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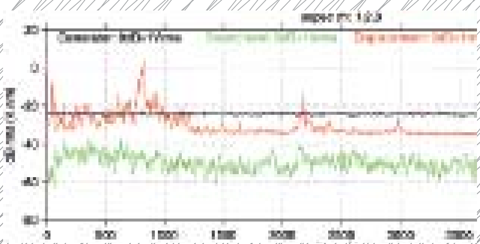
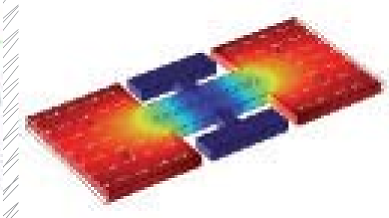
- MICROPRECISION IN THE **EYE**
- MORE THAN **BALL BEARINGS**
- DISTURBING **SOUNDS**
- FEM OF **MEMS RESONATORS**





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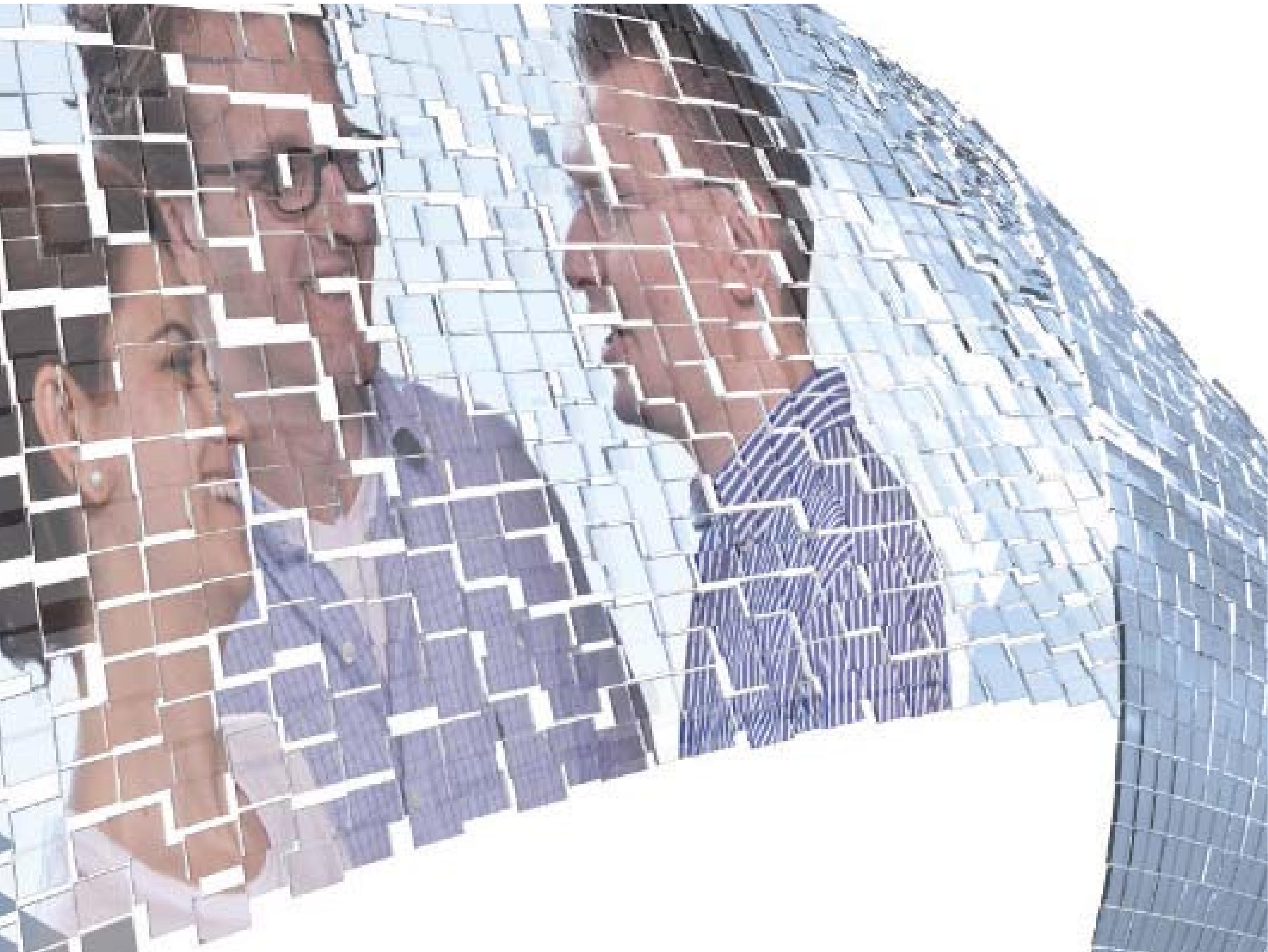

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The main cover photo (the PRECEYES Surgical System) is courtesy of Bart van Overbeeke.

IN THIS ISSUE

ISSUE 2014 1

FEATURES

EUROPE-WIDE CERTIFICATION OF PRECISION ENGINEERS

In the Netherlands, DSPE has taken the initiative to set up a certification method to ensure that relevant post-academic courses lead to certification of precision engineers. This initiative is well appreciated by course providers, precision engineers and the companies employing them. In 2013, the milestone of handing out the 1,000th certificate was reached.

Why is such a certification method important?
The technology fields that are essential to know and apply to make advancements in precision engineering are rapidly developing. Post-academic courses that provide state-of-the-art technology knowledge, by excellent 'teachers', are therefore needed.

For the engineers taking (or considering) a course, it is beneficial if they can present proof that they have followed (or are asking to go to!) a relevant course of high quality to their employer. For the employers, it is beneficial to know that such a course is deemed relevant for the practising precision engineer (that's part of the certification process) and given by effective and state-of-the-art experts and professors in that particular field. For the course providers, certification means recognition for the quality level of the course, allowing them to distinguish themselves from the course providing crowd.

Taking it to European level
In 2013, the European Society of Precision Engineering (euspen) discussed the DSPE approach and concluded that a similar certification program could also be relevant and beneficial at the European level. As a result, an initiative has started to bring a similar certification method in place over countries in the EU. The DSPE method is taken as 'template' for the European program wherever possible. However, Europe consists of quite some countries with different languages, laws, and ways to organise universities and post-academic teaching programs. In addition, not every country has an obvious 'DSPE equivalent', and finally an extensive network of experts at European companies needs to be built to support the certification process. All in all, this is going to be a long journey, but the first discussions have started.

Next steps include identifying and setting up national certification organisations and/or a European certification organisation and networks of industry experts that can advise on course content quality and industrial relevance throughout Europe. Decisions to admit courses to the certified course program might be taken by the euspen education section of the euspen council (board) based upon proposal and assessment by the national and/or European organisations.

In developing the approach, euspen plans to stay in close contact with DSPE and both organisations will work to align the existing DSPE certification method and also to ensure that the existing DSPE certificates will be recognised then as European certificates as well.

Jelm Franse
Senior director Mechanical Development, ASML, and council member, euspen

BRINGING MICROPRECISION TO MICROSURGERY

Experienced eye surgeons who are fifty years old and up are sometimes forced to stop performing vitreo-retinal eye surgery because of the increasing tremors in their hands. Using PRECEYES Medical Robotics' innovative precision surgical tool can, however, minimise these unwanted hand tremors, allowing surgeons to continue in their profession for as long as they like. It also enables surgeons to perform eye surgery that was impossible to do up to now, i.e. injecting medicine into affected veins with micrometer precision.

