite close to the traditional timescale based on the rotation of the earth (UT1) by introducing corrections of 1 second if the difference became too large. By now, we see that accurate time and synchronisation are necessary ingredients for operating critical infrastructures like electric power grids, navigation systems, telecommunication networks and computer networks. In these infrastructures, introducing leap seconds always runs the risk of temporarily losing synchronisation and consequently critical infrastructure potentially going down.

Therefore, the operators of these infrastructures are calling more and more loudly for a new common universal timescale without the inconvenient steps of leap seconds. A joint working group with representatives from BIPM and ITU has now drafted a proposal for a new definition of UTC to solve the issue. The current proposal essentially allows for the difference between UTC and UT1 to increase to more than 1 s. So far, no new limitations for the difference between UTC and UT1 have been defined in the proposal. This has been left for further, future discussions.

The difference between UTC and UT1 will still be monitored by the International Earth Rotation and Reference System

Service (IERS) and will be published to be easily accessible for applications that need this information, such as astronomic observatories.

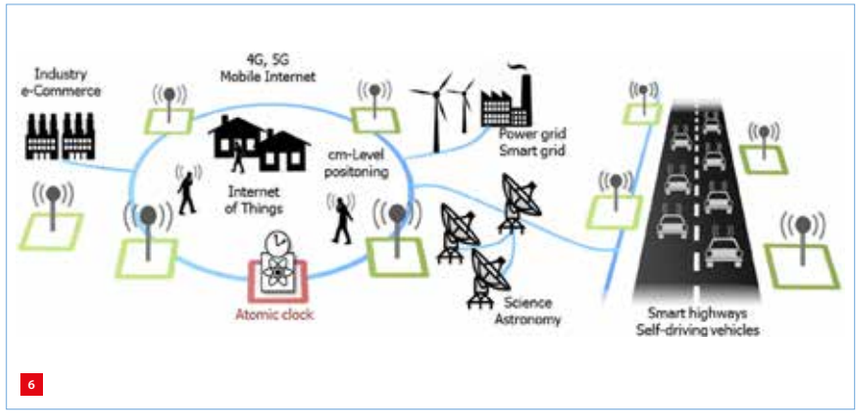
Although some organisations do not wish to wait another year to abolish leap seconds, others have indicated that they need sufficient time to implement this revised definition of UTC. It has therefore been proposed that the new definition of UTC shall become effective from the year 2035. In the General Conference on Weights and Measures (CGPM) that will be held in November 2022, representatives of national governments will cast the final vote on this proposal for a new UTC.

New applications

With the improvements in timekeeping and time-distribution techniques, new applications are born as well. The relation between timekeeping and navigation is about as old as mankind. With each improvement in our ability to keep track of time, our abilities for positioning and navigating have improved as well. Only a few decades after the invention of atomic clocks, the Global Positioning System (GPS) was launched. With modern GPS receivers smaller than the size of a wristwatch, we can determine our position with an accuracy of about 10 m. However, because of the weak signal from GPS satellites, positioning only works well in open outside areas.

The new generation of atomic clocks, combined with new technologies for distributing time and frequency signals over optical fibre networks, allows us now to overcome this weakness of satellite navigation. In the research project SuperGPS, funded by the Dutch Research Council (NWO), scientists at TU Delft and VU Amsterdam have joined forces to develop the technology for a terrestrial navigation and positioning system (TNPS) that is based on a combined optical fibre and wireless network for accurate time and frequency distribution. A conceptual diagram is shown in Figure 6.

The TNPS uses a backbone of optical fibres (blue lines) for distributing accurate time and frequency signals from



Conceptual diagram of a terrestrial navigation and positioning system based on a combined optical-wireless telecom infrastructure for accurate time and frequency distribution. (Source: SuperGPS, www.tudelft.nl/citg/over-faculteit/afdelingen/geoscience-remote-sensing/research/projects/supergps, courtesy of TU Delft and VU Amsterdam)

a centralised timescale realisation based on atomic clocks (red box). These accurate time and frequency signals synchronise a network of wireless transmitters (green boxes). The transmitters are actually very similar to base stations for mobile-phone networks, except that an improved synchronisation device needs to be included. The transmitters then broadcast synchronised navigation messages in a similar way to navigation satellites. However, the structure of the navigation signal has been modified to be less susceptible to intended or unintended disturbances.

An interesting aspect of this concept is that it can be implemented in existing telecom infrastructures with limited modifications and without a significant loss of bandwidth for regular telecom services. And, alongside the advantage that this TNPS can also work indoors, a demonstration at The Green Village at TU Delft – with synchronisation support from the atomic clocks at VSL – has shown that a positioning accuracy of 10 cm can be achieved.

This achievement is a major step towards autonomously driving vehicles. Imagine yourself in a car, driving in auto-pilot mode, sitting back and relaxing – listening to Bob Dylan's "The Times They Are A-Changin'".

REVOLUTIONISING HOROLOGY

Silicon has established itself as an alternative to some of the more traditional materials used in watchmaking. This is due to its characteristics, such as low specific mass, high Young's modulus, low hysteresis, favourable thermal properties, and high manufacturing accuracy. Key components can be made smaller, more accurate, and more energy-efficient, while still constituting a mechanical watch. In particular, with the introduction of compliant mechanisms made of silicon, horology has entered a new era.

Introduction

The mechanical watch as it is known today stems from the 1675 invention of the balance wheel by Christiaan Huygens. Up until this date, the watch movement was one of the most precise mechanical systems. To put that into perspective, a mechanical watch oscillator can maintain its precision remarkably to within 0.001%, i.e. only 1 sec in 24 hours, without electronics. Nevertheless, the last 20 years have seen exciting new developments within the field of horology innovation.

Innovations in manufacturing processes have led to the application of new materials. Besides the traditional equipment for milling and turning, movement makers can now use microfabrication methods to produce state-of-the-art silicon components. Silicon holds many benefits, such as being a very hard, lightweight and non-magnetic material. These benefits facilitate the creation of more accurate, durable, low-maintenance devices.

EDITORIAL NOTE

Input for this article was provided by Robyn Gerlach, R&D engineer at Flexous Mechanisms (www.flexous.com).

The Slimline Monolithic Manufacture of Frederique Constant, featuring a high-frequency pivot oscillator designed by Flexous. (Photo: Eric Rossier)

Applications of silicon range from wheels to springs and even to the replacement of complete functions with components that look nothing like the traditional components. An interesting example of this can be seen in the high-frequency pivot oscillator designed by the Dutch company Flexous Mechanisms for the Slimline Monolithic Manufacture of Swiss watchmaker Frederique Constant (Figure 1).

Benefits

Silicon exists in different configurations but is often used in its single-crystal form, also referred to as monocrystalline silicon. The benefit of the single crystal is that the material can be described with a Hookean material model, as there is almost no hysteresis during deflection and, therefore, no energy dissipation. This means that the deflection of the material can be modelled very accurately, and the motion can be repeated many times without diverging from the original path. Besides ensuring the repeatability of the motion, the lack of hysteresis also results in very little fatigue. There are applications known, for instance, in sensors, where the lifetime of parts exceeds billions of cycles without any signs of material failure.

Silicon components have been part of electronics and vehicles for a long time. Many sensors, such as pressure sensors and accelerometers, indispensable in the automotive industry, are made from silicon. Today, the most significant technology driver in silicon component development are applications in consumer electronics, smartphones, laptops, and tablets. The best-known application is microelectronic chips, made on silicon wafers using different micro-fabrication techniques. Their usage in these consumer products gives evidence of their great reliability in different environments for a large range of temperatures and magnetic fields, and their overall durability.

The Netherlands is one of the world's leading countries in developing the machinery for the semiconductor processes

(companies such as ASML) and producing the semi-finished products (NXP), and also has the expertise for production and integration of the resulting structures (companies such as Philips).

Other benefits of using silicon include the accuracy that can be achieved in manufacturing. The relatively low weight and high Young's modulus of the material offer opportunities to create very slim and small parts that are less influenced by gravity, and hence a change in movement orientation, than conventional parts. The following sections feature application examples of silicon in traditional and not-so-traditional watch components, demonstrating how the benefits of silicon play a key role in improving performance.

Manufacturing

In some sense, all manufacturing methods used in horology might be regarded as microfabrication, due to the size and desired accuracy of the parts. However, what we are referring to today as microfabrication is the process of manufacturing micrometer-scale structures by using semiconductor processing technology. This includes various techniques to define a desired monolithic device. Generally, it comprises three main processes: material layer deposition techniques, for adding thin layers of desired materials to the substrate; patterning techniques used to transfer a design geometry onto the substrate; and etching techniques for transferring the design by removing material from the substrate.

As geometries were more demanding, requirements for high-aspect-ratio anisotropic etching became tighter. Thus, Robert Bosch GmbH developed a completely new plasma etching method for deep reactive-ion etching (DRIE) in 1994, which is popularly known as the Bosch process. This process enabled more creative designs and more scalable production. The advantages of this process were one of the main drivers for introducing silicon-based components into the world of mechanical watches, presenting a manufacturing method that enables high aspect ratios, is scalable, and has high precision.

One of the benefits of high-aspect-ratio structures is that very thin flexures can be created. Being able to use a wide range of flexure thicknesses gives engineers the freedom to create designs that were not possible traditionally. Producing flexures in this way is a very specialised process that requires a lot of knowledge and experience, where controlling the etching process to match the actual part as close to the design as possible is key to achieving the desired behaviour. Flexous has all the knowledge in-house, creating the opportunity for mechanical engineers to work together closely with process engineers, in order to jointly optimise the designs.

Replacement

When silicon is used to replace parts of traditional mechanisms, it adds to the system's accuracy due to the material's lightness, reducing the effect of gravity. Besides that, the antimagnetic property of silicon also contributes to creating a more accurate system. These days watches are more often in contact with magnetic fields as these are created by many of our electronic devices, including smartphones, computers, and radios. Even magnetic closures on handbags can create a large disturbance in the movement. Well-known applications for silicon are sensitive components in a watch, such as the balance spring and the escapement wheel (see the brief watch glossary in the text box).

For the conventional hairspring, there was only one supplier that could produce the highest quality for a competitive price; Nivarox, part of the Swatch group, on which the whole Swiss watch industry relied. To create a competitive alternative to this, a few companies started to experiment with other materials and investigate their benefits. This contributed to the development of the silicon hairspring, which at this point is still patented and therefore only

A brief watch glossary

A mechanical watch has a face, hands and an internal mechanism, called the movement, comprising at least five parts:

- A mainspring (contained in a barrel) that stores mechanical energy to power the watch.
- A balance wheel, provided with a balance spring (hairspring), that oscillates back and forth to serve as the timekeeping element.
- A gear train (or wheel train) that transmits the force of the mainspring to the balance wheel and guarantees the correct transmission ratio to get seconds, minutes, and hours. To set the time and wind the main spring, a separate geartrain is integrated, called the keyless works.
- An escapement (of which the anchor escapement is a specific version) that keeps the balance wheel vibrating by giving it a push with each swing, and allows the watch's gears to advance or 'escape' by a set amount with each swing, producing the familiar 'ticking'.
- An indicating dial that displays the time in readable form.

(Source: en.wikipedia.org/wiki/Mechanical_watch)

available to a limited group of companies and their watches; proper examples are the Tissot Gentleman Powermatic and the Longines Ultra-Chron.

Besides the hairspring, other fast-moving components could benefit greatly from the properties of silicon. The escapement, for example, requires high accuracy and preferably also insensitivity to influences from gravity or magnetic fields. An interesting example of a silicon escapement can be seen in the Horage Supersede, which is not only antimagnetic but also has a 55% higher efficiency than conventional Swiss lever escapements [1]. The Oris Big Crown Pointer Pate Cal 403 has a silicon escapement and anchor, reducing the influence on their movement by magnetic fields by more than 90% [2].

Innovative components

Mechanical wristwatches have been regulated by balance wheel assemblies for more than three centuries. The energy flows from the energy storage through the gear train to the escapement wheel, which interacts with the oscillator; conventionally, this oscillator is an assembly of a balance wheel and a balance spring. The escapement provides energy that maintains the oscillation of the balance wheel, which then regulates the speed of the escapement wheel and thereby the unwinding of the mainspring in the barrel.

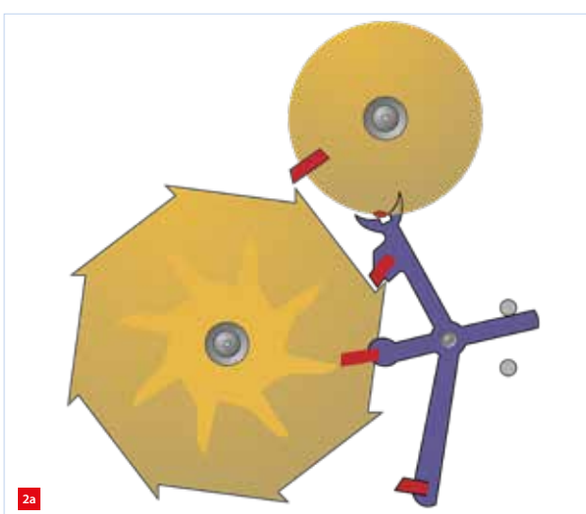
Besides a few non-commercialised concepts, there has been very little development in regulators (regulator is escapement + balance). On an industrial scale, only two types of escapements are being produced, the Swiss lever escapement and the co-axial escapement, invented by English watchmaker George Daniels and adopted by Omega (Figure 2). For the oscillator, the classical balance wheel has the full monopoly in the world of mechanical wristwatches. Over the last few years, however, some brands have presented new possible solutions for this application, but none of them have been integrated into a commercially available watch, up until now. These solutions are all based on compliant mechanisms, but they each exploit the material properties in a different way and each have their own topology.

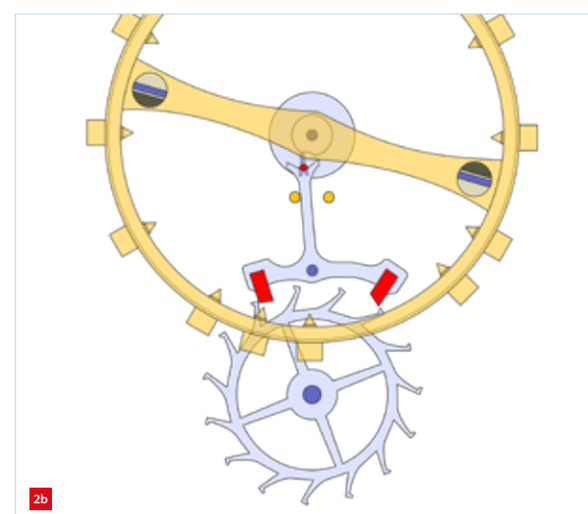
It all started with the Parmigiani Senfine concept watch in 2016, followed by the Zenith Defy Lab in 2017 and the Ulysse Nardin Freak NeXt in 2019. These have been launched as concept watches and were produced only in limited numbers, so none of these became widely available. This was the case until last year, when Frederique Constant had a revolutionary launch with its Slimline monolithic manufacture, putting an innovative oscillator in an obtainable watch [3]. In the industry, this was considered the start of a new era in horology.

Concept watches

In the Senfine, Parmigiani integrated its silicon-based mechanical watch regulator: the Genequand system. It has two main elements containing an oscillator, which replaces the traditional balance wheel, and a so-called grasshopper escapement.

The monolithic oscillator is designed to have an amplitude of only 16°, which is low compared to the amplitude of the traditional balance wheel, which is up to 300°, but high relative to the amplitude of other oscillator concepts, which we will discuss later. Also, the frequency of the oscillator, 16 Hz, is different from what we know from traditional systems, usually 4 Hz. Higher frequencies give the possibility to achieve more accuracy in the system, also more on that





The only two types of escapements that are being produced on an industrial scale. (Images: Fred the Oyster, Wikipedia)
(a) Swiss lever escapement.
(b) Co-axial escapement.

later, when we look at even higher frequency systems. The concept of the grasshopper escapement has already existed for a very long time, but it has not been used in a wristwatch before. One of the main differences with a traditional Swiss lever escapement is the constant contact with the oscillator [4].

Zenith presented a full-dial oscillator in its Defy Lab prototype. In terms of size, it might be bigger than any of the other ones, being 0.5 mm thick and covering the full dial, but it is a real eye-catcher. The system includes a tuning mechanism that can be used to adjust the frequency. With a frequency of 15 Hz and 6° of oscillation amplitude, it can be up to three or four times more efficient than the conventional system. With an accuracy of only 0.5 s/day it fits well within the COSC (*Controle Officiel Suisse des Chronometres*) standard (see below) of –4 to +6 s/day. This raises the question whether we need to have a new standard for this new class of oscillators [5], but more on that later on.

The Freak NeXt contains an innovative 3D flying oscillator, comprising four different layers of 32 silicon blades. The mass is created by adding a solid layer serving as a flying wheel. The exact weight and weight distribution can be tuned with the adjustment screws, similar to the traditional balance-wheel design. All errors due to gravity are even further reduced because the oscillator rotates with the hands as time passes. It operates at a frequency of 12 Hz with an amplitude of about 45°. Ulysse Nardin has developed its own silicon constant-force escapement, which uses two stable positions of a buckled silicon flexure. This enables the escapement to constantly provide energy, cancelling out the influence of the varying torque that is supplied by the barrel [6].

Commercial silicon-oscillator watch

The regulators in the new Frederique Constant watches (Figure 3) are made from silicon and use the mechanical properties of the material to obtain the desired behaviour of masses and springs oscillating to keep time. The concept is known as compliant mechanisms or flexible mechanisms and is used in many other applications. By developing compliant mechanisms, the number of parts can often be drastically decreased, sometimes even to a monolithic one-piece design. In all of these devices, the frequency is usually higher and the amplitude of the oscillation lower, both contributing to a higher accuracy.

The Slimline monolithic manufacture is an example of a movement with an ultra-high-frequency monolithic silicon oscillator, which is obtainable in stores today. Frederique Constant uses a flexible pivot oscillator in which the anchor is already integrated. In this way, it succeeded in combining 26 parts, as present in the traditional system, into one

3

Close-up of the monolithic oscillator mechanism in the new Frederique Constant watch. It contains a total of six flexures; the escapement wheel is shown in purple. (Photo: Eric Rossier)

monolithic part. The oscillator is equipped with two adjustment masses similar to those in the traditional balance. As described previously, this oscillator also benefits from having a limited oscillating range, being just 6°. The frequency is ten times higher than found in most mechanical watches, and amounts to an astonishing 40 Hz, or 288,000 vibrations per hour.