FRANS ZUURVEEN

PRECEYES Medical Robotics

In 2011, Thijs Meenink acquired his doctorate with a dissertation called "Vitreo-retinal eye surgery robot: sustainable precision". He studied under Maarten Steinbuch, head of the Control Systems Technology Group of Eindhoven University of Technology's Department of Mechanical Engineering, and together with fellow graduates Gerrit Naus and Maarten Beelen he started PRECEYES Medical Robotics. His aim was to further develop his robot technology and transform it into a practical surgical instrument (see Figure 1).

1 *Thijs Meenink and the PRECEYES Surgical System.*

Today, their company receives financial support from – among other sources – Technology Foundation STW. Meenink, Naus and Beelen are looking for partners to help manufacture and market their product. Successful animal testing has already been performed and actual surgery of the human eye using the medical-approved product is planned for 2016.

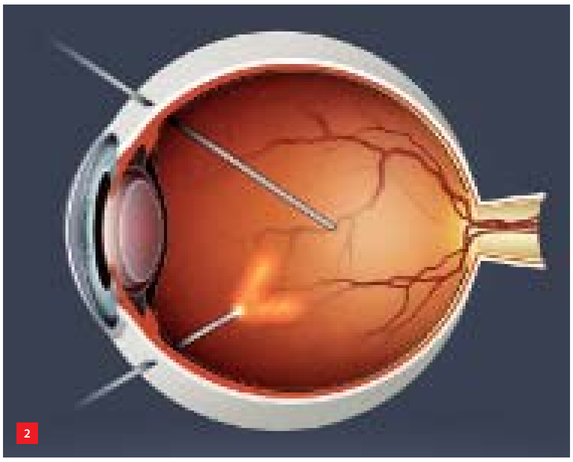
WWW.PRECEYES.NL

AUTHOR'S NOTE

Frans Zuurveen is a freelance text writer who lives in Vlissingen, the Netherlands.

Surgery at the anterior segment of the eye mostly aims to treat a cataract by replacing a problematic lens with an artificial lens. This solves sight issues for millions of people every year.

In general, operations in the posterior segment of the eye, called vitreo-retinal surgery, are more challenging. This type of surgery tries to solve problems in the vitreous humour and at the retina, with the macula as the most delicate area. Such surgery is performed in a minimally-invasive way, which is why a surgeon enters the eye through an extremely small opening in the sclera, the protective outer layer of the eye. Instruments can then enter the eye through such an opening (see Figure 2), usually by inserting a thin tube, known as a trocar or cannula. The needle-like instruments have a diameter smaller than 0.6 mm. D.O.R.C. (Dutch Ophthalmic Research Centre) [1] provides such instruments, e.g. forceps, scissors, trocars, etc. (see Figure 3).



2 *Surgical instruments entering the vitreous humour of the eye through small openings in the sclera.*

3 *A surgical forceps of gauge 23, i.e. outside diameter 0.4 mm, from the D.O.R.C. delivery programme.*

4 *Vitreo-retinal eye surgery. The surgeon looks into the patient's eye through a microscope. For better stability, they put their hands on the patient's forehead.*

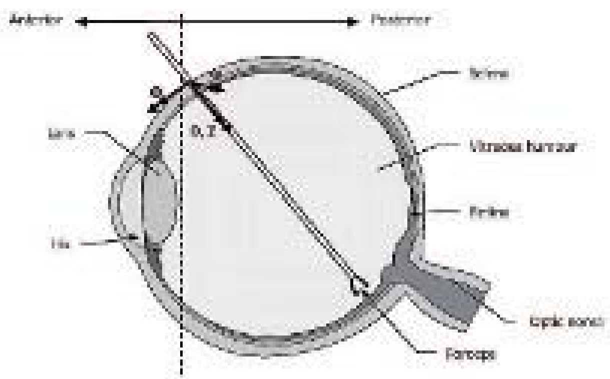
Vitreo-retinal procedures treat disorders such as retinal detachments, vitreous haemorrhages (bleedings) and several retinal pathologies, including holes in the macula and the unwanted formation of membranes. Human manual precision is 100 μm at best and this decreases as people get older. Furthermore, this precision is hardly sufficient for such operations. An even higher precision would be required for several vitreo-retinal disorders that currently cannot be treated. One example is surgery of retinal vein occlusions, which could be treated by directly injecting medicine into the affected vein, which has a diameter of between 10 and 100 μm. This is practically impossible to do by hand. As such, it has been impossible for conventional surgery to treat retinal vein occlusions until now. The PRECEYES Surgical System will solve this problem by assisting the surgeon and providing a precision that is 10 to 20 times higher.

Figure 4 gives an example of vitreo-retinal eye surgery. Aided by low-magnification binoculars, the surgeon looks into the patient's eye through the eye lens. Two or three trocars are placed in the sclera: one or two for ophthalmic tools and one for an illuminating device. Besides a miniature forceps, the surgeon can also use a vitrectome, which cuts the more or less liquid vitreous humour and sucks it away. For better stability, the surgeon puts his hands on the patient's forehead, maintaining the position of the tool with respect to the head.

Four degrees of freedom

The above explains that the main reason for designing an assistant for vitreo-retinal surgery is to improve the positional steadiness of the operating tool with respect to the patient's eye, i.e. improving the surgical precision. All the tool's movements share a single motionless point. This is the point where the tool enters the eye, i.e. the trocar in the sclera. Figure 5 illustrates the degrees of freedom (DoFs) required to reach the relevant part of the inner eye volume with a tool tip: rotations φ, ψ and θ, and translation z. The manipulation of the instrument tip, e.g. the gripping motion of a forceps, can be considered as a fifth DoF. Figure 6 shows a tool tip in a dummy eye.

Figure 7 shows the instrument manipulator, which performs the movements of the ophthalmic tool according to the above-mentioned four DoFs. The mechanism is a double parallelogram linkage system (see Figure 8). For the φ rotation, the complete linkage system moves around the stationary φ shaft, indicated in Figure 7a. The ψ rotation occurs when an oblique rod connecting points A and E in Figure 8 is being changed in length. This rod is shown in Figure 7.



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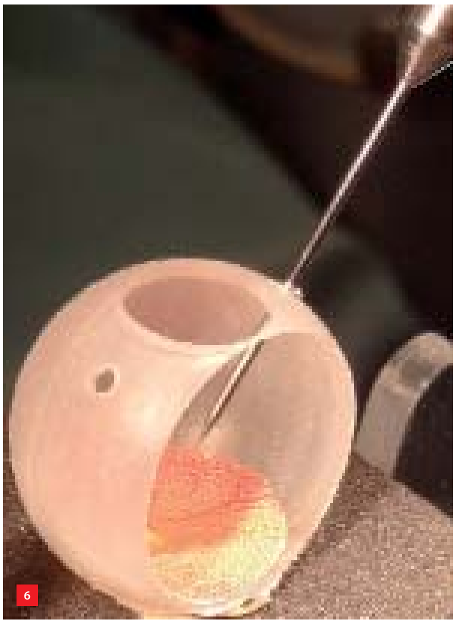

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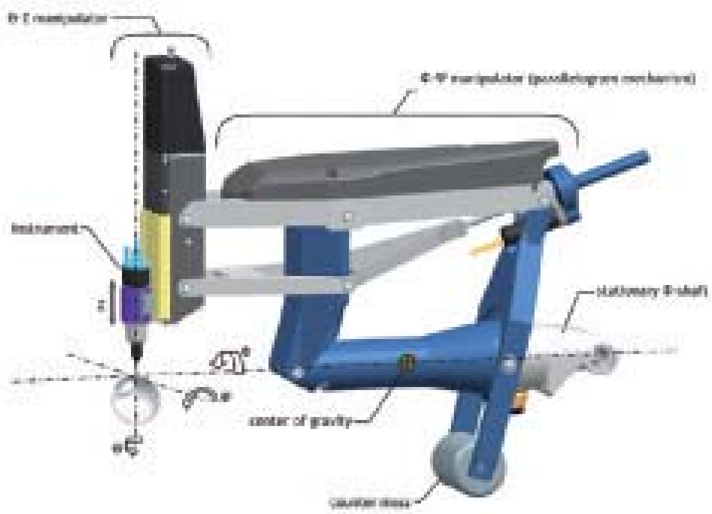
- **5** *The DoFs necessary to reach the most important part of the inner eye with a tool tip.*
- **6** *An ophthalmic tool tip in a dummy eye.*
- **7** *The instrument manipulator.*
  - (a) *CAD drawing.*
  - (b) *Picture of prototype.*
- **8** *Schematic drawing of the linkage mechanism of Figure 7. The φ rotation on the left, the ψ rotation on the right.*

The linear DoF z and the rotational DoF θ are integrated in the linkage rod CD of Figure 8 (see Figure 9). Besides the four above-mentioned DoFs, the assisting system needs another three linear DoFs. That's because the linkage mechanism shown in Figure 7 has to be positioned in such a way that the relevant point P in Figure 8 coincides with the appropriate trocar in the eye being operated on.



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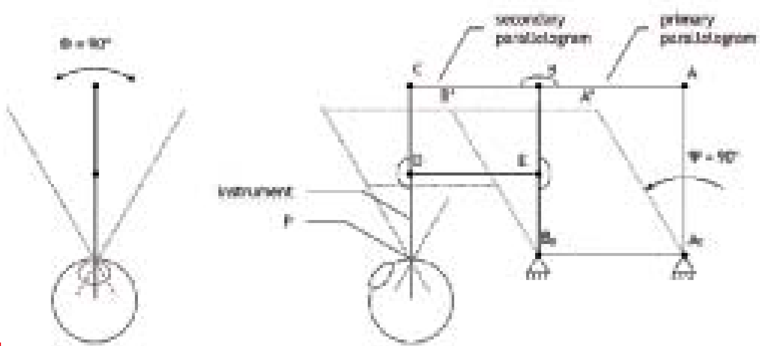

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Therefore, this linkage mechanism is mounted on a separate XYZ stage, partly visible in Figure 7b. All pivot points and moving rods are provided with encoders and actuators.

The motion controller

Figure 10 illustrates how a surgeon uses a motion controller to manipulate the ophthalmic tool in the instrument manipulator, according to the master-slave principle. A push button has to be engaged to make the instrument manipulator move. Figure 11 shows three rotational axes

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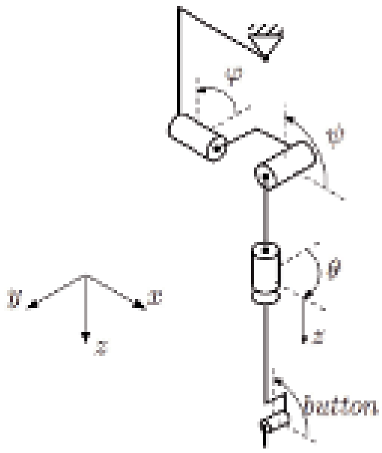
11a

and one linear guide in the motion controller, which each correspond to a DoF in the manipulator. In each of them, an angular or linear encoder, together with a transducer is incorporated.

These encoders measure the movement of each joint of the motion controller. This motion signal is filtered, position-scaled and subsequently used as a reference signal for the accompanying DoF of the instrument manipulator. At the instrument manipulator, the position of each DoF is also measured using encoders. This position is used in a feedback control loop, which ensures that the manipulator tracks the reference signal of the motion controller, by generating actuator forces.

9 *Practical realisation of the degrees of freedom z and θ.*
10 *Manipulating the ophthalmic tool via the motion controller.*
11 *The motion controller.*
(a) CAD drawing with the corresponding DoFs in the manipulator of Figure 7a.
(b) Schematic.

11b



Mechanical design

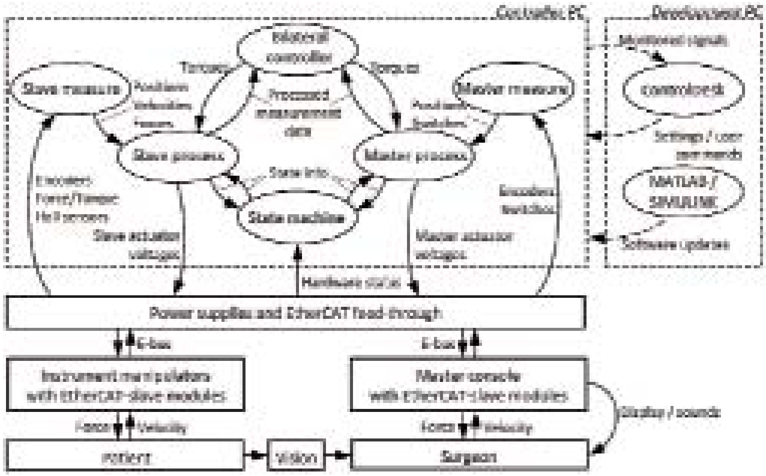
The starting point was to design a mechanism with low inertia, high stiffness, low friction and zero backlash. Low inertia and high stiffness have been realised by designing thin-walled components from aluminium with an outside diameter as large as practically possible. This resulted in a total manipulator and controller mass of about 800 g, including a mass of 500 g for the counterweight. As such, tungsten carbide was selected because of its high specific density.

Low friction and zero backlash could be attained by selecting pre-tensioned ball bearings for the pivot points. For the linear drives, pre-tensioned nut-screw combinations were applied. Backlash-free drives were the result of applying frameless and brushless DC servomotors glued inside their housing. The motors were placed as near to the rotation point as possible to make the drive extremely stiff.

The manipulator is connected to the XYZ stage, via the hinge in point A_0 of Figure 8 and a safety pawl in B_0, visible in the lower left of Figure 7b. In case of emergency (e.g. power failure, surgeon warning, extreme patient movement detection), the pawl disengages, making the manipulator move away. As a result, the tool retracts without damaging the sclera, thanks to a rotation of the manipulator around the hinge, visible in the lower right of Figure 7b.

Software architecture

Figure 12 provides a schematic overview of the software system. The EtherCAT protocol has been adopted for communication between the hardware devices and the controlling PC. The electronic controlling modules are integrated into the upper link of the manipulator (see Figure 7b) including signal pre- and post-processing units and motor amplifiers. This local signal processing minimises wiring and ensures that analogue signals do not have to be transmitted over long distances.
The controlling PC runs at 1 kHz in real time. The figure illustrates the control software architecture with post-processing of measurements performed by the manipulator and the controller. Motor currents, velocities and voltages



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12 *Schematic overview of the software system.*

are being monitored with well-defined safety levels. The software includes error handling and safety procedures in case of failure, which ensures that the system is operated safely at all times.

The software also includes a weight-compensation algorithm for the motion controller, force and position scaling and hand tremor filtering. A force signal based on a virtual spring is also transmitted to the controller to alert the user when the instrument manipulator reaches the limits of its workspace.

To conclude

Tests have been executed on membranes in chicken eggs and on dead and living pig eyes, both of which are rather similar to human eyes. The tests proved the functionality and the added value of the high-precision PRECEYES Surgical System. It has clearly been shown that this innovative assistant allows the surgeon to manipulate their surgical instruments with an intrinsic accuracy of 10 μm in an intuitive and comfortable way. ■

REFERENCE

[1] F. Zuurveen, "Microchirurgie in het oog", *Mikroniek* Vol. 46(2), pp. 11-15, 2006.