The Frederique Constant oscillator is not the first one that uses the principles of compliant mechanisms to create a one-piece silicon regulator. However, there are some notable innovations present in this elegant design. For example, it is the first time that the anchor has been integrated in the oscillator design. Not only is it part of the oscillator, but it is also placed on the flexures, which allowed for a drastic reduction of the size. In addition, it is the first silicon oscillator that has a diameter similar to that of the classical spring, less than 10 mm, while it is much thinner, only 0.3 mm. The resulting reduction of weight and size compared to the traditional component, in combination with the small movement amplitude, yields a much more energy-efficient component. Even though it runs ten times faster, it can last up to 80 hours on a single standard barrel [7] [8].

Challenges

One of the main drivers for new developments in horology is accuracy. The manufacturing accuracy of each key component will determine the timekeeping accuracy of

the whole movement. For that reason, it is essential to have dedicated characterisation and measurement equipment to verify the product quality according to a specified standard, such as ISO 3159: Timekeeping instruments – Wrist-chronometers with spring balance oscillator.

Standard manufacturing methods for watch components have tolerances of 5-10 µm. Therefore, a traditional microscope is more than sufficient for quality control of these parts. In the case of silicon-based watch components made using semiconductor manufacturing techniques with resolutions often better than 1 µm, this is not sufficient; more advanced measurement equipment is needed. As the accuracy of the traditional microscopes is limited by the wavelength (range) of visible light, high-precision measurement equipment usually takes a smart route to get around this. For instance, electron microscopes can produce more accurate results as the wavelength of electrons can be up to 100,000 times shorter than that of (visible-light) photons.

Besides the fabrication accuracy, the accuracy of the kinematics and dynamics of the components can also be of great importance for some components. For classical systems, obtaining the timekeeping accuracy is often still achieved by visual measurements of the hands. To this end, test engineers would set the watch and allow it to run for multiple hours. They would then measure the deviation between the time shown by the hands and by a very accurate clock, for instance an atomic or GPS clock. However, these measurements provide very little information about the performance of the individual components.

To be able to look at the performance of the components in more detail, various methods can be used, such as optic or acoustic measurements. Optic measurements rely on sending signal pulses, light waves, which are reflected by the part surface and then detected by a sensor. In this way, a very accurate location can be determined, which can be used to obtain information on the frequency of the part. The maximum obtainable accuracy of these measurements is determined by the wavelength of the signal. In acoustic measurements, the vibrations of the component itself are used as a signal that is collected by a sensor. This is a method that is also used for conventional watches, but here the balance wheel has a higher mass than most silicon oscillators. Consequently, the sensor needs to be more sensitive, in order to allow the accurate collection of oscillator vibrations.

There are several ISO standards for timekeeping devices, but they have all been drafted for conventional movements and components. As mentioned above, the accuracy of production, the material properties, and the resulting silicon components might require special standards. Silicon is not a metal, and it is a non-magnetic material. Thus, it should be straightforward to satisfy regulations concerning the influence of magnetic fields, such as ISO 764: Horology — Magnetic resistant watches. Nevertheless, it does not directly solve the antimagnetism challenge issue of the whole watch as other components are usually still made from metal alloys.

Although silicon has a much higher yield strength than standard materials used in watches, crystalline silicon is brittle in specific crystalline orientations. To satisfy ISO 1413 (Horology — Shock-resistant wrist watches), the design must apply clever geometries to restrict the movement of a part and its contact with other parts.

Finally, the essential standard in the watch industry is the COSC standard, i.e. ISO 3159. In the case of silicon-based balance springs, applying this standard is straightforward. In some sense, the requirements for the accuracy of keeping time in s/day can be applied to other designs as well. However, for high-frequency compliant-mechanism-based silicon oscillators, there are no standardised accuracy characterisation methods. To properly guarantee the quality of these oscillators, a special category would be needed. Redefinition or expansion of the ISO 3159 standard could possibly cover watches with silicon-based compliant mechanism components. For now, companies such as Flexous need to set their own standards, as they do by pushing the limits of technology and listening closely to customer feedback.

Conclusion and outlook

Silicon has proven to be a great alternative to some of the more traditional materials in watchmaking, and its implementation keeps developing in unexpected, ground-breaking directions. Innovative brands are already applying this material, but even some more traditional brands seem to have understood the potential. Overall, the number of watches containing silicon parts is rising significantly, most of which exhibit an unparalleled performance. In other words, silicon is earning its position in the watch industry.

Consequently, in the future, silicon-technology adoption will most likely continue to grow, introducing specialised measurement equipment, quality standards, and even more movements containing silicon parts. Why stick to the conventional regulating organs when there is an entire range of key components that can be made smaller, more accurate, and more energy-efficient while still constituting a mechanical watch? In recent years, Flexous has become a driving force behind this vision.

It will be exciting to see what this high-tech Dutch company could bring to the traditional Swiss watch industry in the upcoming years in order to, after nearly 350 years, once again establish a perfect marriage between the Netherlands and Switzerland in horology. This time it is cutting-edge innovation and precision that could potentially impact precision engineering as a whole. In addition, an interesting time will follow for the development of silicon parts, since the patent concerning the silicon hairspring will expire in the autumn of 2022. This will open up new opportunities for the entire watch industry and stimulate the urge to come up with new smart innovations in the aspiration to create the most accurate and energy-efficient mechanisms.

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ONE BY ONE

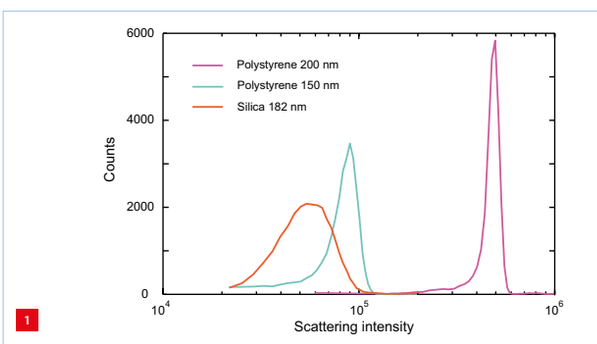
Measuring nanoparticles becomes increasingly important in healthcare, pharmacology, and environmental sciences, but measuring and obtaining relevant information from single nanoparticles requires cutting-edge technology. Therefore, we are developing a metrological flow cytometer that will be capable to traceably measure the concentration, size, and refractive index of single nanoparticles directly in suspension. This new instrument will have multiple applications not only for the detection of extracellular vesicles, but also for the determination of nanoplastics or the calibration of reference materials.

MARTINE KUIPER

Introduction

Nanoparticles are receiving an increased interest for use in agriculture [1], environmental sciences [2, 3], healthcare [4] and pharmacology [5]. Therefore, traceable measurements of nanoparticles are becoming increasingly important. When measurements are traceable, they can be linked to the International System of Units (SI) by (inter)national measurement standards.
Current techniques might be able to measure the size of nanoparticles or the refractive index of bulk material, but what they lack is the ability to measure the refractive index of nanoparticles, or to do traceable measurements in fluid. Presently, the refractive index of single nanoparticles can be neither traceably nor untraceably measured. Traceable refractive index measurements of nanoparticles are necessary, since the bulk refractive index of a material can differ from the refractive index of nanoparticles (either in solution or as a collection of individual particles) of that same material [6].

The refractive index is a material property and can be used to distinguish between materials, or to determine which material it concerns. Without knowledge of the refractive index, nanoparticle sizes cannot be traceably measured in light-based detection methods such as flow cytometry.



Scattering of polystyrene and silica nanoparticles. While 200-nm and 150-nm polystyrene particles can be distinguished, 150-nm polystyrene and 182-nm silica particles are indistinguishable despite their refractive index difference.

Metrological flow cytometer

Figure 1 shows the light-scattering intensities of three different particles measured using flow cytometry. The light scattering signal of particles depends on their size and refractive index. We can see that polystyrene particles of 150 nm and 200 nm can be distinguished, but that 150-nm polystyrene and 182-nm silica particles cannot be distinguished. Thus, without knowledge of both the size and refractive index of these particles, flow cytometry cannot distinguish between similar scattering signals. While particle sizes can be measured with techniques such as atomic force microscopy, the refractive index of nanoparticles cannot yet be traceably measured.

Because there is no technique able to measure the refractive index of particles in fluid, we developed a measuring set-up at the Dutch National Metrology Institute VSL in collaboration with Amsterdam UMC, as part of the METVES II project. The set-up, called the metrological flow cytometer, can be used to traceably determine both size and refractive index as well as number concentration of nanoparticles.

Principle of flow cytometry

Flow cytometry is a light-based detection method that detects microparticles and nanoparticles in fluids. Currently, commercial flow cytometry is mostly used to measure the cells present in blood plasma, but flow cytometry has the potential to measure nanoparticles present in all body fluids [4, 7].

Figure 2a shows the principle of commercial flow cytometry. In flow cytometry, the sample flow, which contains the particles that we want to measure, has a lower flow rate than the sheath flow. The flow rate difference results in hydrodynamically focussing of the sample flow into a narrow stream in the centre of the flow cell. Ideally, the particles in the sample flow pass the laser one by one to avoid swarm

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The author would like to thank Edwin van der Pol (Amsterdam UMC), Richard Koops (VSL) and Rienk Nieuwland (Amsterdam UMC) for their input and contributions to the research underlying this article.

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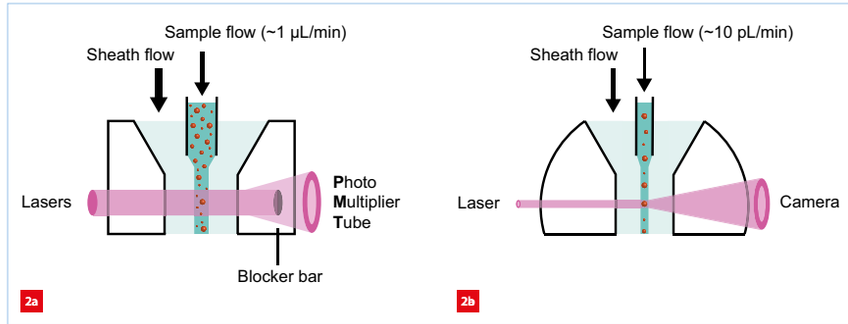
detection. When the particles are illuminated by the laser beam, light is scattered by the particles into all directions. The scattering signal is measured in forward scattering and sideward scattering directions on the detectors. The detectors of commercial flow cytometers are either photomultiplier tubes or photodiodes. The measured scattering signal of the particles can provide information about concentration, size and refractive index of the particles.

For the scattering signals to provide information about concentration, size and refractive index of the particles, flow cytometry measurements are combined with Mie theory to relate the scattering signal to the particle diameter [8]. Mie theory is used to calculate the angular light scattering by particles. The angular scattering on all detectors is then used to calculate the scattering cross-section of the particle. Using assumptions about input parameters for the refractive index of both the particles as well as the medium surrounding the particles, the scattering signals are related to diameters. Since information on the refractive index of the medium surrounding the particles was lacking, we developed a new measurement set-up for traceable refractive index determination of both liquids and solids [9].

Unique features

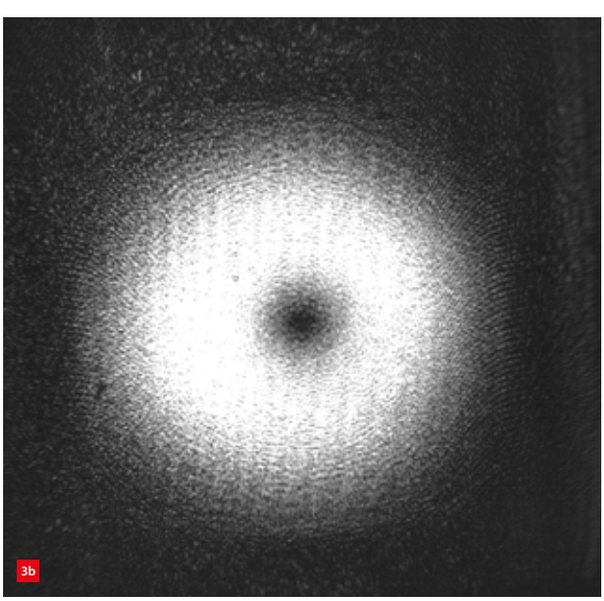
Figure 2b shows the features of the metrological flow cytometer, which is not built to measure microparticles such as cells, but for traceable measurements of nanoparticles in fluids. To enable traceable nanoparticle measurement, we provided the metrological flow cytometer with seven technical improvements over commercial flow cytometers. These technical improvements were made from a metrology perspective to measure as accurately as possible, and they would not be feasible on commercial flow cytometers dedicated to measurements of clinical samples. For example, commercial flow cytometers need to measure with a high flow rate, because statistical information about the presence of particles in clinical samples is required.

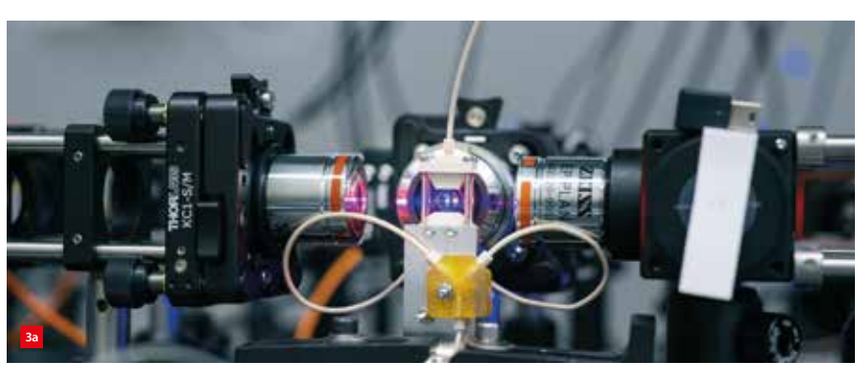


Principle for two types of flow cytometers, differing in beam shape, interrogation volume, flow rate, detectors and fluid cell design; see the text for elaboration.
(a) Commercial flow cytometer.
(b) Metrological flow cytometer.

First, the metrological flow cytometer measures angle-dependent light scattering of single nanoparticles. Commercial flow cytometers cannot distinguish angle-dependent light scattering, since the signal on the photomultiplier tube or photodiode only gives a total scattering intensity. By changing the detectors in the metrological flow cytometer to cameras, we can resolve angle-dependent light scattering. The angle-dependent light scattering is measured in back-, forward-, and side-scattering directions. The spherical shape of the flow cell, shown in Figure 3a, minimises the effect of refraction by the flow cell wall on the measured angle-dependent light scattering.

Second, a Laguerre-Gauss beam illuminates the nanoparticles. Figure 3b shows an example of the (transversal) intensity profile of this specific beam type, which is always donut-shaped, on the forward-scattering camera. The shape of the incoming Laguerre-Gauss beam makes the blocker bar present in commercial flow cytometers unnecessary. A blocker bar is used to block the light coming directly from the laser, such that only the scattered light can be detected. Additionally, the Laguerre-Gauss beam enables us to find unique solutions for the refractive index and size of the particle. When the





Two technical improvements of the metrological flow cytometer.
(a) Spherical flow cell. (Photo: Marcel Cloo)
(b) The Laguerre-Gauss beam, a donut-shaped beam, shown on the camera in forward-scattering direction.

particle is moving through the beam, the particle experiences an angular phase gradient, and gives an interference pattern when not in the exact centre of the Laguerre-Gauss beam [10].

Additionally, the fluidics of the metrological flow cytometer have technical advantages over the fluidics of commercial flow cytometers. So, as a third technical improvement, the metrological flow cytometer has calibrated syringe pumps to control the sheath and sample flow. The syringe pump is calibrated with a relative measurement uncertainty in the flow rate of $2.75 \cdot 10^{-3}$. Fourth, the syringe pump lets the sample flow with a flow rate 125,000-fold lower than in commercial flow cytometers. Fifth, the sample passes through an interrogation volume 500-fold smaller. Sixth, as a result of the low flow and small interrogation volume, single particles can each be measured for half a second, which is a 2,500-fold longer measurement time than in commercial flow cytometers.

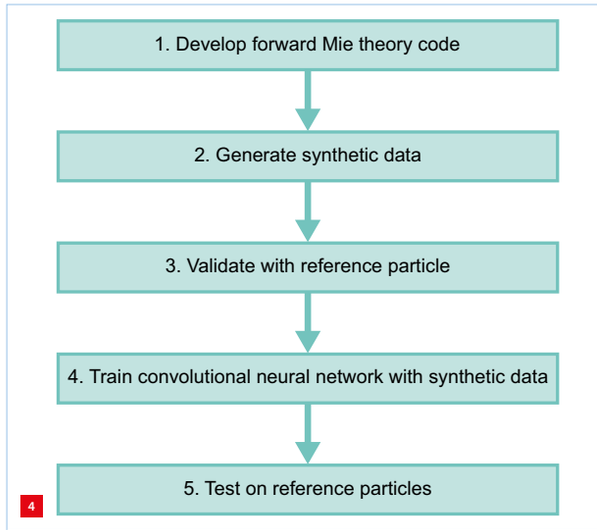
Seventh, a machine learning algorithm, a convolutional neural network, is being developed to relate signals to theory and determine nanoparticle properties. Figure 4 shows the structure used in the development of the convolutional neural network. A forward Mie theory code is developed for generating synthetic data of both solid nanoparticles and core-shell nanoparticles (such as extracellular vesicles) illuminated by a Laguerre-Gauss beam. Using the forward Mie theory code, synthetic data is generated. This data matches the data measured by the metrological flow cytometer as close as possible in terms of background noise and size correlation between the images and the camera.

In the next step, the generated synthetic data is validated using a traceable reference particle of known size and refractive index. When the synthetic data is validated, the data is used to train a convolutional neural network. The convolutional neural network uses the scattering images to determine (i) the radius of the particle, (ii) the refractive index of the particle, (iii) the thickness of the shell, and (iv) the refractive index of the shell in case of core-shell nanoparticles. We will test the convolutional neural network using a set of reference particles, and extend the model to provide an uncertainty analysis of the determination of radius, refractive index and shell thickness.

Using the metrological flow cytometer, we will perform the first traceable concentration, size, and refractive index measurements of nanoparticles.