SPECIAL MATERIALS MOVE ON

Despite the innovative power of additive manufacturing, the 2013 Precision Fair showed that the vast majority of precision products are still being made by conventional machining methods: chipping material from solid. Even the chipless technology of casting seems to be losing some of its significance. It was also clear that precision equipment designers are increasingly relying on the special properties of high-tech materials such as titanium alloys, engineering plastics and ceramics.

AUTHOR'S NOTE

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FRANS ZUURVEEN

In the 1970s, titanium emerged as a promising engineering material. At that time, a simple slogan said that titanium combines the lightness of aluminium with the strength and stiffness of steel. Closer observation reveals, however, that titanium's specific gravity is about 60% of the specific gravity of steel, but still 1.7 times higher than the specific gravity of aluminium. Indeed, Young's modulus of titanium is 1.5 times higher than that of aluminium, but nevertheless about half the Young's modulus of steel.

1 *A combination of ten different bicycle sprocket wheels made of titanium by ZME.*

Titanium on show

Today, the excellent mechanical properties of titanium alloys are the main reason for their application in the aviation industry. In some respects, this may be regarded as precision technology, but it was not on display at this Precision Fair, however. Applications of titanium that were on show could generally be split into corrosion and chemical resistance on one side, and excellent behaviour in vacuum on the other. This last property is due to the homogeneity of the crystal lattice, which results in lower hydrogen permeation and secondary gassing.

For a long time now, the rather poor machinability of titanium alloys has been considered a drawback for their application. But this fair showed that technological experts have succeeded in overcoming this by modifying machining conditions. Precision engineering studio ZME in Utrecht had a bicycle pinion combination made of titanium on display. Their piece integrates ten different sprocket wheels (see Figure 1). ZME is proud of its latest acquisition, a Swiss-made Willemin Macodel 508 MT machining centre with a working area of 450 x 250 x 425 mm^3. The speed of the milling spindle of this machining centre is 42,000 rpm; the workshop is temperature-controlled, of course. ZME precision products are inspected using a Mitutoyo non-contact Laser Scan Micrometer.

Jeveka exhibited special fasteners for high-vacuum applications made of titanium alloy TiAl6V4 (see Figure 2). What makes these fasteners unique are the extra holes for outgassing and the special surface treatment. Besides

2 *Jeveka high-vacuum fasteners machined from titanium alloy TiAl6V4.*
3 *Precision products from PEEK, machined from solid by Vd Berg Kunststofbewerking.*
4 *An X-ray fluorescence assembly made for PANalytical by the Nijdra Group.*

cleaning, this treatment includes electro-polishing and kolsterising, a process named after inventor Ben H. Kolster. This process introduces carbon atoms into a surface without any dimensional change.

Non-metallic materials

PEEK (polyether ether ketone, or Ketron) and PAI (polyamide-imide, or Torlon) are some of the modern engineering plastics whose mechanical, chemical and thermal properties often allow them to be used to replace metals. They can be applied at temperatures up to 250 °C and are stronger and stiffer than common or garden-variety plastics such as polystyrene. Their Young's modulus is about 5% of that of aluminium.

Vd Berg Kunststofbewerking exhibited precision products machined from solid PEEK for ASML (see Figure 3). PEEK was chosen because of the heat resistance and low levels of gassing. The usual process of injection moulding could not be applied because of the extreme precision required.
Vd Berg also succeeded in solving the problems associated with machining a fragile product like the one shown below left in Figure 3. Special measures were taken to minimise deformation by cutting forces.

Other non-metallic materials used for precision products are ceramics. They are stiffer than plastics, of course, with a Young's modulus in compression comparable to that of steel. The well-known drawback associated with them is that tensile stresses should be limited.

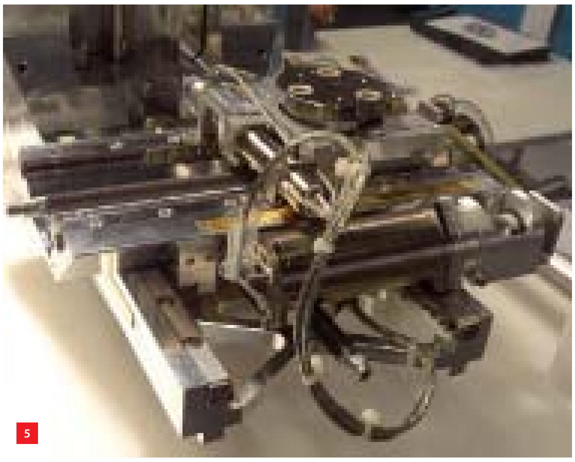
Some exhibitor stands featured the use of ceramics in precision products. FRIATEC Technische Keramiek is part of FRIATEC AG in Mannheim. It produces several kinds of ceramics: aluminium oxide, zircon oxide, silicon nitride and silicon carbide, and products made from these base materials. Ceratec Technical Ceramics does not produce these base materials as such, but precision parts machined from them, including bearings for pumps transporting highly abrasive fluids. Formatec Ceramics also produces ceramic parts, not by grinding but by an injection moulding process. Once a mixture of plastic and ceramic powder has been injected into a tool, the plastic is burnt away in a subsequent sintering step.

Machining metals

As usual, many firms with high-precision workshops showed their skills in producing metallic parts. Figure 4 features an X-ray fluorescence assembly for PANalytical which was made entirely by the Nijdra Group [1]. Nijdra not only produces all of the components, it also takes care of the complete assembly and mechanical testing. What is remarkable is the precision journal bearing which has a clearance of only 1 µm.

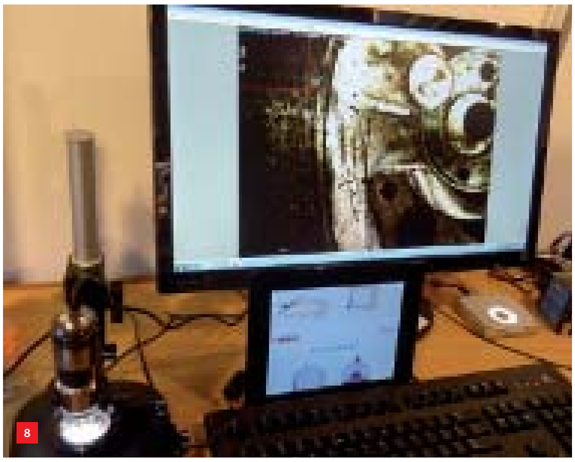
Another precision assembly is a specimen stage, made and co-engineered by Frencken Engineering (see Figure 5). This stage is an important part of a Scanning Electron Microscope (SEM), developed and marketed by FEI. Besides having three linear degrees of freedom, the stage provides specimen tilt and rotation.

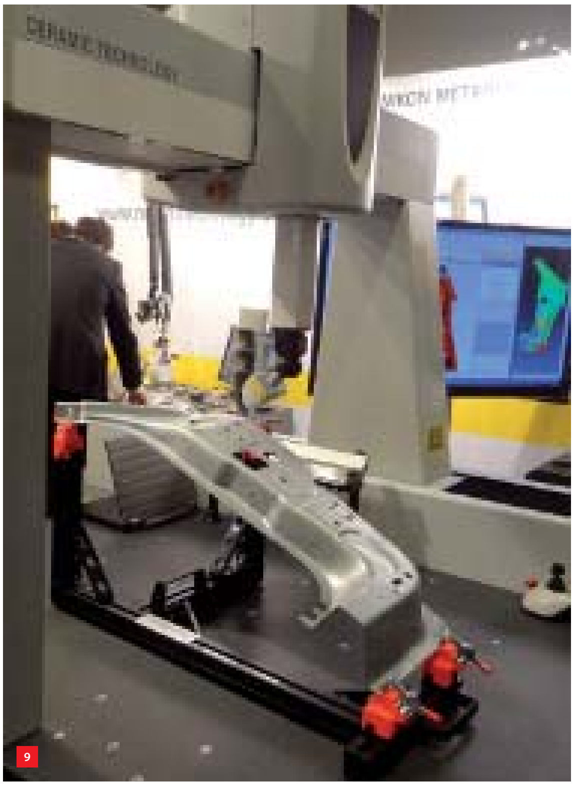
Botech, a renowned supplier of granite precision parts, recently became part of the NTS-Group, which designs (opto-)mechatronic systems. Figure 6 features a display of mechatronic components on a Botech granite base plate.