Applications

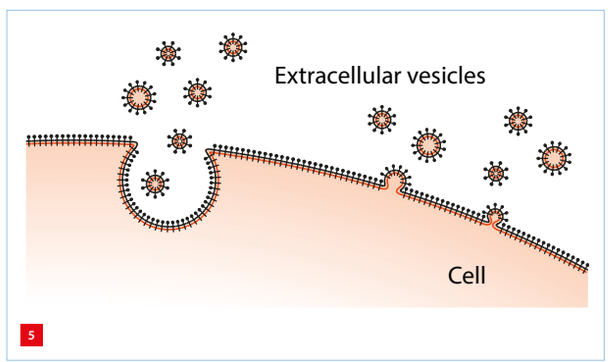
Determination of the physical properties of nanoparticles is in high demand in a broad range of applications, including (i) reference materials [4], (ii) extracellular vesicles [4], (iii) nanoplastics [2], (iv) particulate matter [3], and (v) drug-loading liposomes [5].



Steps performed by the machine learning algorithm to gather size and refractive index information of the nanoparticles.

The first application, the characterisation of reference materials, is highly relevant in metrology, since this is important both for determining the quality of the reference materials and using the reference materials for calibration of apparatus such as commercial flow cytometers. As mentioned above, Mie theory can be used to relate scattering signals to diameter and refractive index.
However, commercial flow cytometers require calibration using reference materials of known size and refractive index before biological samples can be measured. Currently, the properties of biological samples are determined using reference materials of known size and assumed refractive index [4]. By calibrating reference materials on both size and refractive index, nanoparticle properties can be determined without doing assumptions about reference materials.

The second application focusses on the nanoparticles that can be found in the biological samples measured by flow cytometry, namely extracellular vesicles, i.e. nanoparticles released by all cells in the human body, as shown in Figure 5. Extracellular vesicles are present in all body fluids, including blood, urine, saliva and even sweat. Additionally, extracellular



Extracellular vesicles are small nanoparticles released by all cells within the human body.

vesicles have properties that can change with disease, such as differences in concentration, markers on the extracellular vesicle surface or content of the extracellular vesicle. Therefore, extracellular vesicles are an ideal non-invasive biomarker.

However, since extracellular vesicles are so small, mostly below 200 nm, detection of extracellular vesicles has its challenges. Additional challenges arise from the heterogeneity of body fluids, since these contain extracellular vesicles from different origins as well as other particles within the size range of extracellular vesicles [4]. Single detection of extracellular vesicles based on size and refractive index detection can give extra insight into their concentrations, and result in their clinical detection.

The third application is detection of nanoplastics. Worldwide, there is an increasing concern about the effect of plastic pollution on health and environment. Therefore, detection of nanoplastics becomes increasingly important. Nanoplastics can be found in ocean and fresh water [2], soil [11] and even in your blood [12]. Due to their heterogeneity, plastic nanoparticles are difficult to quantify [2]. Therefore, detection of single plastic nanoparticles in liquids would give new insights about the origin of nanoplastics present in water, soil or blood. These new insights could prove crucial in a battle against plastic pollution.

The fourth application in which single-nanoparticle detection would be important is the measurement of particulate matter, particles in air. Particulate matter includes nanoparticles released during mining, combustion, or transportation [3]. While particulate matter is mostly present in air, particulate matter can also be suspended in water [3], or transported to the bloodstream through inhalation [13]. Single-particle detection could give information about the origin of the particulate matter and its spreading, or provide insights for studies about toxicity.

The fifth and final application we will discuss is the use of nanoparticles for drug delivery. Due to their small size, nanoparticles have unique biological, chemical and physical properties, making them ideal drug carriers for precision medicine. Nanoparticles can be engineered to hold certain drugs, and can carry these drugs to the right location in the human body.
There are three classes of nanoparticles for drug delivery: (i) polymeric, (ii) inorganic, and (iii) lipid-based. Using single-particle detection, nanoparticle size and content can be measured. Ideally, the chemical composition of such drug-loaded nanoparticles can be detected. In the future, Raman spectroscopy can be added to the metrological flow cytometer for determining the chemical composition of nanoparticles.

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OPTICAL, TACTILE, X-RAY

In coordinate measuring technology, mainly tactile and optical sensors and X-ray computed tomography are used. An essential distinguishing criterion for these sensors is the physical principle of the transmission of the primary signal. This article gives an overview of the three sensor types and their respective fields of application.

RALF CHRISTOPH, HANS JOACHIM NEUMANN AND SCHIRIN HEIDARI BATENI

Sensors differ in their functional principle and structure consisting of mechanics, optics, electronics, and software, and thus in their characteristics – a basic understanding is helpful for achieving an optimal application. Optical sensors, for example, can be used for the fast, non-contact measurement of fragile workpieces, and those with small features. However, surface properties of the objects to be measured can play an important role, which complicates optical measurements, whereas tactile measurement is largely independent of these properties. Spatially extended objects, including internal structures, pose their own challenges, as they are hard to measure in a tactile fashion. Here, X-ray computed tomography provides a solution for complete measurement.

Optical sensors

Optical sensors act like the eye in a measuring microscope, either perpendicular to the optical axis in the object plane (lateral sensors - image processing) or along the optical axis when focusing (axial sensors - distance sensors). In order to be able to carry out a 3D measurement of workpieces with optical sensors, a combination of both sensor types is required. With optical sensors, many measuring points are acquired very quickly or even simultaneously. Compared to other sensors, their use therefore usually leads to much shorter measuring times. For this reason, they are used for a wide range of workpieces in production control.

Flexible image processing

The image processing sensor images the measuring object through a lens onto a matrix camera. The camera electronics convert the optical signals into a digital image, which is used to calculate the measuring points in a computer with the appropriate image processing software.

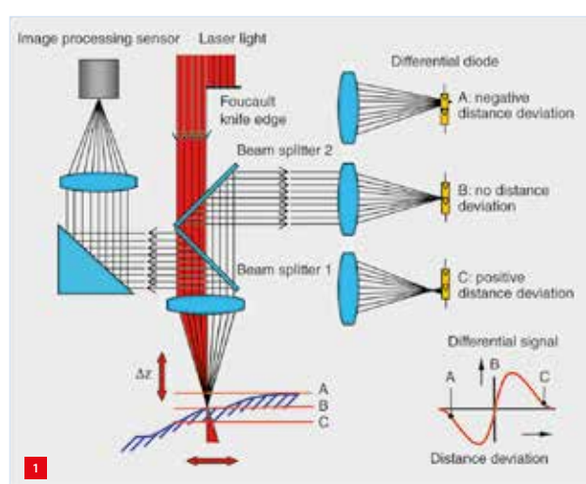
In contour image processing, contours are extracted by suitable mathematical algorithms. This makes it possible to detect and filter out disturbing influences during measurement. Many 3D measurement tasks can be performed by combining image processing and focus variation techniques using the same sensor hardware. The determination of the dimensions of plastic parts, as well as the geometry of sealing grooves and plug cavities, is a main field of application.

Fast laser distance sensors

In Foucault laser sensors, a laser beam is "cut off" by a Foucault edge in the beam path and is imaged onto the object at the triangulation angle determined by the lens aperture. The signal evaluation is performed, for example, via differential photo diodes (Figure 1). In practical use, such a Foucault laser sensor is preferably integrated into the beam path of an image processing sensor. Thus, it is possible to switch between both sensors without mechanical movement. Several hundreds to thousands of points can be measured per second. This sensor is accordingly used for contour measurement on workpiece surfaces or, for example, also for flatness measurement.

Chromatic focus sensors

The optics of chromatic focus sensors (either point or line sensors) are designed in such a way that the different working distances are particularly pronounced for different colours of light (colour length error). The best focused colour of light has the strongest intensity at the measuring point. This intensity is determined with an integrated spectrometer and the corresponding distance value is



Laser sensor using the Foucault principle integrated into an image processing sensor (illumination systems not shown). (All images: Werth)

AUTHORS' NOTE

Dr.-Ing. habil. Ralf Christoph is the owner and managing director of Werth Messtechnik and head of development. Dipl.-Ing. (FH) Hans Joachim Neumann was a coordinate measuring pioneer in the early days of his career at Zeiss and was actively involved in standardisation work for decades; he is an honorary member of the VDI. Dr.-Ing. Schirin Heidari Bateni is the technical editor of Werth. Werth Messtechnik, with headquarters in Giessen (Germany), is a specialist in coordinate metrology with optics, probe, computed tomography and multi-sensor systems.

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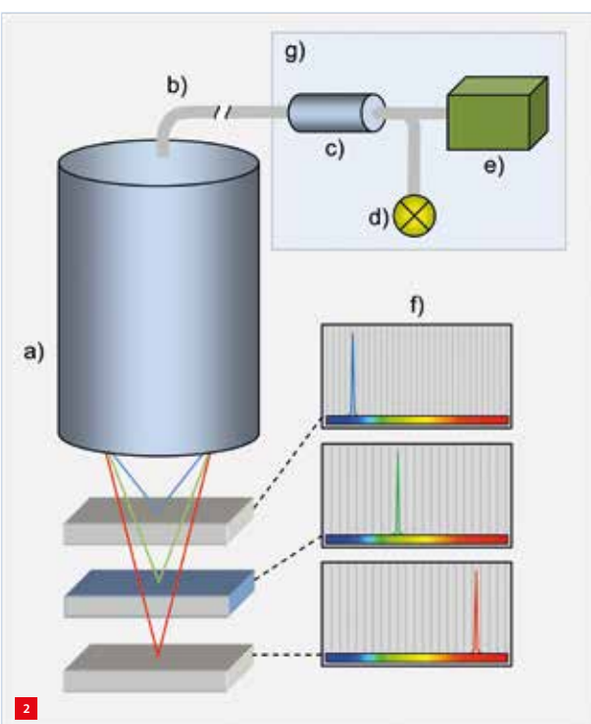
assigned to the detected colour (Figure 2). The application possibilities for chromatic sensors correspond in principle to those of the Foucault sensor. However, the measurement of surfaces is possible for both diffusely reflecting and shiny surfaces, since direct reflection does not interfere; this can pose a problem.
The arrangement of a series of optical fibres allows the realisation of the same principle as a line sensor. These sensors combine a high measuring speed with low measuring uncertainty.

Focus variation
Focus variation sensors use the same hardware as image processing. When moving the sensor along the optical axis, a sharp image is generated for an image section in only one position. The contrast is used as a parameter for the sharpness of an image. From this the sensor position and thus the position of the point on the surface is determined.

If the procedure is performed simultaneously for each pixel of the camera, a large number of measuring points are obtained as a point cloud within a few seconds. This method enables a particularly simple and fast 3D acquisition of surface topographies on workpieces made of various materials.

Confocal area sensors
A confocal area sensor projects light onto the object via an imaging system with pinholes. If the projected light spots are defocused by moving the sensor head, the light spots on the object become darker. Therefore, when the sensor head is moved relative to the object, an intensity curve is created. The maximum of the intensity curve represents the location of the object surface.



Chromatic focus sensor. The measurement head (a) is connected to the analysis box (g) by a long optical fibre (b), to reduce heat input. Here, a fibre coupler (c) is used to connect the broadband white-light source (d) and the spectrometer (e). The spectra (f) represent the distances between the object and the measurement head.

Due to the intensity evaluation, confocal area sensors, in contrast to focus variation sensors, can also measure reflecting surfaces, for example, regardless of the contrast of the workpiece surfaces. Applications include the measurement of stamping tools or coin embossing punches.

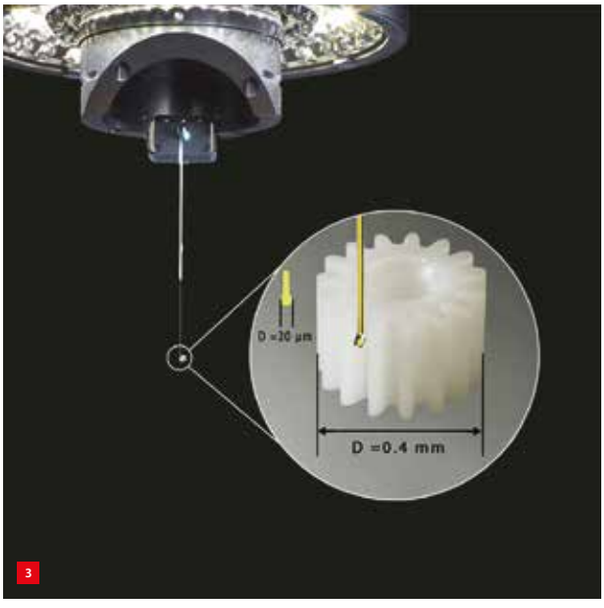
Tactile sensors

The operating principle of all tactile sensors is based on mechanical contact with the measured object. From this, the electrical signals for further processing are derived. A distinction is made between trigger and scanning touch probes. The measurement result includes both the geometry (i.e. shape and size) of the probing form element (sphere) and the spatial position and geometric shape of the object surface to be measured. The position of the probing point during tactile scanning is determined by a mathematical correction from the known coordinates of the centre of the probe sphere, taking into account the workpiece geometry.

Tactile measurement corresponds to the traditional manual measuring methods (caliper dial gauge) and is largely independent of the surface properties of the objects to be measured. With “star probes” and corresponding change racks, an object can be measured three-dimensionally from all directions with relatively little effort.

Tactile-electrical sensors
With touch trigger probes, a signal (trigger) for reading out the scale systems of a coordinate measuring machine (CMM) is generated as soon as the probe tip touches the measuring object. The measuring point results from the coordinates of the measuring device and refers to the centre of the probe sphere. The common disadvantage of all touch trigger probes is that the CMM is brought into contact with the measuring object to determine a measuring point, and then has to be moved out of contact again.

In a scanning probe system, the sensor has its own displacement measuring systems (scales, inductive sensors, optical measuring systems). If the probe tip is deflected in any direction when touching the measuring object, the magnitude of this deflection can be determined from the information of these displacement measuring systems. The measuring point is obtained by superimposing the sensor deflection on the sensor position in the coordinate system of the machine.



Measurement of a micro-gear with the Werth Fiber Probe – the fibre is guided in a metal tube.

For the measurement of single points, the measuring principle of the scanning probe system makes it possible to continuously record measuring points during the entire probing process (deflection and return). From this, averaged and thus reproducible measuring points can be determined. The complete course of the probing process can also be recorded and the probing point for an assumed deflection of zero (probing with 0 N probing force) can be extrapolated from this. This is useful, for example, when measuring flexible workpieces.

In combination with an appropriate control system, measuring touch probes can also be used for automatic scanning of the surfaces. With this method many surface points can be measured in a relatively short time. The scanning can also be performed on unknown 3D surfaces or by taking into account given paths (e.g. from CAD data). This makes it possible to scan much faster, because the control process after probe deflection becomes easier or can even be omitted completely. The use of measuring probe systems is universally possible, provided that the workpiece properties allow it (sensitivity, feature size).

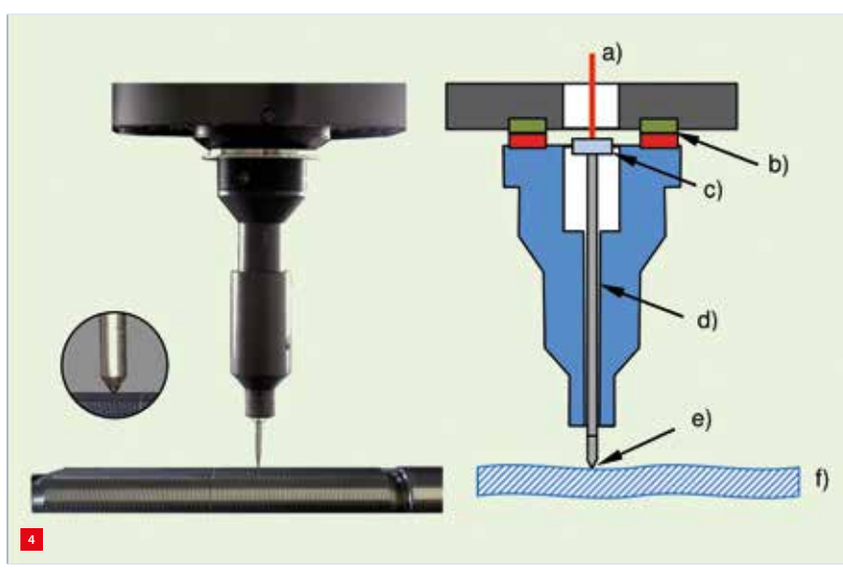
Tactile-optical micro-probe

Conventional tactile sensors have in common that the signal is transmitted from the probing sphere via a rigid shaft to the actual sensor (switch, piezo element). Since any flexing of the stylus affects the measurement result, the aim is to use the stiffest possible stylus shafts. In connection with the sensor technology used, this leads to relatively large dimensions and probing forces.

These disadvantages are avoided with scanning tactile-optical sensors by using the stylus shaft only for positioning the tip. For the Werth Fiber Probe, for example, the determination of the deflection of the tip in lateral directions to the shaft (x, y) is carried out with an image processing sensor. Due to the scanning sensor principle, single point measurements as well as scanning procedures can be achieved. Typical applications for the fibre probe are bores and slots with dimensions from less than 0.5 mm down to several tens of micrometers, fibre-optic connectors, micro-gears (module of approximately 0.1 mm, see Figure 3), and fuel-injection nozzles. The fibre probe is also suitable for roughness measurements.

By integrating an additional optical distance sensor, the probe deflection in shaft direction can also be measured. The Werth Fiber Probe 3D, for example, can be used in all operating modes that are also available for conventional measuring probes. Applications include the measurement of micro-optics (lenses for cell phones) and moulded rubber parts, as well as the scanning of micro-gears.

Due to the small dimensions and probing forces, the fibre probe can be used on particularly touch-sensitive or easily deformable measurement objects. A further advantage is that the image processing and the distance sensor can also be used for direct optical measurement of the workpiece geometry. A device equipped in this way can be used as an optical-tactile multisensor CMM without additional sensors. Due to its principle of operation, the fibre probe is currently one of the most accurate sensors for CMMs, other than the image processing sensor.