5 An SEM specimen stage made and assembled by Frencken Engineering for FEI.

6 An intricate assembly of NTS mechatronic components on a Botech granite base plate.





7 Precision bearings from the Rodriguez delivery programme.

8 The Dino-Lite digital microscope, marketed by Schut Geometrische Meettechniek.

9 The Nikon Altera 15.10.8 CMM. The deviations (with respect to CAD data) of the real product that is being measured are displayed on the right.

Rodriguez specialises in the production of thin cross-sectioned precision ball bearings in large diameters (see Figure 7). These components never form a standard solution for bearing problems, but are the result of ample customer consultation.

Stolle Nederland provides large – cast or welded – base plates for machines. Stolle recently acquired a Mikromat 20V machining centre. This precision milling machine has a working area of 5,700 x 2,650 x 1,950 mm^3 and an accuracy of 10 μm in the complete range.

Precision measuring

No precision products can be made without accurate measuring. Many well-known measuring machine suppliers presented their large coordinate measuring machines (CMMs), such as the Nikon Altera 15.10.8 (see Figure 8). Nikon Metrology claims to be the only manufacturer to guarantee the accuracy of its CMMs for ten years.

At the opposite end of the spectrum to this large CMM with an X stroke of 1,500 mm is the Dino-Lite digital microscope (see Figure 9), exhibited by Schut Geometrische Meettechniek. A USB cable conveys the 5 MB image to a PC. The DinoCapture software then facilitates the measuring of product details in this image.

Another small but very practical measuring tool is the Mahr MarCal wireless calliper (see Figure 10). It is quite an

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10 *A Mahr MarCal wireless calliper.*

Concluding message from the organisation

The 13th Precision Fair organised by Mikrocentrum in the Koningshof in Veldhoven on 3 and 4 December 2013 attracted 275 exhibitors and a record number of more than 4,000 visitors, 12% more than in 2012. More than 10% of the visitors were from outside the Netherlands, with special delegations from Germany, Switzerland and Sweden.

Big Science

A large delegation from CERN gave a series of presentations to highlight the business opportunities the organisation has to offer. The Netherlands invests €39 million in CERN every year, the idea behind which is that a large part of the money will be reinjected into Dutch industry in the form of orders and knowledge and technology transfer. However, in reality, this is not happening.

There are massive opportunities now available because of the overhaul to the LHC (the Large Hadron Collider with which the Higgs particle was discovered) and the development and construction of the new CLIC (Compact Linear Collider). Another example of this promising Big Science presented at the Precision Fair is ESS (European Spallation Source), a new neutron microscope in the Swedish city of Lund. The institute is going to invest €1.8 billion to have this built by 2020 or thereabouts. There are opportunities in this area as well for high-tech companies that can meet the ESS specifications.

Conference programme

The conference programme for the Precision Fair included 18 keynote speakers and 42 exhibitor presentations. The keynote tracks dedicated to CERN, ESS and the roadmap Advanced Instrumentation of the Dutch top economic sector High Tech Systems and Materials addressed new business.

The main focus on the second day of the fair was on the developments in Additive Manufacturing for precision engineering. ASML, TNO and Fraunhofer ILT gave presentations on this. The afternoon was set aside for euspen (European Society for Precision Engineering and Nanotechnology). Exhibitor presentations on topics such as micromachining, engineering, motion control and measuring were also part of the programme. Presentations can be downloaded from the website, www.precisiebeurs.nl/programma.

The next Mikrocentrum Precision Fair will be held on 12 and 13 November 2014.

WWW.PRECISIEBEURS.NL

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achievement to accommodate a digital measuring scale as well as a signal emitter in an extremely small space.

Another very interesting and helpful tool is the Faro Laser Tracker (see Figure 11). With no contact, the base instrument measures the distance to an SMR (spherically mounted retroreflector) by emitting laser pulses and determining the time required to cover the distance to the SMR and back. For that purpose, the SMR houses an orthogonal prism, which reflects incoming light in exactly the same direction. Another Faro product is the Laser Scanner, which directly images its surroundings, i.e. without an SMR. In this image, large distances can be determined to an accuracy of about 2 mm. This is not as precise as the accuracy of the Laser Tracker, which can reach 15 µm.

Miscellaneous

Houmaro proudly calls itself a “Total Tooling Provider”. It specialises in helping customers resolve their milling problems. Besides a rotational accuracy of a few micrometers, the Houmaro milling tools, diamond ground from tungsten carbide, are modified in such a way that burring is minimised or even eradicated (see Figure 12). Houmaro tools also reduce chatter, with higher workpiece accuracy as an obvious result.

11 The Faro Laser Tracker contact-free measuring system.

12 A milling tool, diamond ground from tungsten carbide by Houmaro.

13 A diamond wheel for grinding LCD glass, produced by Mintres. Below a detail is shown.

Mintres specialises in magnetron sputtering and manufacturing diamond and ceramic products for thermal management. What is of more interest to precision technologists is the company’s patented production of scribing wheels for LCD glass (see Figure 13).

With a demonstration of no-glasses 3D television, precision technology was also on display at the Tegema stand. Tegema develops products, processes and systems, from idea to prototype or pre-production series. It helps SeeCubic by micro-positioning and bonding a stack of layers of refractive and diffractive optical elements onto a liquid-crystal display. The SeeCubic 3D system works by directing the light of individual sub-pixels from the LCD screen into space, thereby generating virtual pixels which form a complete view for each eye of the viewer.

Technology Hotspot

The Technology Hotspot once again gave students from various educational institutes the opportunity to show off their burgeoning skills in the application of precision mechanics. A good example is a pick & place system with stepping motors developed by enthusiastic students from the HU University of Applied Sciences Utrecht (see Figure 14). It was great to see that young people do not regret deciding to study the sciences and/or engineering; this bodes well for the future of precision technology in the Netherlands. ■

REFERENCE

[1] F. Zuurveen, "Mastering X-ray diffraction and fluorescence", *Mikroniek* Vol. 53 (3), pp. 26-31, 2013.

14 *A pick & place system with stepping motors developed by students from the HU University of Applied Sciences Utrecht.*

Interest from Vietnam

Among the international visitors to the 2013 Precision Fair was a delegation from Vietnam, headed by the deputy minister of Industry and Trade, Le Duong Quang. He was in the Netherlands to attend the 18th Session of the Conference of States Parties of the OPCW (Organisation for the Prohibition of Chemical Weapons), which was held in The Hague. Taking Vietnam's extreme interest in the high-tech industry, Mr Quang decided to attend the fair even though it was not part of his official schedule.

Vietnam has long been a high-growth country in South East Asia. The mechanical engineering industry is currently booming and very dynamic, which is attracting a lot of foreign investment. This has resulted in a demand for advanced machines (especially machine tools), technological solutions and knowledge transfer.