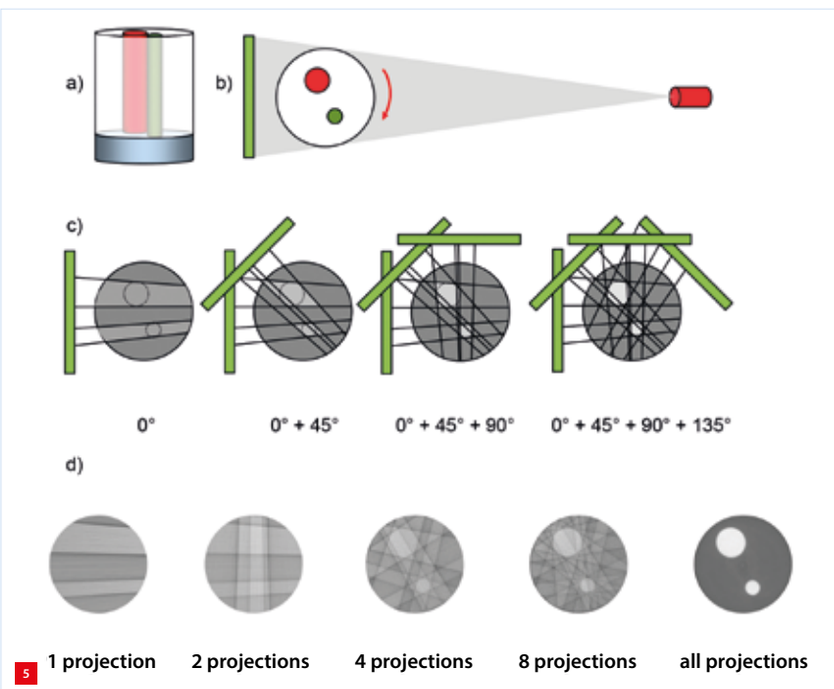
Werth Contour Probe: additional equipment for tactile contour measurement with distance sensors.
(a) Measurement beam.
(b) Magnetic interface.
(c) Mirror.
(d) Guide.
(e) Probe tip.
(f) Workpiece.

Tactile-optical contour sensor
The tactile-optical contour sensor (Werth Contour Probe) combines the stylus known from contour measuring devices with a laser distance sensor and image processing (Figure 4). With this contour sensor, roughness and contour measurements can be performed with high accuracy in a CMM. By placing the contour probe in a change rack, it is possible to measure directly with the laser sensor or image processing, alternatively. The integration of the tactile-optical contour sensor in a CMM allows the measurement in the workpiece coordinates in any scanning direction. Application examples are profile measurements on gear segments and roughness measurements on stamped and bent parts.

X-ray computed tomography

For X-ray computed tomography (CT), the ability of X-rays to penetrate objects is used. Starting from a point source, the X-rays pass through the object to be measured and reach the X-ray sensor. Part of the radiation is absorbed on its way through the object. The longer the range of radiation is in the object, the less radiation escapes behind the object. Furthermore, the absorption depends on the type of material. By shifting the axis of rotation or the measuring object relative to the X-ray unit (source and sensor), the magnification and thus the resolution can be adjusted.

In Werth's OnTheFly-CT, for example, a few hundred to a few thousand of such 2D radiographic images are taken one after another in different rotational positions of the object to be measured. Mathematical methods are used to calculate a volume model that completely describes the geometry and material distribution of the workpiece (Figure 5). In order to determine dimensions from the volume data, the exact position of the material transitions (e.g. from metal to air) is calculated from the amplitudes of the voxels (volumetric pixels: volume image points) in the surrounding area. By including the amplitude information, the achievable resolution of the edge location determination is significantly higher than that given by the centre-to-centre distance of the voxel raster (subvoxeling).



5 *Calculating volume data by back projection of the filtered radiographic images.*
(a) Object.
(b) X-ray beam path in one section plane.
(c) Principle of stepwise back projection and superimposition.
(d) Result of reconstruction with different numbers of back projections for a real workpiece.

To determine dimensions from the measuring points created in this way, geometric elements such as straight lines, cylinders, or planes are calculated from point groups. The selection of the points is usually done with the help of a CAD model. From the geometry elements thus determined, the dimensions are calculated by linking them (e.g. the distance between two planes or circle centres) and compared with the nominal values.

X-ray tube influence on resolution
The X-ray tubes used to generate X-rays are a core component of tomography measuring machines. X-rays are generated in an evacuated tube when a high-energy electron beam hits a metal target. The energy of the generated X-ray radiation depends on the voltage between the cathode and the anode of the X-ray tube and on the target material. This is important for the selection of the X-ray tube, because for optimum measurement results the radiation energy must be matched to the material of the workpiece.

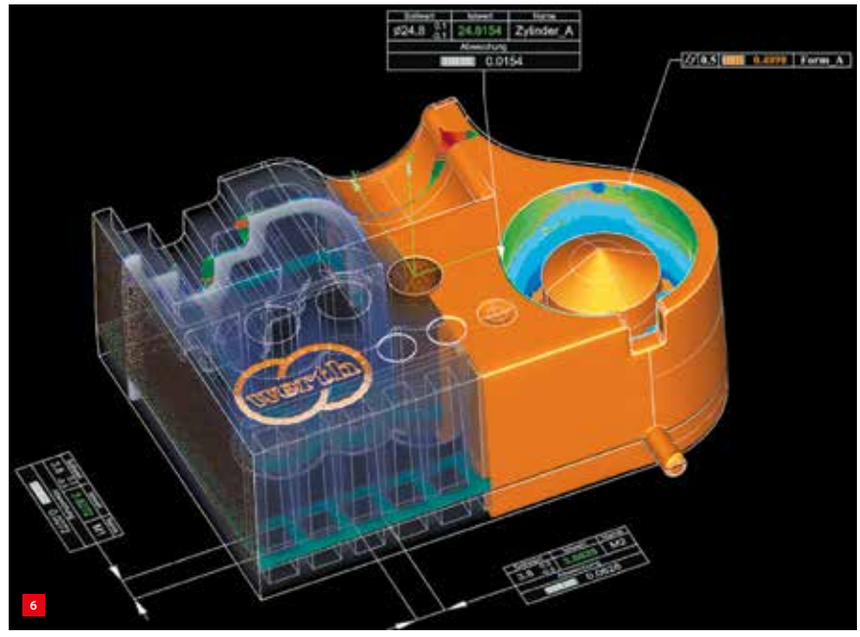
Basically, the targets of X-ray tubes are divided into reflection targets and transmission targets. The difference between the use of reflection and transmission targets is the available radiation power and thus the measurement time in connection with the minimum focal spot size that can be achieved.
In the reflection target, X-rays are reflected by the target. The disadvantage of reflection targets is that small focal spot sizes can only be achieved at very low power (typically 5 µm at 5 W) and thus a long measuring time is required. In most cases, however, a higher maximum power is available, albeit at lower resolution, which is suitable for measuring large workpieces. Transmission targets are penetrated by X-rays. Here, a small focal spot can be achieved even at medium power values (typically 5 µm at 25 W) and most workpieces can be measured quickly with sufficient resolution.

Regular maintenance is required for open X-ray tubes; closed tubes must be replaced completely after a few years. Transmission target tubes in monoblock design combine the advantages of open and closed designs with a long maintenance interval of typically 12 months and a technically unlimited lifetime.

Software tools for universal use

In addition to the method described above for determining geometric properties (dimensions) with the aid of CAD data, there are a number of other evaluation methods (Figure 6). Geometric elements can be calculated from the point cloud without CAD data by an automatic segmentation function after defining a starting point. In the 3D nominal-actual comparison, the software calculates the distances of the individual measuring points to the CAD surface and displays them in colour-coded form. The deviations of the actual geometry from the nominal geometry are thus visible at a glance. Data for the correction of injection moulding tools, for example, are also calculated directly.

Further methods are used to determine drawing dimensions in 2D views and sections using image processing or contour evaluation methods. Other software tools are used for the automatic identification of voids or inclusions in the measured object or of burrs and chips. Raster CT allows the measuring range to be extended or the resolution for the entire workpiece to be increased by joining together several tomographed sections of the workpiece.



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CAD model, CT volume data and measurement point cloud with measured geometric properties; colour-coded deviation display from 3D nominal-actual comparison and 2D sections.

STACKING POSITIONERS

Atom probe tomography has developed into a versatile analytical technique, combining 3D imaging and chemical composition measurements at the atomic scale. The technique relies on a precise, accurate and reliable 3D positioning of the specimen under ultra-high-vacuum conditions. For this, nanoprecise positioners have been stacked to create a multi-axis positioning system.

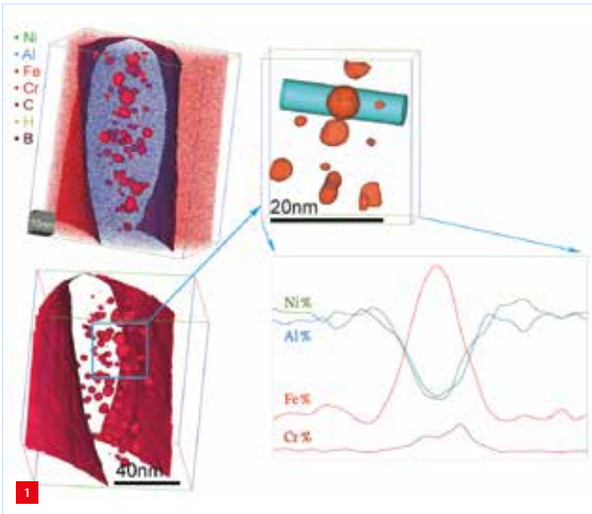
MARKUS MAIER

Introduction

Atom Probe Tomography (APT) is a 3D nanoscale technique for the analysis of different materials based on controlled field evaporation of individual atoms. In practice, the sample under examination is required to have a needle-like shape to generate a highly curved electrical potential at the tip of the specimen, which in turn results in the evaporation of atoms from the surface of the material.

While historically most atom probes used voltage-pulsed fields, since the early 2000s a resurgence of activity in laser-pulse applications can be observed in the community [1]. The electrical field-pulse method introduces a high stress-level on the specimen and is only suitable for metals with high electrical conductivity, whereas the laser-pulse method made APT applicable to a wider range of materials, such as minerals and nanomaterials [2].

Due to the more general applicability, reduced cost and increased efficiency of the technique, and other theoretical and practical advances in the field, the user base of APT has expanded significantly since the turn of the century. The latest APT systems can generate 3D information at near atomic resolution. As such, they are not only used to analyse a sample's chemical composition, but also its morphology and the spatial distributions of its elements [2]. An example of the astonishing ability to observe micro- and nanoscale features by using APT can be seen in Figure 1.



Exemplary APT analysis data, taken from [2].

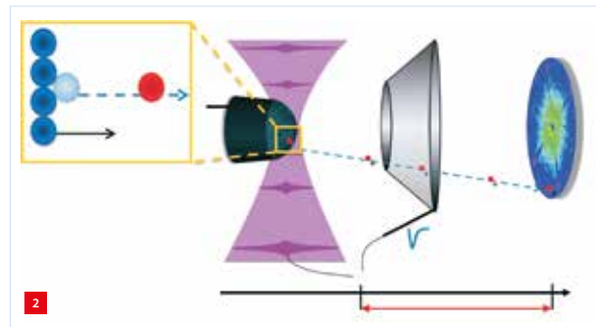
Today, CAMECA(R) is the exclusive manufacturer of atom probe tomography systems and it uses attocube's ECSx5050/NUM/UHV drives for the precise positioning of the specimen with respect to the counter electrode. This article introduces the technique of APT and explains how and why attocube's positioning solution is perfectly suited for the application in the challenging environment of an APT system.

Data generation and collection

The application of an APT system can be roughly divided into three steps:

1. Specimen preparation.
2. Data generation and collection.
3. Data analysis.

Each of these steps is subject to continuous research and improvements. Here, the focus is on the second step; data generation and collection. In this step, the atom probe technique is basically a combination of field evaporation of the atoms from the tip of the needle-shaped specimen and the identification of the evaporated ions by time-of-flight mass spectrometry [3]. Figure 2 shows a schematic set-up of an APT system. The specimen of the material under investigation is subjected to a high-voltage electric field



Schematic view of an atom probe. The specimen (black) with a tip radius of less than 100 nm is subjected to a high voltage and illuminated by either laser or high-voltage pulses, which trigger the field evaporation at the sharp specimen tip. The positive ions are accelerated by the electric field, their impact position and time of flight are recorded with a position-sensitive detector [4].

AUTHOR'S NOTE

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This article is based on attocube's Application Note Motion&Sensing 25.

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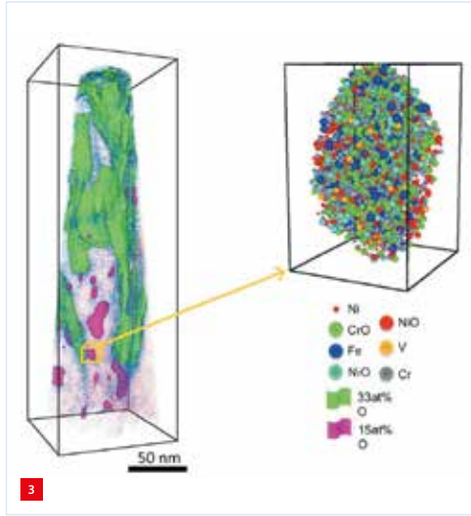
and then a high-voltage pulse or a laser pulse triggers the field evaporation.
To prevent surface migration and to improve control over the field evaporation process, the specimen is cooled down to cryogenic temperatures below 80 K. Furthermore, the analysis takes place under ultra-high-vacuum (UHV) conditions [4].

During the time of flight, spatial differences of the ions (i.e., position of the atoms) are magnified, resulting in an enlarged mapping of the tip surface to the detector [3]. Determining the time of flight (which also yields a mass-to-charge ratio) and impact position of each ion, together with the voltage applied at the moment of evaporation, allows for a tomographic, atomically resolved computer model of the evaporated volume. This data is often represented as a point-cloud in which every point is an elementally identified atom [4]. Figure 3 shows an example of APT data where every single atom is visualised as a member of such a point cloud.



Dataset of an oxidised nickel-based alloy. On the right, a close-up of the orange region indicated on the left. Graphic taken from [4].

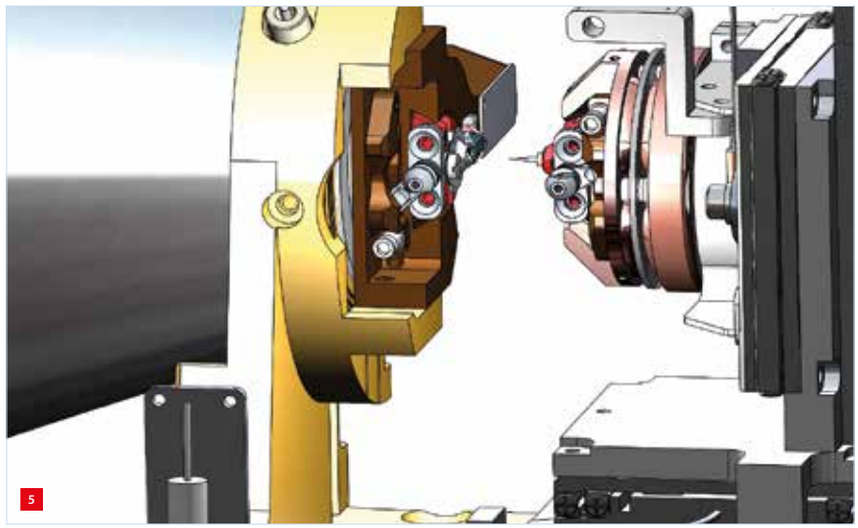
Two ECSx5050 positioners mounted on top of each other and combined with a third one attached to an L-bracket.

Specimen positioning

In order to enable a resolution down to 0.1 nm, the specimen tip with an end radius of below 100 nm needs to be accurately positioned along three axes (x, y, and z) within an UHV environment. This requires a high-precision positioning system such as provided by attocube: compact and modular nanopositioners that can be combined into a multi-axis motion system, offering the highest precision and stability even under challenging environmental conditions.

In the case of the APT application, attocube's ECSx5050 drive with integrated encoder for closed-loop control is used to accurately position the specimen inside the system. This drive is specifically designed for UHV conditions and provides high-resolution positioning over a travel range of 30 mm; in this application the range is about 10 mm. For xyz-positioning, two ECSx5050 positioners can be mounted on top of each other and combined with a third one attached to an L-bracket; see Figure 4. Their high accuracy is achieved with crossed-roller bearings.

Figure 5 shows a representation of the set-up. Not only does the large range of motion and precise control allow the user to align single specimens, it also facilitates the use of arrays of specimens. A CAMECA-developed microtip array can carry as many as 25 specimens onto the stage at one time, and the stage with its closed-loop control, combined with machine vision for additional optical position feedback, allows unattended analysis of each specimen.



Set-up of the APT system with the sharp specimen on the right. The multi-axis positioning system behind and below the specimen is based on piezo stick-slip technology, which allows for fast coarse positioning in the mm range and nanoprecise fine positioning. (Image: CAMECA)

Conclusion

Atom probe tomography has developed into a versatile analytical technique, with CAMECA's solution enabling both 3D imaging and chemical composition measurements at the atomic scale. The APT procedure relies on a precise, accurate and reliable positioning of the specimen. With nanometer resolution, attocube's ECSx5050/NUM/UHV provide a solution for the demanding application of 3D positioning under UHV conditions inside the APT system with extremely high throughput through automated serial analysis.

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SHINE

For part inspection, laser scanning has become a viable alternative for tactile measurement thanks to technological improvements, the latest being dynamic exposure settings and automatic noise elimination.

Introduction

In the past, part inspection was mainly about tactile measurement. Technological improvements that delivered greater accuracy and easier usage have however seen laser scanning become an increasingly important and viable alternative for many inspection tasks. Laser scanners can acquire more than a million points in a second, covering an entire object instead of just a few key features. The result: an easy-to-understand colour map, comparing actual with nominal data; i.e., the acquired point cloud against the CAD model.

The first generation of laser line scanners required optical exposure settings defined and fixed manually by the user for the type or colour of material to be measured. An early laser line scanner could only scan one surface colour in one pass. Next, automatic exposure was introduced, meaning that for every scan line, the scanner would find the best settings automatically, according to the surface colour perceived by the scanner's camera. However, in this case the entire scan line always needed to be on the same surface colour because every point on the scan line was measured at the same exposure setting.

Then, Hexagon introduced the 'flying-dot' scanning concept: scanners could adjust the exposure setting on every single point along the laser line and therefore scan any material in any orientation. As a drawback, the motorisation needed to enable this type of scanning made the technique slower.

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The Absolute Scanner AS1 from Hexagon

Today, the laser line scanner market for portable metrology systems has evolved even further. The introduction of functions such as dynamic exposure settings and automatic noise elimination have allowed great improvements in scanning usability and data quality. The Absolute Scanner AS1 (Figure 1) from Hexagon uses a set of optical algorithms known as SHINE (Systematic High-Intelligence Noise Elimination), which empowers scanning on challenging materials such as chrome and shiny black or on multi-colour surfaces by filtering scan data outliers without compromising scanner performance and accuracy. This article introduces technical characteristics and benefits of SHINE technology.