At the Precision Fair, the deputy minister was impressed by the advanced level of Dutch precision engineering and he revealed his interest in cooperation between Vietnam and the Netherlands for this industry and other high-tech related industries. He met with DSPE president Hans Krikhaar to discuss collaboration opportunities. The meeting was organised by NBI International (partner for Nation Branding & Investment), represented by Chris Aelberts, Director, and Yen Nguyen, Vietnam Business Unit Manager, in cooperation with the Vietnamese Embassy in the Netherlands, represented by Nguyen Hai Tinh, Commercial Counsellor; see Figure 15.

Options that were discussed included an introductory seminar, for example during the NBI Expo in Eindhoven, the Netherlands, 6 to 8 May 2014, and international business assistance for DSPE members, aimed at Vietnam to begin with.

15 *Meeting at the Precision Fair, from left to right Yen Nguyen and Chris Aelberts (NBI International), Le Duong Quang (deputy minister, Vietnam), Hans Krikhaar (DSPE) and Nguyen Hai Tinh (Vietnamese Embassy in the Netherlands). (Photo: Jan Pasman)*

SENIOR AND JUNIOR **TALENT IN THE SPOTLIGHT**

During the 2013 Precision Fair (see the preceeding article), two awards were handed out under the auspices of DSPE. Henny Spaan received the Rien Koster Award for his work in precision engineering as a scientist, designer and entrepreneur. Marc Janssens received the Wim van der Hoek Award for the meticulous and practical graduation project he did at ASML Research Mechatronics.

The Rien Koster Award is given to a mechatronics engineer/designer who has made a significant contribution to the field of mechatronics and precision engineering. The award was handed out for the sixth time on Tuesday, 3 December. On this occasion, the focus was on measuring: without precision measuring, a precision design cannot be realised. On behalf of the jury chaired by Ton Peijnenburg, Manager Advanced Developments at VDL ETG, Rien Koster, after whom the award was named, presented the award to Henny Spaan, founder and director of IBS Precision Engineering (see Figure 1).

Measurement technology

Henny Spaan graduated from Eindhoven University of Technology with a measurement technology project. He went on to do doctoral research into improving the precision of a milling machine by way of software

1 *Henny Spaan (right) receiving the Rien Koster Award from the award's namesake. (Photo: Jan Pasman/Mikrocentrum)*

compensation. He then founded IBS to market this software compensation. His company was originally located in offices of Eindhoven University of Technology, but moved to Best in 1998 and settled in Eindhoven in 2004. Using milling machine software as a starting point, he developed software for measuring machines. This led to him developing and producing complete measuring machines, as a result of which the engineering agency IBS has grown into a manufacturer of extremely precise measuring machines.

Enterprising

The jury valued the close collaboration with knowledge institutes and measurement institutes in the Netherlands and abroad that Henny Spaan seeks when developing concepts for top-end measuring machines and calibration tools. Spaan's enterprising spirit also provides work opportunities at IBS as well as work for a large number of suppliers. Finally, the jury set great store by Spaan's evident professionalism and commitment. He was a co-initiator of the Precision Fair, plus he was actively involved in euspen (European Society for Precision Engineering and Nanotechnology) for many years. As the president of euspen from 2009 until 2011, he put a lot of effort into bringing precision engineering professionals closer together. The jury felt it was only right to give the Rien Koster Award to this versatile practitioner of precision engineering for his work as a scientist, designer and entrepreneur.

The importance of designing

With its Rien Koster Award, DSPE wants to highlight the importance of designing to the precision industry. Globally, the Netherlands plays a leading role in this industry, which in broader terms can be dubbed 'the high-tech systems' sector. As a group leader at Philips CFT (Centrum voor Fabricagetechnologie [Centre for Manufacturing Technology]) and professor at the University of Twente, the award's namesake M.P. (Rien) Koster has made a major contribution to the Netherlands' position in this sector. Koster is also the author of the renowned book "Constructieprincipes voor het nauwkeurig bewegen en positioneren" [Construction principles for precision movement and positioning)]. The Rien Koster Award comprises a sum of money, made available by The High Tech Institute, and a trophy made by students of the Leidse instrumentmakers School (LiS).

Design engineering award

The following day, on Wednesday, 4 December, jury chairman and DSPE board member, Jos Gunsing (lecturer in Mechatronics at the Avans University of Applied Sciences in Breda and technology innovator at Marome-Tech in Nijmegen), presented the Wim van der Hoek Award. This award (also known as the Constructors

2 *Marc Janssens, winner of the 2013 Wim van der Hoek Award. (Photo: Frans Zuurveen)*

Award) was introduced in 2006 to mark the 80th birthday of the doyen of design engineering principles Wim van der Hoek. The design engineering award is presented every year to the person with the best graduation project in the field of design in mechanical engineering at one of the three universities of technology. This award includes a certificate, a trophy made by LiS and a sum of money (sponsored by the 3TU Centre of Competence High Tech Systems).

Meticulous design and a practical test

The 2013 Wim van der Hoek Award went to Marc Janssens, who graduated in Mechanical Engineering from Eindhoven University of Technology (see Figure 2). He did his graduation project entitled "Design of a short stroke reluctance actuator support structure for WS450" at ASML Research Mechatronics in Veldhoven. This project concerned the suspension of an actuator (brake), focusing primarily on absorbing the impact forces using a mechanism onto which a stator had been fixed. Janssens' work concentrated mainly on the statically determined design of the construction and optimisation of its frequencies. He also spent the requisite time on the thermal aspects in conjunction with the dissipation of impact energy, and the lifespan of the system. The jury praised the meticulous design and the fact that Marc not only created the design on paper, but also built a prototype to actually test the actuator. ■

DISTURBING SOUNDS

With its micro/nanometer precision specifications, precision engineering equipment is sensitive to internal and external disturbances. We will present a measurement method to quantify the acoustic vibration sensitivity of a precision positioning system. The frequency-dependent behaviour of the system as well as the expected nonlinearities are good reasons to use filtered white noise as an excitation signal.

ASMA QADIR AND PIETER NUIJ

With its micro/nanometer precision specifications, precision engineering equipment is sensitive to internal and external disturbances. Internal disturbances can include reaction forces, electromagnetic fields, heat, etc. External disturbances can be floor vibrations, magnetic field interference, temperature variations and pressure surges in the environment due to sound.

Air pressure variation can be responsible for significant levels of undesired displacement in high-precision machinery. High-level air pressure variation produces sound or acoustic disturbances, which leads to a displacement in flexible systems characterised by internal stiffness and damping.

Pressure x *dA = Force*

Force / Stiffness = Displacement

The acoustic error budget for precision machinery may very well be in the order of nanometers. Very small excitation levels are sufficient to produce the prescribed level of response. However, in order to allow for a reliable analysis of acoustic excitation influence, it should be the main source of excitation in the system, resulting in a required test level which could drive the system well over the prescribed maximum response limit. Therefore, to draw conclusions about the sound pressure level being sufficient to produce the limit response level, results need to be extrapolated based on assumptions about system behaviour.

AUTHORS' NOTE

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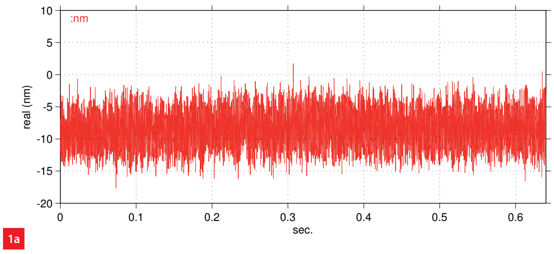
Measurement principle

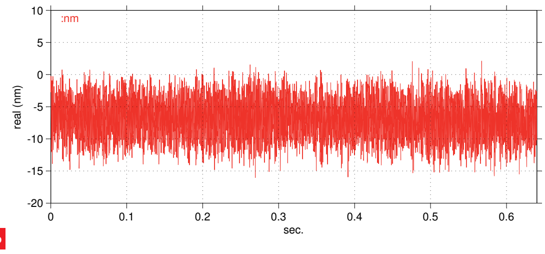
The measurement principle for these acoustic measurements is to drive the system with a known sound pressure level and known frequency content and to measure the response as a function of frequency.