Dynamic exposure

While scanning speed (in terms of points collected per second and per line) has consistently increased over the years since non-contact scanning measurement was first introduced, the complexity of measurement surfaces has also grown, as the application of scanning technology has broadened into new areas of manufacturing.

The need to scan different types of surfaces when inspecting manufactured parts is driven by the rapidly increasing demand from manufacturers to use different materials, such as (carbon-fibre) composites, as well as different finishing materials. And of course, other conventional surfaces such as plastics and aluminium remain in demand and are often used alongside new materials and finishes.

One example of a real-world laser scanning application is the manufacturing of composite components, where the original material is dark with a knitted texture, while coatings can provide for other colours (Figure 2a). Here, an exposure change of the scanner would be necessary to adapt to the surface.

Another example can be found in the maintenance, repair and overhaul area of gas or steam turbines, where the reworking of the turbine blades is common as they are exposed to high loads (Figure 2b). After the blade polishing process, a quick way to inspect the reworked blades is to create a 3D scan and compare the results with the master CAD. Because of the shiny surface of the blade and the curvature of the leading and trailing edges, a correct exposure setting for the laser scanner is needed to avoid the risk of outliers on the edges.

In the automotive industry, some car parts are provided with a dark glossy finish on trimlines around the surface or sometimes over the surface. Having to inspect and scan these shiny surfaces requires a very high laser line intensity and correct camera exposure; too high laser intensity could lead to outliers around the scan data.

EDITORIAL NOTE

This article is an abridged version of an online publication by Hexagon Manufacturing Intelligence.

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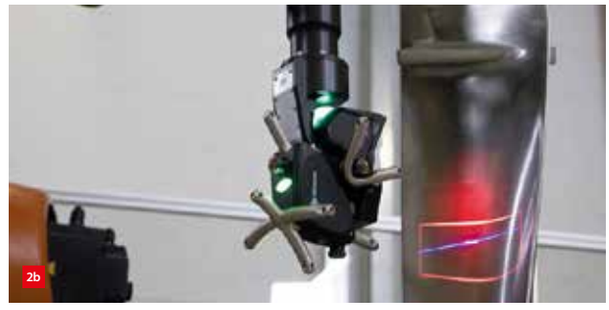


Examples of real-world laser scanning applications.
(a) Composite component manufacturing for F1 racing cars.
(b) Reworking of turbine blades.

Fundamentally, all these examples show how often operators need to find the right exposure settings and laser intensity to use when scanning different surfaces.

Balancing scan settings

With typical laser scanners, a measurement session would begin with the operator needing to choose appropriate settings for the part's surface. Is it pale or dark, shiny or matte, rough or smooth? This complexity can cause inter-operator variability in the scanner settings and hence the scan data, introducing room for errors.

Figure 3 shows the relationship between the part's surface darkness and the scanner's optical settings. As a surface becomes darker, the exposure time of the scanner's camera (here shown as 'Exp. time') must be increased to be more sensitive to incoming light, because a dark surface returns less laser light to the scanner's sensor. The operator should therefore move the cursor to the right to a higher percentage value in order to scan the part correctly.

However, this increase also raises the risk of spurious data (or 'noise') appearing in the scan. A smooth part might appear rough in the scan or outliers might give the scan an incorrect shape. Equally, if the settings are too low, there might be areas of missing information in the scan. Therefore, it is often difficult to find in the settings the correct compromise that will allow the part to be measured in the most effective and accurate way possible.

High-dynamic range technology

A solution is provided by SHINE, which stands for Systematic High Intelligence Noise Elimination. It is a patented type of high-dynamic range technology that allows measurement of surfaces of different colours and levels of glossiness in a single scan pass. By using three different exposure levels for each measured scan line, all surface information is captured using the optimum settings at all times; one low-level exposure captures light or matte surfaces, a second high level exposure captures high-gloss and dark surfaces, and a medium-level exposure is used for other surface types.

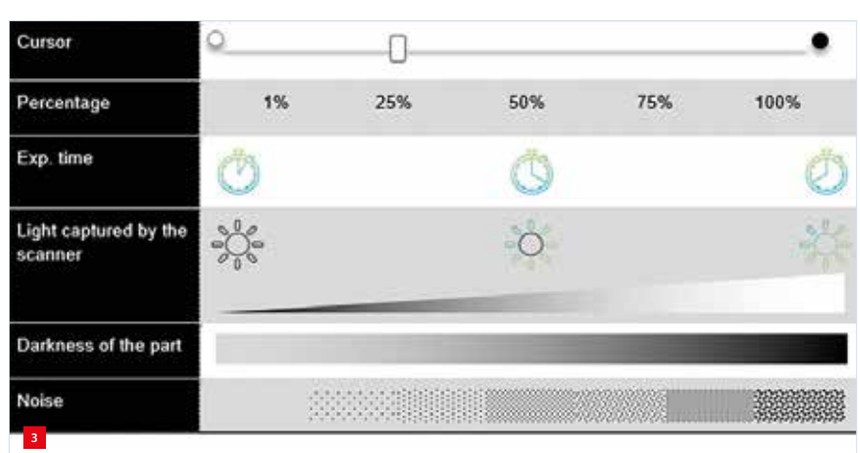
This automatic adjustment to a more optimum exposure level also allows for much cleaner data collection, as the noise created by scanning a surface at an unoptimised exposure setting is eliminated. SHINE requires little training, as no knowledge of the scanner settings is required, while fully automatic settings improve reproducibility, and also saves time, as there is no need for running trials on the part before starting the measurement job.

Multiple positioners

A laser scanner works by capturing 2D scan lines from the part surface. To provide a final 3D point-cloud to the user, this 2D information from the scanner must be combined with positional data that locates it in 3D space. This positional data comes from a 'positioner', which generally carries the scanner around the part. Examples of positioners include articulated arms, laser trackers and coordinate measuring machines (CMMs). Hexagon's AS1 was the first scanner on the market that is compatible with multiple positioners, so that it can be swapped between laser tracker and portable measuring arm systems on the fly.

Conclusion

SHINE is a powerful set of algorithms that have transformed the usability of laser scanning. Embedding this technology in the AS1 has resulted in a scanner that can deliver accurate and fast results with minimal user intervention.



Scanner settings adjustment options.

MINIMISING SPHERICAL ABERRATIONS

Temperature-controlled optical profilometry has historically been a difficult procedure due to imaging issues caused by spherical aberrations. In this case study, Linkam Scientific Instruments and Sensofar Metrology demonstrate an experimental set-up in which these problems have been minimised. Using Linkam's precision temperature control chamber with Sensofar's Linnik objective lens allows accurate measurement of 3D topographic profiles of nanoscale materials. As an example, the changes in the topography of silicon wafers as they evolve with temperatures from 20 up to 380 °C are presented.

ROBERT GURNEY AND DAVID PÁEZ

Introduction

Rapid thermal processing (RTP) is an important step in the manufacturing process of silicon wafers. The wafer is rapidly heated to high temperatures for a short period of time, and then slowly cooled in a controlled manner, in order to impart the desired semiconducting properties to the wafer. However, RTP causes thermal stress leading to problems in photolithography that may affect the performance of the device, such as breakage due to thermal shock or dislocation of the molecular lattice. Understanding the behaviour of a wafer under these conditions can help optimise the process, improving semiconductor properties and wafer durability.

A key method of evaluating the effects of temperature change during wafer manufacturing is to measure the surface roughness of the wafer as a function of temperature. To do this, the surface roughness is observed by an interferometric technique in conjunction with using a thermal chamber, allowing the temperature to be raised to values similar to those during the manufacturing process, while inspecting the sample through microscopy.

There are several factors that introduce some complexity in obtaining these interferometric measurements. Firstly, in order to visualise the sample and obtain the data while accurately controlling the temperature in the chamber, it is necessary to make observations through the chamber's optical window. The window is 0.5 mm in thickness, but in some cases, this can be as much as 1 mm, depending on the degree of thermal insulation required. This window, being of a different refractive index to air, introduces optical aberrations and misalignments that, when analysing silicon wafers, should be corrected in order to obtain reliable data.

Furthermore, when the temperature inside the chamber is increased, heat is emitted to the exterior through the observation window, and this is not ideal for optical microscopy. In the air close to that window, the temperature can reach levels up to 60 °C, which can lead to deformation of the objective lens, again introducing aberrations.

This work presents a study of the effect of the RTP process on silicon wafers while accounting for optical aberrations brought about by temperature changes. Two samples were used, corresponding to different chip designs from silicon wafers. Sample A was 2.8 mm x 1 mm in size, whereas sample B was 3.0 mm by 2.35 mm. Silicon wafers have typical surface roughness values at the sub-micron scale, so the ideal optical technology for this application is coherence scanning interferometry (CSI, ISO 25178, part 604). CSI introduces only 1 nm of measurement noise, regardless of the magnification of the lens being used.

Optical configuration

In order to address the experimental issues of interferometry at varying temperatures, a Linnik interferometer is used. Such a two-beam interferometer introduces the use of measurement optics within the reference arm of a classic interferometer. This allows for compensation and correction of the aforementioned effects of the optical window, such as chromatic dispersion and optical aberrations, which enables employing brightfield objectives that have a greater working distance than traditional interferometric objectives.

The optical configuration is shown in Figure 1. For the design and construction of the Linnik objective, two Nikon 10x EPI objectives (MUE12100) with 17.5 mm working distance were used. The same configuration is available with 10x SLWD objectives (Nikon, MUE31100), providing a 37 mm working distance. This makes the thermal emissions from the camera almost imperceptible to the lens and will not affect or damage the measurement quality. The Linnik

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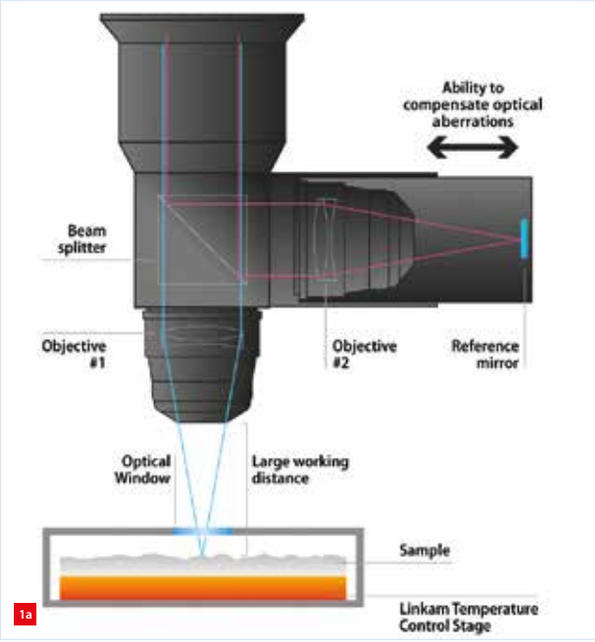
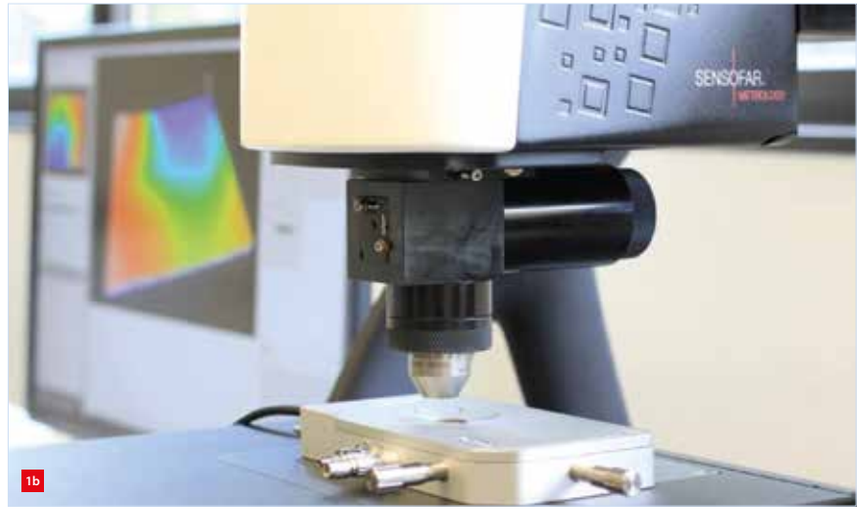




The optical configuration featuring the Sensofar optical profiler with the Linnik objective and the Linkam temperature control stage.
(a) Schematic.
(b) Experimental set-up.

objective was mounted on a Sensofar 3D optical profilometer (S neox), which combines four optical technologies in the same sensor head: confocal, CSI, PSI (phase shifting interferometry) and focus variation. These techniques are covered in ISO 25178.

The temperature is controlled using a Linkam LTS420 chamber and the T96 temperature controller, which allows the temperature to be ramped and controlled between −195 and +420 °C to a precision of 0.01 °C, while the sample roughness is observed through the chamber window. The chamber also allows control of the pressure and humidity, but this has not been investigated here.

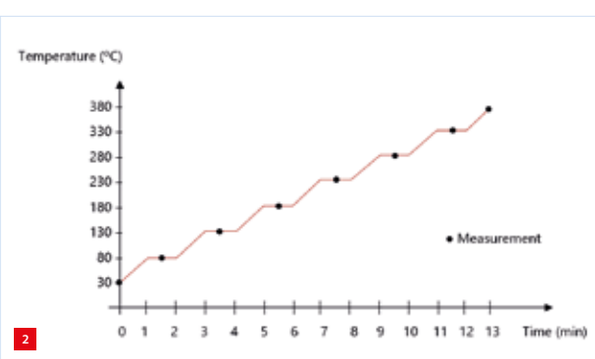
Experiments

The wafer sample was placed in the Linkam chamber under the S neox optical profiler with the Linnik configuration. The acquisition routine consisted of ramping the temperature from 30 to 380 °C in steps of 50 °C, taking eight topographic measurements of the sample at each step (Figure 2). This procedure was repeated for two samples.

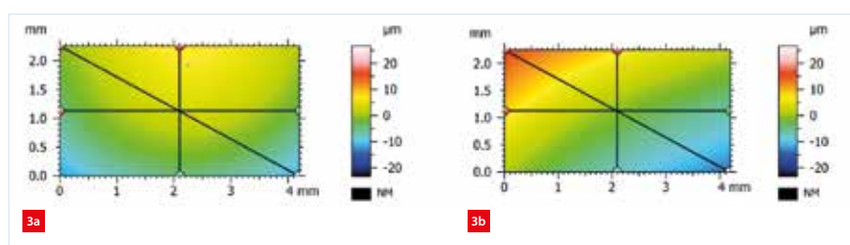
Using Sensofar's SensoMAP software, the results were visualised and analysed by creating a template and applying it to all samples. The template extracts three profiles in each topography (horizontal, diagonal, and vertical) and their representation in the same plot, and furthermore builds a sequence of the topographies to export it as a video and represent it in a 4D plot.

Two topographic images of sample A were imaged using the above methodology and are shown in Figure 3 as 2D height maps. The three solid lines represent the three different profiles (horizontal, vertical and diagonal) extracted for each topography. The profiles in each direction are shown in Figure 4, where we can see the evolution for the different temperatures at which the sample was taken. The images show that when heating the sample, its topography changes.

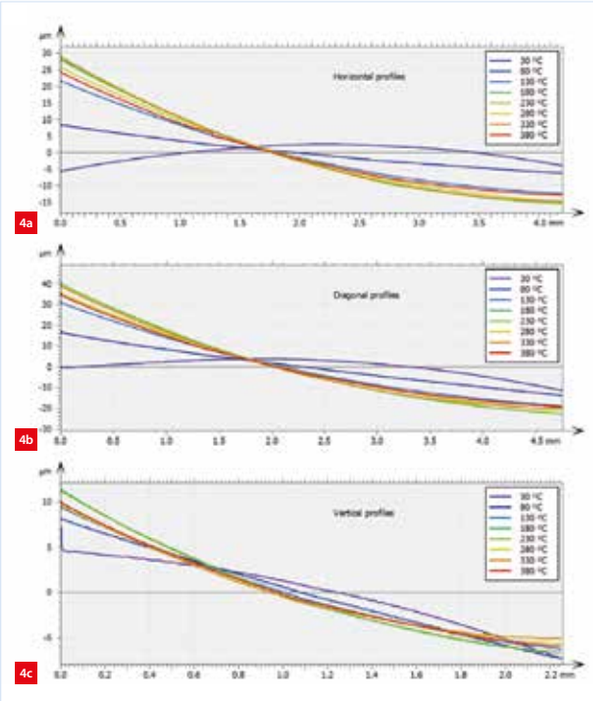
The data can be plotted in 3D topographic images as shown in Figure 5. By stacking the 3D images as a function of temperature, creating a "4D plot", showing the topographical changes at different temperatures using the same height colour scale, it is demonstrated how the samples



Time-temperature graph showing the temperature steps at which optical measurements were taken.

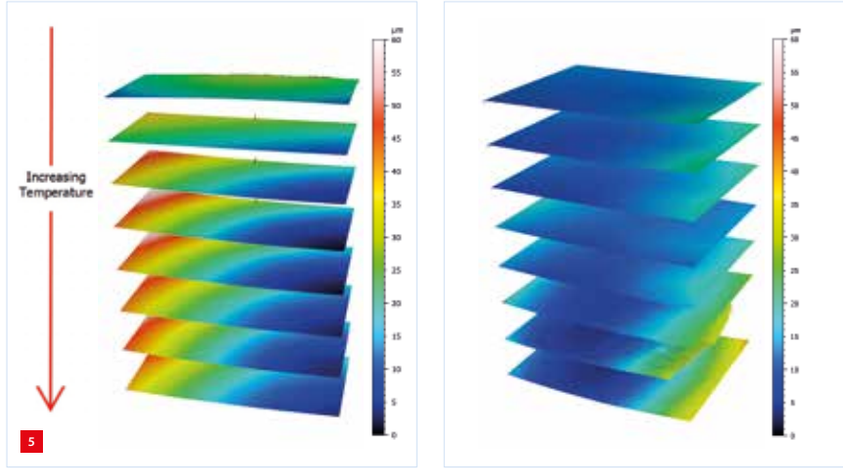


2D height maps showing the topography of sample A at different temperatures.
The black lines indicate the three directions at which profiles were taken for further studies.
(a) 30 °C.
(b) 80 °C.



Profiles extracted in different directions from the measurements of sample A at eight different temperatures.
(a) Horizontal.
(b) Diagonal.
(c) Vertical.

bend as temperature changes. It is clear that the higher the temperature, the greater the bending experienced by the samples. To quantify the bow of the samples, two different parameters were used. The first is S_z, which is the surface roughness parameter for the maximum height of a surface according to ISO 25178. The second is W_z, corresponding to the (1D) counterpart of S_z in profile analysis (ISO 4287). Both S_z and W_z were obtained after applying an S-filter to the surface (or profile) with a 0.8 mm cut-off. In this way, only the longer spatial wavelengths remain on the surface, getting rid of roughness and only leaving waviness for bow analysis.