Measurements are to be carried out in nominal operating conditions, with the system running in its fully operational state. That could include activated servo loops, vacuum pumps and any cooling mechanism being fully functional, amongst many other auxiliary systems. As mentioned earlier, reliable conclusions about the error budget and the consequent improvements/changes in the system to mitigate the influence of acoustic excitations can only be drawn if the acoustic excitation influence can be isolated from the other sources of disturbances influencing the system. That condition can be met by driving the system in such a way that the response is observable and can be manipulated or 'switched on/off'.

Furthermore, such an observation can only be expected to be made for signals displayed in the frequency domain, since time domain signals do not allow for easy separation of the influence of error sources. As an example, Figure 1 shows the time-domain representations of an output signal of a system with and without forced acoustic excitation. Figure 2 shows the corresponding frequency-domain descriptions. Disturbance sources are clearly present but indistinguishable in the time domain. In the frequency domain however, the contribution of the individual error sources can be separated. In Figure 2a, the spectrum clearly shows the presence of several tonal components superimposed on a flat noise spectrum. In Figure 2b, the response to a forced acoustic excitation is clearly visible and can be quantified in this way.



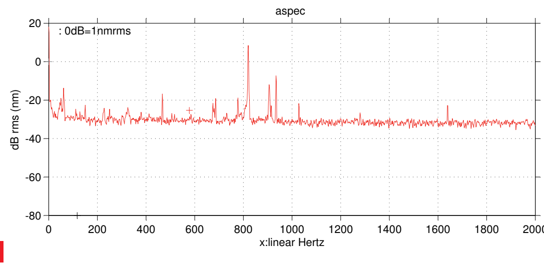
1a



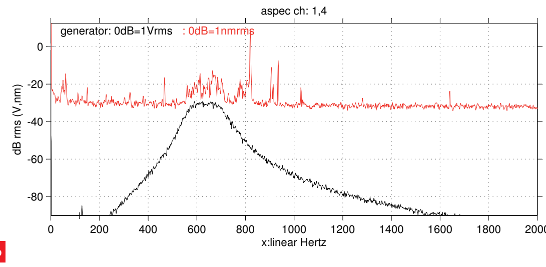
1b

1 *System response in time domain.*
(a) Without forced acoustic excitation.
(b) With forced acoustic excitation.

2 *Spectrum of the system response.*
(a) Without forced acoustic excitation.
(b) With forced acoustic excitation.



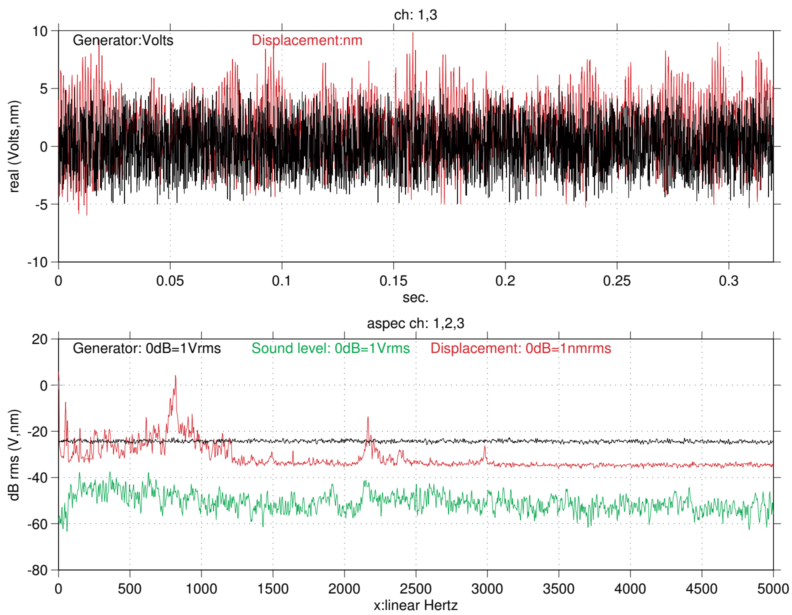
2a



2b

Excitation input

The excitation signal should allow the observation of frequency-dependent behaviour. The input should be able to excite relevant frequencies sufficiently to lead to a response that is observable and distinguishable in terms of frequency ranges of interest. The contributions from different error sources should be distinguishable. In addition, any nonlinearity in the system should be detectable.



3

3 *Response of a model system to an acoustic white-noise input. The upper plot shows the time domain, while the lower plot shows the spectra. It is difficult to distinguish between vibration response due to acoustic white-noise excitation and response due to other vibration sources.*

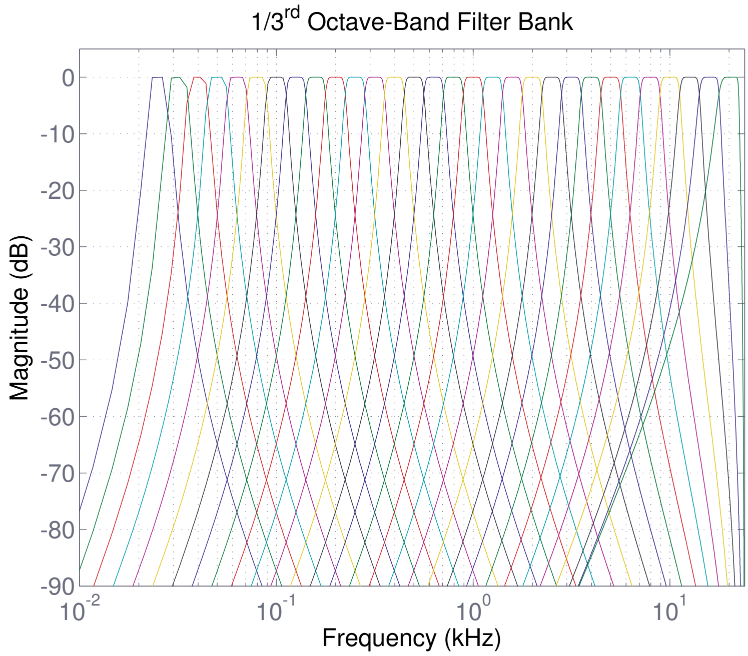
For analytical purposes, the statistical properties of an input signal, e.g. the relationship between peak-to-peak and RMS, or a crest factor, are useful tools that could determine which signal is chosen as input. Several kinds of excitation inputs can be considered for this purpose.

White noise

A white noise signal has a flat power spectrum with the advantage of having known statistical properties. The system response to a white-noise excitation is expected to result in power concentrated in the resonance frequencies of the system (see Figure 3). The contributions from different error sources however, are difficult to separate. What's more, the response will not allow the detection of nonlinear effects, which are characterised by a system response also showing in frequencies not excited by the input disturbance. With uniform excitation over the frequency range, it is not possible to distinguish between nonlinearity influence and excitation influence in the response at a given frequency or frequency range. Moreover, to generate white noise will require compensation of the characteristics of the speakers and the room. An equaliser is also required to make the spectrum flat across the whole frequency range of interest.

Swept sine

Swept sine treats discrete frequency points separately when used as an excitation signal. It will allow for the detection of nonlinearities in the system. The method would be 'sequential' however, moving from one frequency to the next, extending the testing time significantly.



4 One-third octave band filter characteristics.

A very narrow filter (e.g. 1/12th octave) will give a finer frequency resolution, but more time will be required to cover the full frequency range. The one-third octave filtered signal is typically used as a good compromise between frequency resolution and required measurement time.