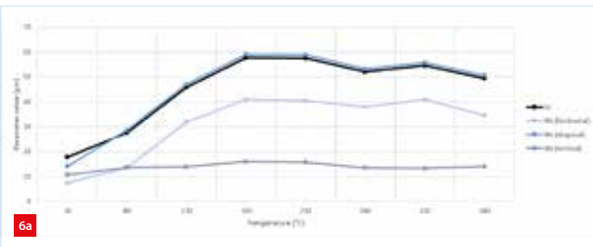


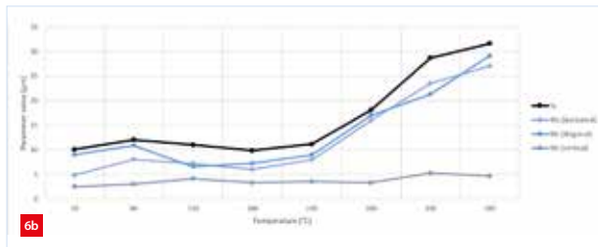
Stacked 4D view of the topographies extracted from samples A (left) and B (right) for visual comparison of the observed bow change when samples go from 30 to 380 °C. The scale on the right of each graph runs from 0 to 60 µm.

The resulting parameters for samples A and B are depicted in Figure 6. For sample A, an almost-linear relationship between bow and temperature is observed up to 180 °C, after which the bow stabilises from 180 to 380 °C. On the other hand, sample B did not show any noticeable bow change until the temperature rose above 230 °C.

Conclusion

The feasibility of the proposed configuration has been proven by successful roughness and waviness measurements at different temperatures. Two different behaviours of the surface topography were observed, depending on the chip design. Sample A showed an early bending behaviour when heating up the sample, whereas sample B exhibited bending at a later stage. The S neox 3D optical profiler with a Linnik objective has been shown to be a fitting complement for Linkam's LTS420 chamber to perform such experimental measurements. Moreover, different brightfield objectives are compatible with the Linnik configuration, offering working distances up to 37 mm and magnifications up to 100x for applications that require high lateral resolution.





Bow evolution in two samples as a function of temperature. Waviness parameters W_z were extracted from the horizontal, diagonal and vertical profiles in Figure 4. Roughness parameter S_z was computed from the surface roughness. All parameters were obtained after applying an S-filter of 0.8 mm.
(a) Sample A.
(b) Sample B.

UPCOMING **EVENTS**

12-16 September 2022, Porto (PT)
European Optical Society Annual Meeting 2022
This event provides a platform for experts in the field of optics and photonics, bridging the gap between research, education and industry.

WWW.MYEOS.ORG/EVENTS/EOS/EOSAM2022.HTML

22 September 2022, Veldhoven (NL)
Techcafé
Third edition of this DSPE-Mikrocentrum collaboration, featuring the theme of digital twinning.

WWW.DSPE.NL/EVENTS

27-30 september 2022, Utrecht (NL)
World Of Technology & Science 2022
Four 'worlds' (Automation, Laboratory, Motion & Drives, and Electronics) and Industrial Processing will be exhibiting in the Jaarbeurs Utrecht.

WWW.WOTS.NL

27-30 September 2022, Besançon (FR)
Micronora 2022
This international microtechnology trade fair focuses on miniaturisation and integration of complex functions, covering a broad multi-technology offer, ranging from R&D to sub-contracting and production technologies.

WWW.MICRONORA.COM

28-30 September 2022, Huddersfield (UK)
SIG Meeting Structured & Freeform Surfaces
Special Interest Group Meeting, hosted by euspen and dedicated to replication techniques, structured surfaces to affect function, precision freeform surfaces, large-scale surface structuring, surfaces for nanomanufacturing, and metrology.

WWW.EUSPEN.EU

10-14 October 2022, Bellevue, WA (USA)
ASPE Annual Meeting
The 37th Annual Meeting of the American Society for Precision Engineering (ASPE) will have special focus areas in precision engineering for virtual and augmented reality, aerospace engineering and large-scale metrology.

WWW.ASPE.NET

11-13 October 2022, Stuttgart (DE)
parts2clean 2022
This international fair will provide comprehensive information on cleaning systems, alternative cleaning technologies, cleaning media, clean-room technology, quality assurance and testing procedures, cleaning and transport containers, disposal and reprocessing of process media, handling and automation, service, consulting, research and technical literature. Read the article on precision cleaning on page 44 ff.

WWW.PARTS2CLEAN.DE

12-14 October 2022, Eindhoven (NL)
Optomechanical System Design course
The course focuses on the mechanical and mechatronic design of optical systems, and is intended for mechanical, mechatronic and optical engineers involved in optomechanical system design. It will also be a very valuable course for any engineer interested in optomechanical design approaches and solutions.

WWW.DSPE.NL/EDUCATION

1-2 November 2022, Enschede (NL)
International MicroNanoConference 2022
Event at the University of Twente, hosted by MinacNed, the Dutch Association for Microsystems & Nanotechnology.

WWW.MICRONANOCONFERENCE.ORG

15-16 November 2022, Den Bosch (NL)
Special Interest Group Meeting: Precision Motion Systems & Control
The second edition of this SIG Meeting is organised prior to and partly in parallel with the Precision Fair 2022 (see below).

WWW.EUSPEN.EU

16-17 November 2022, Den Bosch (NL)
Precision Fair 2022
The 21th edition of the Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum.

WWW.PRECISIEBEURS.NL

22 November 2022, Veldhoven (NL)
Health Tech Event
This new conference is organised by Brainport TechLaw, Jakajima and Mikrocentrum. It covers the interaction between innovation and regulation in the areas of medical devices, instrumentation, consumables, software, data-driven healthcare and healthcare platforms.

WWW.HEALTHTECHEVENT.EU

24 November 2022, Utrecht (NL)
Dutch Industrial Suppliers & Customer Awards 2022
Event organised by Link Magazine, with awards for best knowledge supplier and best parts & process supplier, and the Best Customer Award.

WWW.LINKMAGAZINE.NL

A COMMUNITY REJOICING AFTER TWO YEARS OF VIRTUAL CONFERENCES

Euspen has just hosted its 22nd International Conference & Exhibition in Geneva, Switzerland, after two years of virtual conferences. After the hiatus due to the world-wide Covid-19 pandemic, the precision engineering community could finally rejoice in listening and seeing in-person keynotes and technical presentations complemented with a jam-packed exhibition area.

DISHI PHILLIPS

AUTHOR'S NOTE

Dishi Phillips is the executive director of euspen (European Society for Precision Engineering and Nanotechnology).
The euspen community links industrialists, researchers, respected authorities, new and established players alike, worldwide. It is euspen's mission to advance the arts, sciences and technology of precision engineering, micro-engineering and nanotechnology; to promote their dissemination through education and training; and to facilitate its exploitation by science and industry.

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The annual euspen International Conference & Exhibition always attracts high-level interest from the precision engineering community and this was celebrated by bringing together delegates in Geneva, Switzerland, for its 22nd international event. This year, the participants were treated to prestigious visits to CERN participating in guided tours and technical tours. Sandwiched between the beginning and the end of the conference week, the tours immersed them into the world's largest particle physics laboratory (Figure 1).

Tutorials

In between the tours, delegates were offered a choice of two tutorials in the morning of Monday 30th May 2022. Nicolas Jobert from Alma Consulting, France, delivered his "Analysis and Design Concepts for Ultrastable Mechanical Systems: Thermal Effects" tutorial, providing attendees with a framework for designing mechanical systems with high immunity against thermal effects, i.e. temperature drifts and/or thermally induced elastic distortions. Prof. Alex Slocum from MIT, USA, delivered his ever-popular tutorial "FUNdaMENTALs of Precision Design" virtually due to a change in his travelling plans. Both tutorials were well attended and provided a great start to the week with many colleagues networking.

Inside the tunnel of the Large Hadron Collider (LHC) at CERN. (Image credit: Samuel Joseph Hertzog, CERN)

Workshops

The afternoon workshop "Metrology of machine tools and industrial robots geometry and compliance" was delivered by Prof. Andreas Archenti from KTH Royal Institute of Technology, Sweden, and Prof. René Mayer, École Polytechnique de Montréal, Canada. This covered the indirect measurement of geometric error addressing the methods, uncertainty, thermal dependence and compensation, as well as compliance testing and its use for the compensation of machine tools and industrial robots.

The euspen workshop focussed on the European framework for continuous professional development in precision engineering for advanced manufacturing (PREFAM). This workshop was exclusively available as a hybrid option. The PREFAM project offers high-quality learning opportunities to individuals for specialised competences, to strengthen employability and personal development in strategic industries.

Keynotes

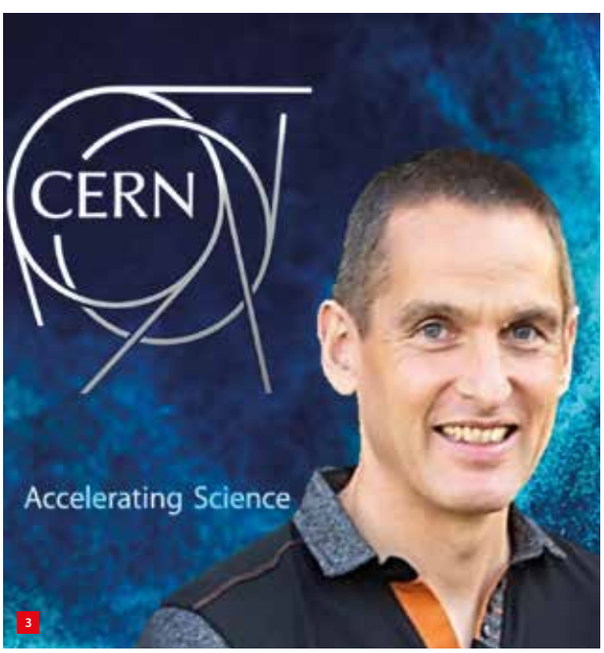
The president of euspen, Dr Hélène Mainaud Durand, officially opened the conference on Tuesday, warmly welcoming all attendees to Geneva. Just before the start of the keynote presentations, it was very fitting that a short speech was delivered on behalf of Prof. Pat McKeown; the founding father of euspen (Figure 2).

The euspen Conference opened with "A few words" from Prof. Pat McKeown; the founding father of euspen. (Image source: www.cirp.net)

CERN

The first keynote aligned perfectly with local host CERN and was delivered by Dr Rhodri Jones (Figure 3), head of CERN's Beams Department: "Present and future CERN projects and their associated engineering challenges".

In building the Large Hadron Collider (LHC), CERN had to overcome numerous technological challenges, breaking new ground in superconductivity, high-speed electronics, cryogenics, vacuum technology, material science and many other disciplines. This is continuing for the high-luminosity upgrade of the LHC foreseen to take place in 2026-2028, aiming to increase the total amount of physics data collected by a factor of ten compared to what is achievable with the current LHC.



Dr Rhodri Jones, head of CERN's Beams Department, talked about the technological challenges for the next LHC upgrade and a next generation of particle physics accelerators.

Dr Begoña Vila, instrument systems engineer from NASA Goddard Space Flight Center, presented the on-ground testing and on-orbit commissioning planning and execution for the James Webb Space Telescope.

At the same time the ground is being prepared for a next generation of particle physics accelerators, with research and development ongoing for a 50-km linear collider, a 100-km circular collider, a muon collider and novel, compact plasma accelerators. All of these imply a leap forward in terms of conception and currently achievable technology, as Jones discussed in his presentation.

James Webb Space Telescope

Dr Begoña Vila (Figure 4), instrument systems engineer from NASA Goddard Space Flight Center, Maryland, USA, presented a keynote regarding the commissioning of the James Webb Space Telescope, which was successfully launched last winter; "The James Webb Space Telescope: testing on ground to ensure on orbit performance", a subject of much topical interest.

The James Webb Space Telescope is the largest, most complex telescope being launched into space to date. It includes segmented folded mirrors and a folded sunshield deployed on orbit, and instruments with state-of-the-art infrared detectors and different science capabilities operating below 45 K. A rigorous test campaign including ambient and cryogenic tests to verify the health, performance and operations readiness in the conditions it will see on orbit was completed prior to the launch.

A detailed commissioning plan starting a few days before launch and running for six months afterwards was developed and simulated in multiple rehearsals – it includes the first month for deployments, three months for the alignment of the mirrors, cool-down activities and two months for the calibration of all the instruments and their various observing modes. Meanwhile, the first observations of this incredible telescope have been published.

Vila presented a summary of the on-ground testing and on-orbit commissioning planning including challenges and contingencies preparation as well as an update of the execution.

Geneva
Thirdly, delegates were treated to a historical account of "Geneva's special contribution to Precision Manufacturing and Metrology in Europe" by Dr Thomas Sesselmann from Heidenhain, Germany.
Interchangeability of parts with utmost dimensional accuracy, no matter where they were manufactured, has been the most important condition of industrial mass production. Europe's developing industries of the 1860s had been suffering from the inadequacy of the various existing length standards of the time. They laid all their hope in the advances brought forward by the International Meter Convention of 1875, which agreed on a new meter standard to be made of a platinum alloy. It was, however, so difficult to manufacture that it took until 1887 to produce the thirty sets of prototypes for each participating country of the Meter Convention.

Industry could not wait that long. Therefore, it was a breakthrough for the manufacturing community that a Geneva enterprise, the Société Genevoise d'Instruments de Physique (SIP), managed to build the replicas of the length standard earlier than the standard itself was completed, and even in far higher numbers and from a far more sophisticated material, Invar. Only in this way was it possible to narrow manufacturing tolerances down to a range enabling mass production of goods using automated processes. SIP continued to dominate the world of European Precision Manufacturing for the decades to come. In 1928, SIP was the pioneer to mount length standards for position feedback as integral parts into machine tools, laying the foundation for today's closed-loop machine tools of the highest accuracy.

Lastly, Prof. Darwin Caldwell from Italian Institute of Technology delivered a fascinating presentation on "The use of humanoids and AI in the industrial processes and manufacturing".
The 29 additional oral presentations filled the plenary for the three days, with most sessions ending with an industry presentation from one of the 29 exhibitors who filled the exhibition area with their latest products and developments. An area of the exhibition area was dedicated to CERN who created an LHC Interactive Tunnel; one activity included the opportunity of playing Proton Football, producing more protons the harder you kicked. Support from euspen's regular and new exhibitors was truly appreciated.

Students

Euspen prides itself on delivering a platform to support students on their journey. This included the ten student scholarships (courtesy of Heidenhain) that are awarded each year and, for the first time, a dedicated student/recruitment networking evening. Sponsored by ASML and Zeiss, students had immediate access to world-class leaders who shared their philosophies and recruitment processes. Students were also encouraged to sign up and become members of the organising committee for euspen's upcoming Sustainable Energy Systems event, as it is only with the support of the younger generation that we can work together to address global issues.

Students were at the forefront again with the euspen Talent Programme (ETP). This year, the aim of the challenge was "to study and propose an automated solution to determine the 6-DoF (degrees of freedom) position of components on a mounting girder". 27 Students were placed into international teams matching skill sets and experiences, creating nine teams, to participate in a two-stage challenge.

In Stage 1, each team were be asked to develop a solution to a 'virtual CERN challenge'. Each team presented their final solution in a short video to the euspen-selected judgement panel. From Stage 1, three teams were shortlisted and invited to CERN to begin Stage 2, in which each team participated in a practical alignment challenge using laser trackers and developing a final alignment procedure (target within 30 µm and 100 µrad positional accuracy). Each team was judged on teamwork, alignment speed and developed solution.

Next year in Denmark

The conference week was interspersed with social events, including a welcome reception taking place at the iconic Globe of Innovation & Science (Figure 5), and – all in all – did not disappoint. The sheer number of activities, networking and collaborations that took place, made up for the past two years. Now, euspen looks forward to welcoming the precision engineering community next year to Denmark, where the Technical University of Denmark will become the local hosts for the 2023 Conference.

The welcome reception of the euspen Conference 2022 took place at CERN's iconic Globe of Innovation & Science. (Image credit: CERN)

Awards

- Lifetime Achievement Award (Figure 6):
  Dr Wolfgang Knapp (metrology consultant, the 1998-2018 head of the metrology sector at the Institute of Machine Tools and Manufacturing (IWF) at ETH Zurich, Switzerland, and the 2013-2015 euspen president), for his long-term contribution to the field of precision engineering and nanotechnology.
- Best oral presentation:
  Dirk Mergelkuhl (CERN),
  "Geometrical measurement concept for the ATLAS New Small Wheel"
- Poster 1st prize:
  Florian Weigert, *et al.* (Technische Universität Ilmenau, Department of Mechanical Engineering, Institute for Design and Precision Engineering, Precision Engineering Group),
  "Model-based determination of the reproducibility of kinematic couplings"
- Poster 2nd prize:
  Elias De Smet, *et al.* (Micro & Precision Engineering Group, Division Manufacturing Processes and Systems (MaPS), Department of Mechanical Engineering, KU Leuven, Belgium),
  "Soft machines for force-free micromachining processes"
- Poster 3rd prize:
  E. Uhlmann, *et al.* (Fraunhofer Institute for Production Systems and Design Technology IPK, Germany, Institute for Machine Tools and Factory Management IWF, Technische Universität Berlin, Germany),
  "Diamond slide burnishing for the finishing of electrical discharge machined surfaces"

6

Dr Wolfgang Knapp received the Lifetime Achievement Award for his long-term contribution to the field of precision engineering and nanotechnology. On the right, the president of euspen, Dr Hélène Mainaud Durand.

PRECISION CLEANING

Particulate cleanliness specifications in the single-digit micrometer range and below, as well as extremely demanding specifications with regard to residual filmic-chemical contamination, are the order of the day in many industrial sectors. These can only be reliably met in series production when optimally matched cleaning solutions are used. Precision cleaning is one of the main subjects at the forthcoming parts2clean fair for industrial parts and surface cleaning.

DORIS SCHULZ

Precision cleaning is on the agenda of industries that require ultra-clean surfaces and components, such as optics, medical and pharmaceutical, metrology, electronics, sensors, micro-technology, aerospace, and the semiconductor supply industry (manufacturers of semiconductor production equipment). Sometimes, extremely high specifications for the particulate and filmic-chemical cleanliness of the components are the result. Depending on the industrial sector and components involved, cleanliness criteria such as outgassing rates for organic substances and residual moisture are very strict, and – in the case of surface analyses for residues of inorganic substances – it may also be necessary to comply with limit values down to the atomic percentage range. These requirements result in very demanding tasks for component cleaning that can affect the entire production chain.

Initial conditions and environment

During production, precision parts go through such manufacturing steps as machining, forming, and grinding, which are associated with the introduction of dirt. Very high cleanliness requirements can only be met if the components consistently meet a defined initial condition. Important aspects are, among others, the clean execution and quality of upstream processing steps, the avoidance of re- and cross-contamination by upstream or downstream processes as well as by the part handling, the quality of a deburring action and/or the surface finish. The design of adequate part take-ups as well as adapted handling and environmental conditions are further issues that should be taken into consideration (Figure 1).

Ultra-fine cleaning

Wet chemical processes are widely used in ultra-fine cleaning and are considered as state of the art. The cleaning process is carried out using ultrasonic inline immersion systems, which – depending on the cleaning task – are equipped with an appropriate number of treatment stations for cleaning, rinsing and drying. Alternatively, chamber systems with one or more work chambers are available. These systems can be operated using both aqueous media and solvents. Both system concepts can be connected directly to cleanrooms or integrated into them.

Regardless of whether an inline immersion or chamber system is used, it must be ensured that the materials and manufacturing processes used to construct the cleaning system do not cause re- or cross-contamination.

Using solutions for continuous control and recording of plant and process parameters is often already a standard in wet chemical plants for ultra-fine cleaning. Measuring systems for permanent inline monitoring and control of

Defined ambient and handling conditions, as in this case a cleanroom, are indispensable for ultra-fine cleaning applications in order to meet high cleanliness specifications. (Image source: Fraunhofer IPA)

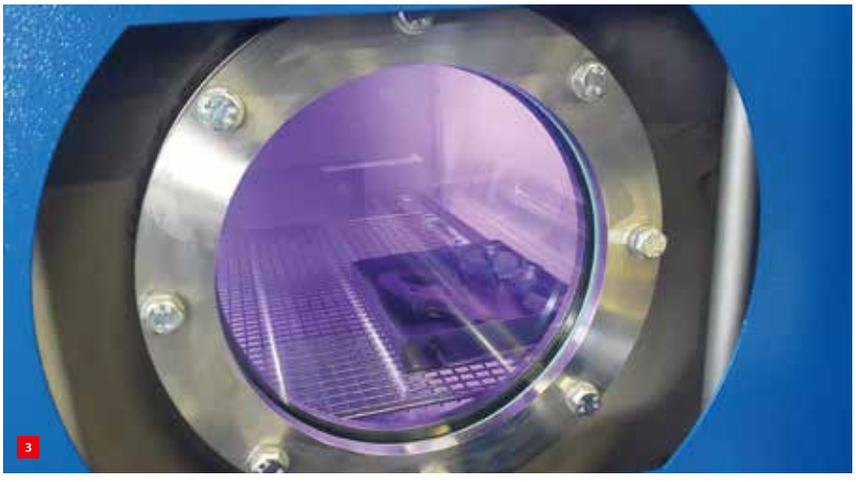
Vacuum-based bake-out systems for the final step in cleaning precision components use high temperatures to remove residual contamination of atmospheric components from the surface. (Image source: VACOM)

AUTHOR'S NOTE

Doris Schulz is a journalist. Her agency, based in Korntal, Germany, specialises in PR solutions for technical products and services. This article was commissioned by Deutsche Messe, organiser of the parts2clean fair, which is scheduled to take place in Stuttgart (Germany) from October 11 to 13, 2022.

The fair will provide comprehensive information on cleaning systems, alternative cleaning technologies, cleaning media, cleanroom technology, quality assurance and testing procedures, cleaning and transport containers, disposal and reprocessing of process media, handling and automation, service, consulting, research and technical literature.

www.parts2clean.de



For ultra-fine degreasing, prior to bonding and coating processes, for example, chamber systems operated with aqueous media or solvents can be equipped with low-pressure plasma. (Image source: Ecoclean)

the cleaning baths not only enable the exact documentation of the conditions during cleaning, but also the automatic replenishment of the cleaning media as required. When providing and preparing the media, it must be ensured that it is of the appropriate quality for the purity requirement, through the use of an ultrapure water supply, for example.

Process engineering aspects

The starting point for the task-specific design of the cleaning system and processes are the materials and geometry of the parts to be cleaned, the degree and type of contamination, and the selection of the appropriate cleaning medium. When determining the process technology, ultrasound or megasonic, spraying, dipping, high pressure and plasma, for example, it must be taken into account that undercuts, blind holes, and capillary, lumen or pore structures of components influence the cleaning effect. This is because cleaning media and process technology can sometimes only reach certain areas with difficulty or not at all. One remedy, for example, is ultrasonic cleaning solutions that work in combination with vacuum. Alternatives include new process technologies such as cyclic nucleation (CNp), vacuum-activated purification (VAP) and pulse pressure cleaning (PPC).

Dry to maximum purity

Various dry processes, such as vacuum baking, plasma and CO_2 snow jet cleaning, are also available for ultra-fine cleaning tasks. Regardless of which process is used to clean precision components, it is also necessary to take a look at packaging and logistics. Is it possible to transport the parts to the next step in a high state of cleanliness?

Vacuum baking

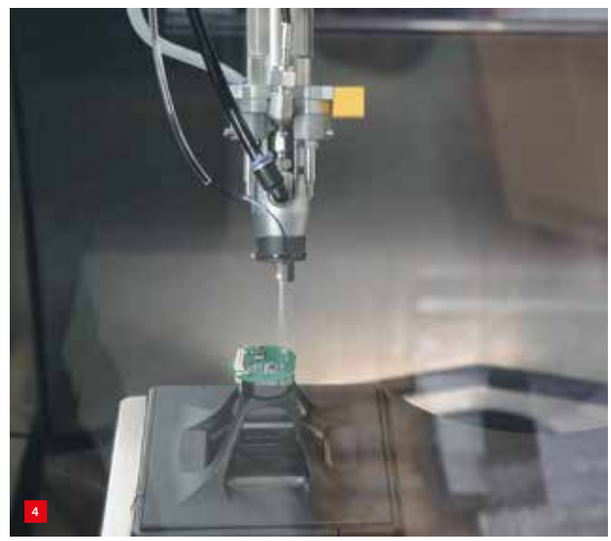
Components are baked under vacuum in specially developed vacuum furnaces. In this process (Figure 2), residues of filmic contaminants are removed from material surfaces at high temperatures (e.g. 180 °C). The adhering molecules then pass into the gas phase due to the vacuum environment and are pumped off. It is also possible to simultaneously determine the molecular components of the outgassing by means of mass-spectrometry-based residual gas analysis (RGA) during the heating process, so that the cleanliness of the components can be tested and confirmed in-situ. A modular configuration in terms of hardware and software enables solutions that are designed for the respective application and components.

Plasma cleaning

Thin residual organic contaminants can also be removed using plasma cleaning (Figure 3), in a process where the surface is cleaned and activated at the same time. This dual function is based on a physical and chemical reaction in the process, through which an increase in surface energy is achieved. The use of so-called 'cold' plasma sources makes it possible to treat even temperature-sensitive materials.

CO_2 snow jet cleaning

The removal of filmic and particulate contaminants down to the submicrometer range is made possible by CO_2 snow jet cleaning, which uses liquid, climate-neutral carbon dioxide as a medium. It passes through a wear-free two-substance ring nozzle, and then relaxes as it emerges to form fine CO_2 crystals, which are bundled by an annular compressed air jacket jet and accelerated to supersonic speed. When the jet of compressed snow air hits the surface to be cleaned, it causes a combination of thermal, mechanical, sublimation and solvent effects. Systems are available in a cleanroom-compatible design (Figure 4) with integrated process monitoring as standard for use in ultra-fine cleaning.



In the JetCell-HP, designed to meet cleanroom requirements, CO_2 snow jet fine-cleaning processes can be automated and integrated into production lines. (Image source: acp systems)

ICONIC DESIGN AND CREATIVE CLOCK

Wim van der Hoek's design principles for accurate movement and positioning can only be applied successfully if accurate measurements can be taken. In turn, it is precisely those design principles that facilitate measurement, as demonstrated by the iconic design of an adjustable slit for a laser interferometer and the creative clock that colleagues built as a work anniversary gift. This fourth in a series of articles features remarkable designs for length and time measurement, as described in DSPE's Dutch-language book "Wim van der Hoek (1924-2019) – A constructive life".

A crucial element in Van der Hoek's design principles is thinking in terms of degrees of freedom and statically determined constructions. An important role in the development of this thinking was played by the physicist Jaap Koning, who founded the Laboratory for Length Measurement Technology as a lecturer in the Mechanical Engineering faculty at Eindhoven University of Technology (TU/e).

Koning was already familiar with concepts such as degrees of freedom and was able to spar with Van der Hoek about this, offering him counterplay where necessary, as recounts Peer Brinkgreve, a member of Van der Hoek's TU/e group at the time. "'That's all nice what you are doing', he (Koning, ed.) would say to Wim. 'For example, you can put a body on three V-grooves, so on six rods, but if you now put them parallel to each other, it won't help you, because then your body can still go in all directions. So, you have to put those rods in different orientations.' Well, then the penny dropped. You could count them (degrees of freedom, ed.), but you also had to be able to reason about them."

The prototype that Hein Ruyten made of an adjustable slit for a laser interferometer.

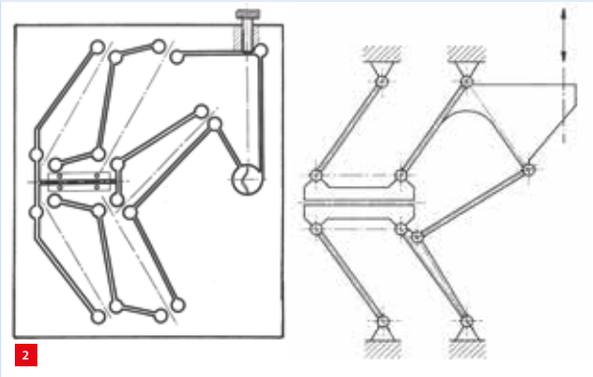
Flexure hinges

The contact between Van der Hoek and Koning led, among other things, to an iconic design on which mechanical engineering student Hein Ruyten graduated in 1976. Iconic because, one, the design would later adorn the cover of the widely distributed textbook *Constructieprincipes*, the continuation of Van der Hoek's DDP (*Des Duivels Prentenboek*, "The Devil's Picture "Book", Van der Hoek's collection of good (and bad) designs) by his successor Rien Koster – and is also still featured on the trophy for the Wim van der Hoek Award. But also, two, because the design is entirely based on a typical VanderHoekean construction element, the flexure hinge.

In this case, the flexure hinge was used for the hysteresis-free manipulation of an optical slit with micrometer accuracy for a laser interferometer. "It started with the conclusion of Koning's Length Measurement course", Ruyten recalls. "The assignment, ultimately part of my graduation with Wim van der Hoek, was to design a symmetrically adjustable slit with high demands on the parallelism of the two edges. I still have the first prototype (see Figure 1, ed.). Wim's department had a precision-mechanical workshop where his students could tinker under the guidance of staff members. There I made this prototype; the slots between the holes just using a fretsaw, that was the easiest. We didn't have CNC milling yet."

Lector Koning was enthusiastic about the design (Figure 2). "Wim, look what I have here", Koning said. "This is the most accurate adjustable optical slit I know and it is more compact and much cheaper than anything commercially available." It could be set free of play, symmetrically with respect to its axis. This was done using a rod mechanism, the hinges of which consisted of elastic elements. These flexure hinges were formed by dimensioning a dam between holes drilled relatively close together with a deliberately chosen diameter.

Over the years, the manipulator has served as a model for many applications of elastic elements. As such, this design is the epitome of an appliance with very precise adjustability that can be made by simple means, where accurate is not necessarily synonymous with expensive. Thanks in part to the use of wire spark erosion and laser cutting, this type of elastic element has become a widely used design principle.



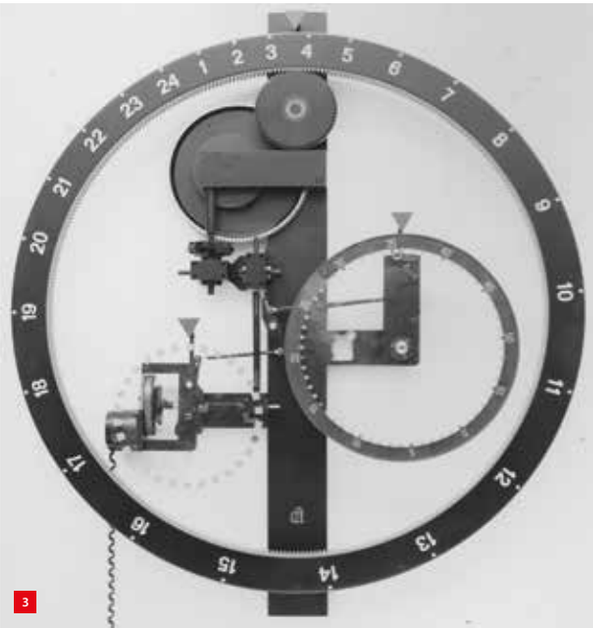
2

Flexure-hinge-based design (DDP 93) for a symmetrically adjustable gap. The adjustment can be made using a rod mechanism (right), the hinges of which consist of elastic elements.

Unconventional watch and clock

In 1974, Van der Hoek celebrated his 25th work anniversary at Philips, where he spent his whole career, aside from the part-time professorship at TU/e. The celebration included a reception by the board of directors. "Jubilee pin, Makkummer plate (typical Dutch pottery, ed.), gold pocket watch and one month's salary", he noted afterwards. He had to move heaven and earth in the Philips bureaucracy for that pocket watch, his son Maarten recalls. A wristwatch with inscription was common, but Van der Hoek never wore one. That's why he preferred a pocket watch on a chain, for in his jacket. "This took quite some effort. Only after the threat that Dad would not accept a wristwatch did the company back down."

The honouree received a 'clock' (Figure 4) from his colleagues at the Philips Centre of Manufacturing Technology (CFT), which they had built themselves – over many (evening) hours.



3

Wim van der Hoek received this unique clock from his colleagues on the occasion of his 25th work anniversary at Philips.

They applied well-known techniques from industrial mechanisation, design principles from DDP and parts of functional elements, such as a large gear ring. A real tech joke was that the 'small hours' on the clock were small (close to each other) and so the clock had a variable rotation speed.

Furthermore, a typical idiosyncrasy of the CFT constructors was that the hands (the triangles standing on their point, at the top for the hours, in the middle right for the minutes and at the bottom left for the seconds) were standing still, while the associated scales were turning – in Figure 4 it is 3:36 AM. The clock did not have its own oscillating mechanism such as a pendulum or an unrest (or balance) wheel. A synchronous motor provided the drive and thus the 50 Hz of the mains dictated the time.

"Wim van der Hoek (1924-2019) – A constructive life"

After Wim van der Hoek passed away in early 2019, DSPE took the initiative to publish a book (in Dutch) about the Dutch doyen of design principles (Figure 4). It covers his formative years, including his World War II 'adventures', his career at Philips and Eindhoven University of Technology, his breakthrough ideas on achieving positioning accuracy and control of dynamic behaviour in mechanisms and machines, and their reception and diffusion. It concludes with his busy retirement years in which he continued to tackle design challenges, technical as well as social, believing that technology should support people.

His specialism, dynamic behaviour and positioning accuracy, was the main subject of his part-time professorship at Eindhoven University of Technology, from 1961 to 1984. There, he endeavoured to enthuse first-years in the mechanical engineering profession and to teach fourth-year students (some 600, over the years) mechanical design. In his lecture notes, he built on his research at Philips. He collected examples of designs that were lightweight, sufficiently stiff and play-free with regard to dynamics in his famous "The Devil's Picture Book" (*Des Duivels Prentenboek*, DDP), which he presented as a source of inspiration for upcoming and experienced designers. Now, this book about Wim van der Hoek conveys the same enthusiasm.

4

Lambert van Beukering & Hans van Eerden (eds.), "Wim van der Hoek (1924-2019), Een constructief leven – Ontwerpprincipes en praktijklessen tussen critiek en creatie", ISBN 978-90-829-6583-4, 272 pages, €49.50 (€39.50 for DSPE members) plus €6.50 postage, published by DSPE in 2020.

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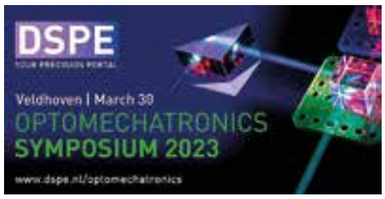
WWW.DSPE.NL

LIVE: DSPE OPTOMECHATRONICS SYMPOSIUM 2023

Next year will see a new, live edition of the DSPE Optomechatronics Symposium, dedicated to the latest developments in optomechatronics. The event will be held in Veldhoven (NL) on 30 March, 2023, at Mikrocentrum, an independent high-tech knowledge institute and DSPE partner.



It will be the fifth edition of the DSPE initiative that started in 2013 as the DSPE Optics and Optomechatronics Symposium in Eindhoven (NL). Later editions were held in Delft (NL) in 2015, Aachen (Germany) in 2017, and again in Eindhoven in 2019. Some of the earlier symposia were part of a DSPE Optics Week, which also featured advanced courses, such as the Optomechanical System Design course.

This course premiered in 2019; it targets mechanical, mechatronic and optical engineers and offers a broad overview of this omnipresent multidiscipline. It contains numerous design examples that illustrate the tricks of the trade in optomechanical system design, which increasingly affects the overall performance of high-tech systems. This autumn, the course will be held on 12-14 October, 2022 in Eindhoven.

At the 2023 symposium, organised by DSPE in collaboration with Mikrocentrum and the German photonics cluster Optence, the keynote speech will be delivered by Zeiss SMT. Additional presentations will be given by representatives from, among others, ASML, Research Instruments, TNO and the universities of technology of Delft and Eindhoven.

For example, Stefan Kuiper, mechatronic system architect at TNO, will talk about the development of deformable mirror technology for aberration correction in high-end adaptive optics systems in the field of astronomy, space telescopes and laser communication. Wim Coene, part-time professor at Delft University of Technology and director of Research at ASML, will discuss the imaging of nanostructures without lenses; see also the article on coherent diffractive imaging in this issue of Mikroniek (page 5 ff.).

Sander Hermanussen, doctoral candidate at Eindhoven University of Technology, will present an adaptive wafer table that can compensate for a mismatch between the wafer surface and the table, similar to how an adaptive mirror system works. Dynamic excitations from the wafer positioning system can also be damped. A set of multilayer piezo-electric actuators are mounted at the back of the table. Both curvature as well as in-plane strain can be controlled by using different electrode patterns. Additionally, the adaptive wafer table has the potential to mitigate friction during wafer load.

Other presentations include optical measurement tool designs. The symposium is targeted at architects and engineers who are involved in the design and realisation of optical hardware. Registration is open. There is room for table-top presentations; organisations are invited to exhibit.

WWW.DSPE.NL/OPTOMECHATRONICS

FOURFOLD ECP2 BRONZE

This summer, four people were awarded a Bronze certificate from ECP2, a European certified precision engineering course programme that is a collaboration between euspen and DSPE. A small ceremony was organised by Jan Willem Martens, founding father of the precursor DSPE certification programme, and DSPE board members Bart Dirkx and Hans Krikhaar (president). The function preceded the second edition of the Techcafé, the new DSPE-Mikrocentrum collaboration, on 7 July at the Mikrocentrum premises in Veldhoven (NL).

Gijs Kramer and Jeroen Janssen received their certificates in person, while Rilpho Donker and Ingo van der Heijden, who were unable to attend, received theirs at a later date. The four had taken ECP2-certified courses between 2008 and 2017, while working at (and switching between) the high-tech companies Alten, ASML, Heidenhain, IBS Precision Engineering, and Philips.

Euspen's ECP2 programme grew out of DSPE's Certified Precision Engineer programme, which was developed in the Netherlands in 2008 as a

Jeroen Janssen (left) receiving the ECP2 Bronze certificate from the hands of DSPE president Hans Krikhaar.

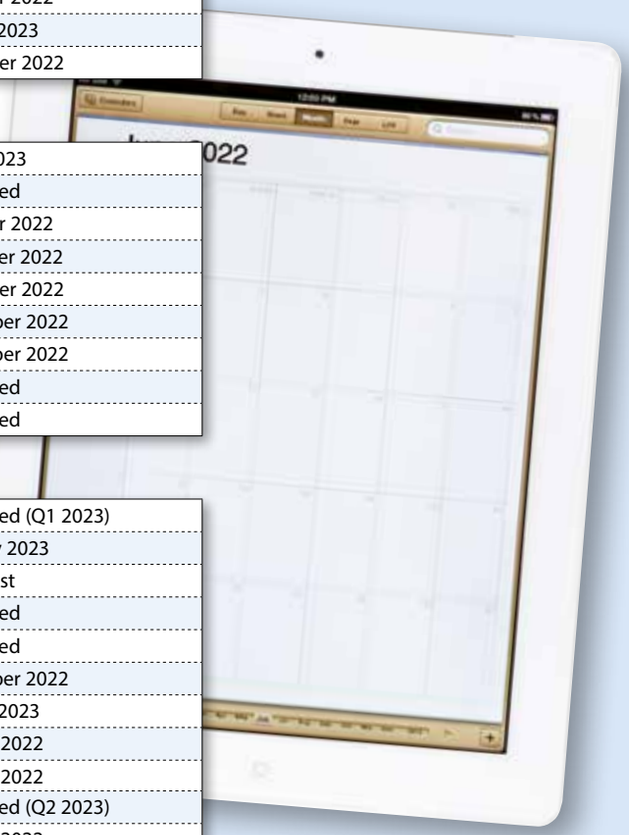
commercially available series of training courses. In 2015, euspen, DSPE's European counterpart, decided to take certification to a European level. The resulting ECP2 programme reflects industry demand for multi-disciplinary system thinking and in-depth knowledge of the relevant disciplines. To promote participation, a certificate scheme was instigated. The Bronze certificate requires 25 points (one point equals roughly one course day), Silver requires 35 points and Gold 45 points, which qualifies a participant for the title 'Certified Precision Engineer'.

WWW.ECP2.EU

Ingo van der Heijden was presented with the certificate at the Experience Center of his current employer, ASML.

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	13 February 2023
Mechatronics System Design - part 2 (MA)	5	HTI	10 October 2022
Fundamentals of Metrology	4	NPL	to be planned
Design Principles	3	MC	28 September 2022
System Architecting (S&SA)	5	HTI	7 November 2022
Design Principles for Precision Engineering (MA)	5	HTI	6 February 2023
Motion Control Tuning (MA)	5	HTI	21 November 2022
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	21 March 2023
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned
Actuation and Power Electronics (MA)	3	HTI	1 November 2022
Thermal Effects in Mechatronic Systems (MA)	3	HTI	13 December 2022
Dynamics and Modelling (MA)	3	HTI	22 November 2022
Manufacturability	5	LiS	26 September 2022
Green Belt Design for Six Sigma	4	HI	26 September 2022
RF1 Life Data Analysis and Reliability Testing	3	HI	to be planned
Ultra-Precision Manufacturing and Metrology	5	CRANF	to be planned
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	to be planned (Q1 2023)
Advanced Optics	6.5	MC	23 February 2023
Machine Vision for Mechatronic Systems (MA)	2	HTI	upon request
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned
Modern Optics for Optical Designers (T2Prof) - part 1	7.5	HTI	23 September 2022
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	20 January 2023
Tribology	4	MC	18 October 2022
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	31 October 2022
Experimental Techniques in Mechatronics (MA)	3	HTI	to be planned (Q2 2023)
Advanced Motion Control (MA)	5	HTI	17 October 2022
Advanced Feedforward & Learning Control (MA)	3	HTI	to be planned (Q2 2023)
Advanced Mechatronic System Design (MA)	6	HTI	to be planned (2023)
Passive Damping for High Tech Systems (MA)	3	HTI	29 November 2022
Finite Element Method	2	MC	3 November 2022
Design for Manufacturing (Schout DfM)	3	HTI	18 October 2022



ECP² program powered by euspen

The European Certified Precision Engineering Course Program (ECP²) has been developed to meet the demands in the market for continuous professional development and training of post-academic engineers (B.Sc. or M.Sc. with 2-10 years of work experience) within the fields of precision engineering and nanotechnology. They can earn certification points by following selected courses. Once participants have earned a total of 45 points, they will be certified. The ECP² certificate is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills, and allows the use of the ECP² title.

WWW.ECP2.EU

Course providers

- High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- LiS Academy (LiS)
  WWW.LIS.NL/LISACADEMY
- Holland Innovative (HI)
  WWW.HOLLANDINNOVATIVE.NL
- Cranfield University (CRANF)
  WWW.CRANFIELD.AC.UK
- Univ. of Huddersfield (HUD)
  WWW.HUD.AC.UK
- National Physical Lab. (NPL)
  WWW.NPL.CO.UK

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  WWW.MECHATRONICS-ACADEMY.NL
- Technical Training for Prof. (T2Prof)
  WWW.T2PROF.NL
- Schout DfM
  WWW.SCHOUT.EU
- Systems & Software Academy (S&SA)

Super resolution through microscopy innovation

Each year, Microscopy Today, an industry-leading publication run by the Microscopy Society of America, selects ten innovations in microscopy or microanalysis that are expected to have the most significant impact in the efficiency and innovation of the microscopy community.

On 3 August 2022, scientists at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory received the 2022 Microscopy Today Innovation Award for their development of a system with bonded x-ray lenses that make nanoscale resolution more accessible than ever before. When the team at the National Synchrotron Light Source II (NSLS-II), a DOE Office of Science user facility, tested the new lens system, they achieved a resolution down to approximately 10 nm.

Among the ten nominations for the 2022 award was the Ultra-X technology, the result of teamwork of microscopy & microanalysis consultant Nestor Zaluzec and the development teams at Sioux Technologies and Thermo Fisher Scientific, both located in Eindhoven (NL). The Ultra-X detector was already rewarded in the Guinness World Records book as the world's most sensitive X-ray detector.

The Ultra-X is a detection system for the Spectra Ultra S/TEM, a high-end transmission electron microscope. It works on the principle of energy-dispersive X-ray (EDX) spectroscopy. A sample is scanned with an electron beam down to atomic level. The interaction of the electrons with the material creates X-rays that are specific to the elements in the sample. The various atoms can be visualised to an accuracy of 50 pm.

The Ultra-X system, nominated for the 2022 Microscopy Today Innovation Award.

WWW.MICROSCOPY-TODAY.COM
WWW.BNL.GOV/NSLS2
WWW.SIOUX.EU
WWW.THERMOFISHER.COM

Aalberts acquires KML

Industrial conglomerate Aalberts, headquartered in Utrecht (NL), has announced the takeover of KML Linear Motion Technology and KML Precision Machining, both based in Vienna (Austria).
KML provides cutting-edge mechatronic solutions performing linear and rotative high-speed movements in complex applications. KML systems are predominantly used as an integral subsystem of machinery, enabling high-performance semicon manufacturing.

Aalberts has advanced mechatronics as one of its core technologies, while semicon efficiency is one of the end markets targeted. KML's portfolio encompasses mainly customised solutions, complemented with standardised linear motor systems and components. KML and Aalberts can offer combined mechatronic solutions to existing key accounts and new customers in the various regions. Technology will be exchanged between the companies to drive innovations and further capacity expansions are planned.

WWW.AALBERTS.NL
WWW.KML-TECHNOLOGY.COM

MathWorks suites for start-ups

MathWorks, a leading developer of mathematical computing software, has expanded its support for the next generation of entrepreneurs. The company now offers tech start-ups access to a pair of standard suites containing Matlab, Simulink, and more than 100 industry-specific toolboxes at a start-up-friendly price. The Suites for Startups provide a full stack of development tools for design and simulation, test and code generation, and include training options in local languages as well as technical support from MathWorks experts.

WWW.MATHWORKS.COM

Geared linear actuators

Faulhaber has launched the Linear Actuator L series. Designed to provide high performances in compact dimensions, these actuators can support high input speed and high output force, and they are suited for a wide range of applications, including robotics, industrial machines and laboratory equipment.

A large number of reduction ratios, uniformly distributed, are available to select the most appropriate configuration to fit various force or speed operating points as required by the application. This new actuator family also offers high flexibility with different screw sizes and types; moreover, a large selection of options is available to match different ambient conditions and make mechanical integration inside applications faster and smoother through various flange and nut configurations.

WWW.FAULHABER.COM

Car technology used to grow tomatoes in Europe

The Certhon Harvest Robot is a new piece of agri-tech that makes it possible to grow and pick fruit such as tomatoes without human intervention. The robot detects, cuts and transports tomatoes to boxes. Furthermore, thanks to its deep learning technology, it has the potential to become more intelligent each time it is used, scouting yields and measuring the climate and health of crops, using data to warn against potential viral infections and ensure higher yields.

The intelligent machine is the result of a collaboration between robotics manufacturer DENSO and greenhouse solutions specialist Certhon, located in Poeldijk (NL). Already trialled in Asia, the Certhon Harvest Robot can form part of an autonomous agricultural system with technology providing the optimal temperature and climatic conditions to grow crops, assisted by robots monitoring, picking and packaging up fruit. Such systems, now being focused on the European market, have the potential to revolutionise the entire food supply chain, making it more sustainable, more reliable, and more efficient in the process.

The Certhon Harvest Robot is modelled on DENSO's range of robotics and automation solutions typically used in industrial scenarios such as vehicle manufacturing. Furthermore, the company's thermal systems – most commonly seen within vehicle air conditioning and radiator systems – are being used to control greenhouse temperatures to create conditions in which crops can grow and the robot can perform its duties, without being affected by weather conditions. DENSO's partnership with Certhon enables it to evolve its technologies together with Certhon's advanced horticultural techniques and cultivation knowledge.

DENSO is a global mobility supplier that develops advanced vehicle technology and components. The company is headquartered in Kariya, Japan, and has European regional headquarters in Amsterdam (NL).

WWW.CERTHON.COM
WWW.DENSO.COM

ASM acquires SiC-epitaxy equipment manufacturer LPE

This summer, ASM International announced the acquisition of LPE. ASM International, headquartered in Almere (NL), designs and manufactures equipment and process solutions to produce semiconductor devices for wafer processing. LPE is a manufacturer of epitaxial reactors for silicon carbide (SiC) and silicon, based in Italy. LPE's focus is on epitaxy tools for power applications, to address the rapidly growing electric vehicle market.

The global automotive industry is investing significantly in chips made from silicon carbide. Because of its wide bandgap, SiC is highly efficient at high voltages offering higher power efficiency, increased power density resulting in reduced component weight and size, as well as faster battery charging times.

"Next to ASM's expanding position in advanced epitaxy applications for the logic/foundry and memory markets, ASM is also a leader in silicon epitaxy solutions for the power electronics, analog and wafer markets. LPE's offering of advanced SiC-epitaxy tools complements ASM's offering", said Benjamin Loh, president and CEO of ASM. Following the close of the transaction, LPE will operate as a product unit under ASM's Global Products organisation.

WWW.ASM.COM
WWW.LPE-EPI.COM

Diamond turning machine integration capability

Zygo Corporation (a division of Ametek) has announced the release of Compass 2™, its latest optical profiler with diamond turning machine (DTM) optimisation and freeform surface metrology capability. Unlike comparable solutions, mould pins remain on their manufacturing fixture during metrology – shortening the time to data processing and minimising uncertainty from remounting and re-aligning the sample. With new interface improvements, so ZYGO claims, the Compass 2 now delivers three times better form deviation performance than the original Compass. It has been designed from the ground up with an emphasis on robust metrology and high confidence, for in-process rather than in-lab usage.

Over the last decade, the Compass and Compass RT metrology systems have served for non-contact, automated 3D surface metrology and production process control for discrete micro-lenses and moulds to compact imaging systems, such as cameras for tablets and smart phones, and automotive vision systems. Now, the Compass 2 is designed for the analysis of rotationally symmetric spherical and aspheric, geometrically truncated, and freeform surfaces. It can measure both discrete lenses and injection moulding pins; and the instrument has been specifically tailored to meet the needs of manufacturers using this process with a series of new capabilities.

Beyond just DTM integration, the Compass 2 has the necessary XYZ precision to report nm-level roughness data that includes automatic generation of high-frequency texture and tooling mark surface maps. New DTM capabilities include tool-path correction support, tool set-up support, and fixture support (a standard vacuum chuck fixture). Freeform support includes both freeform and truncated surface analysis in the Compass 2 software package. Compass 2 uses its ability to track a surface during measurement to capture the freeform surface.

WWW.ZYGO.COM

Dual encoder

Heidenhain presents the KCI 120 Dplus dual encoder, which combines motor feedback and position measurement in one device. It features two absolute rotary encoders without integral bearing, offering high reliability in a rugged and compact design – the low 20 mm profile makes it suitable for tight installation spaces. The encoders permit wide mounting tolerances of ±0.3 mm to ±0.5 mm.

Thanks to the robust inductive scanning method, the KCI 120 Dplus rotary encoders are particularly resistant to contamination and magnetic fields. The rigid design permits high vibration loads of up to 400 m/s^2 on the stator and 600 m/s^2 on the rotor. Positioning accuracy goes down to ±40", at 1,048,576 positions/revolution.

Stage for super-resolution microscopy

ALIO Industries, an Allied Motion Company, has recently released a high-precision focusing stage – the AI-VC-600-Z-SCB – which is critical in such applications as super-resolution microscopy, atomic force microscopy, digital pathology, surface metrology, and industrial manufacturing and inspection applications.

Such applications require nanometer-level resolution and extremely fast millisecond-range response. For example, recent advances in fluorescence microscopy, a type of light microscopy in which one wavelength of light is absorbed and another emitted, allows super-resolution microscopy to observe living sub-cellular structures and activities.

With a 6 mm travel range and a 500 g payload, the AI-VC-600-Z-SCB can achieve 4g100% S-curve peak acceleration (which is equivalent to 2g trapezoidal acceleration) and 300 mm/sec speed with 5 nm resolution, and even 1 nm resolution by reducing the speed capability to 30 mm/sec.

WWW.ALIOINDUSTRIES.COM

Automation Technology

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Micro Drive Systems

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maxon is a developer and manufacturer of brushed and brushless DC motors, as well as gearheads, encoders, controllers, and entire mechatronic systems. maxon drives are used wherever the requirements are particularly high: in NASA's Mars rovers, in surgical power tools, in humanoid robots, and in precision industrial applications, for example. To maintain its leadership in this demanding market, the company invests a considerable share of its annual revenue in research and development. Worldwide, maxon has more than 3.050 employees at nine production sites and is represented by sales companies in more than 30 countries.

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Micro Drive Systems

FAULHABER Benelux B.V.
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FAULHABER specializes in the development, production and deployment of high-precision small and miniaturized drive systems, servo components and drive electronics with output power of up to 200 watts. The product range includes brushless motors, DC micromotors, encoders and motion controllers. FAULHABER also provides customer-specific complete solutions for medical technology, automatic placement machines, precision optics, telecommunications, aerospace and robotics, among other things.

Physik Instrumente (PI)
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Motion Control Systems

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Aerotech's motion control solutions cater a wide range of applications, including medical technology and life science applications, semiconductor and flat panel display production, photonics, automotive, data storage, laser processing, electronics manufacturing and testing.

Motion Control Systems

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Newport Spectra-Physics B.V. is a subsidiary of Newport, a leader in nano and micro positioning technologies with an extensive catalog of positioning and motion control products. Newport is part of MKS Instruments Inc., a global provider of instruments, subsystems and process control solutions that measure, control, power, monitor, and analyze critical parameters of advanced processes in manufacturing and research applications.

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Opt for state-of-the-art motion control systems from the world's leading provider PI. Developed, manufactured and qualified in-house by a dedicated and experienced team. Our portfolio includes a wide and deep range of components, drives, actuators and systems and offers infinite possibilities in motion control on a sub-micron and nanometer scale.

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Optical Components

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Piezo Systems

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As partner for piezo system solutions, HEINMADE serves market leaders in the high tech industry. Modules and systems are developed, produced and qualified in-house.

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Piezo Systems

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High-precision piezo systems and applications that perform on a sub-micron and nanometer scale: world leader PI develops, manufactures and qualifies these in-house. With a broad and deep portfolio with infinite possibilities in components, drives, actuators and systems at hand, our experienced team is dedicated to find the best solution for any motion control challenge.

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Precision Electro Chemical Machining

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Tempcontrol is thé specialist for temperature measurement and temperature control. We produce customer specific temperature sensors, such as thermocouples and resistance thermometers for immersion, surface and air temperature measurement, and we supply a large diversity of quality instruments for measuring and controlling temperature.

Ultra-Precision Metrology & Engineering

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