The corner frequencies of a one-third octave filter can be calculated from:

$$f_{lower} = 0.89 \cdot f^c$$

$$f_{upper} = 1.12 \cdot f^c$$

$$f_{n+1}^c = 2^{1/3} f_n^c$$

Here f_n^c is the centre frequency of the n^{th} filter. ISO has normalised the centre frequency of filter no. 11 to 1,000 Hz, as can be seen in Table 1.

The statistical properties of a one-third octave filtered signal can be shown to resemble those of white noise. This is discussed in more detail while describing the preparation of the excitation signal.

Octave/one-third octave filtered signal

The disadvantage of white noise with respect to its inability to separate the individual contributions of error sources and to indicate nonlinear behaviour, can be remedied by using band-filtered white noise. Common filter shapes are octave and one-third octave filters with a constant-percentage bandwidth. These filters show an equal-pass band when plotted on a logarithmic frequency scale as shown in Figure 4. The power spectrum of this (sub-)octave filtered test signal is flat. The system response outside the excitation frequency band due to the acoustic test signal can be expected to be negligible, except if the system has any nonlinear characteristics, which can then be easily spotted. The measurements in different frequency bands within the full frequency range of interest, can be 'glued' together to represent white-noise characteristics, while allowing for separate excitation at different frequency ranges of interest.

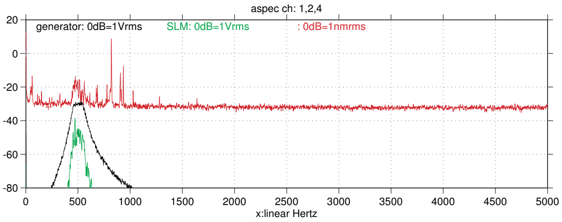
A wide filter (e.g. one octave) will excite a wider frequency range, possibly obscuring the influence of sensitive frequencies spaced close together. In other words, the frequency resolution would be coarser. What's more, with the filter too wide, harmonic components from the response to the lower-frequency components in the excitation signal can interfere with base components from the response to higher-frequency components in the excitation signal, since the filter shape is usually not very steep.

Preparation of excitation signals

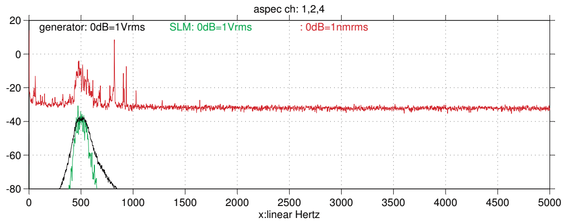
The one-third octave filtered signal is prepared by filtering white noise using one-third octave filters centred at the frequencies present in the ISO standard frequency list (Table 1). White noise can also be filtered by taking the fast Fourier transform (FFT) of its time domain signal and picking out FFT values for the frequencies present in the frequency range of any one-third octave band, followed by an inverse Fourier transform. The resulting time-domain

Table 1. ISO 266 standard centre frequencies for acoustic measurements.

ISO band numbers	Octave band centre frequency [Hz]	One-third octave band centre frequencies [Hz]
1	1.25	
2, 3, 4	2	1.6 .. **2** .. 2.5
5, 6, 7	4	3.15 .. **4** .. 5
8, 9, 10	8	6.3 .. **8** .. 10
11, 12, 13	16	12.5 .. **16** .. 20
14, 15, 16	31.5	25 .. **31.5** .. 40
17, 18, 19	63	50 .. **63** .. 80
20, 21, 22	125	100 .. **125** .. 160
23, 24, 25	250	200 .. **250** .. 315
26, 27, 28	500	400 .. **500** .. 630
29, 30, 31	1,000	800 .. **1,000** .. 1,250
32, 33, 34	2,000	1,600 .. **2,000** .. 2,500
35, 36, 37	4,000	3,150 .. **4,000** .. 5,000
38, 39, 40	8,000	6,300 .. **8,000** .. 10,000
41, 42, 43	16,000	12,500 .. **16,000** .. 20,000



5a



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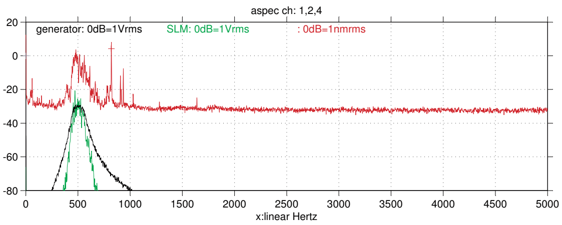


5c

5 *System response spectrum to 500 Hz one-third octave excitation at various sound pressure levels.*
(a) 80 dB.
(b) 90 dB.
(c) 100 dB; the peak at 800 Hz in the response is an indication of a disturbance source other than the acoustic excitation.

signal only contains frequencies present in that particular one-third octave filter. The result, however, will not be a continuous spectrum over the one-third octave frequency range, but a set of discrete frequencies with a non-zero power spectrum at a certain level. Furthermore, each frequency present will have a constant amplitude and phase, independent of time, rendering averaging useless.

System response

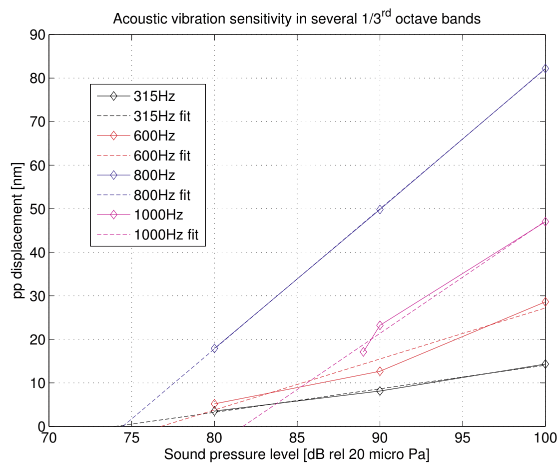
Acoustic error budget for most precision systems is in nanometers. The excitation level leading to the specified disturbance level is also expected to be small. However, actual excitation levels for the purpose of testing and analysis have to be higher than the level required for two reasons:

- The excitation source should be the *main* source causing the measured response while the system is operational.
- The response should be large enough that it can be manipulated or 'switched on/off'.

Figure 5 shows the response of a precision engineering system to acoustic excitation in the 500 Hz one-third octave band at three different excitation levels. There are some interesting features in the response that can be identified.

1. There is a clear peak in the response spectrum in the 500 Hz one-third octave band, indicating the excitation signal has sufficient power to persistently excite the system.
2. The response to the 500 Hz one-third octave acoustic excitation signal is limited to signals in the 500 Hz one-third octave band.
3. Some other peaks can also be seen in the response, e.g. at 800 Hz. These can be attributed to sinusoidal response components due to other vibration sources, which are not correlated to the acoustic excitation. These signals can be dominant in the RMS value computed from the response over the full frequency range. To minimise the influence of these sources, the acoustic signal should be strong. Furthermore, while computing the RMS value of the acoustic response part, the RMS value of the components that are also present when there is no excitation should be subtracted from the integral of the PSD (Power Spectral Density) of the response over the frequency range of excitation.

The results for this excitation level can be extrapolated to nanometer level assuming linear system behaviour. Knowledge of system behaviour is needed to be able to carry out a reliable extrapolation. It has been concluded that since sound pressure level (SPL) is a measure of force acting on the system, the SPL (dB) is proportional to excitation force and thus proportional to displacement. System response to the acoustic disturbance measured as in dBs is therefore expected to be linear with SPL. The system is excited at different SPL levels for one frequency band and the measured response is used to make a reliable extrapolation to small displacement values. Figure 6 shows the extrapolation for the peak-to-peak response to several one-third octave band excitations.



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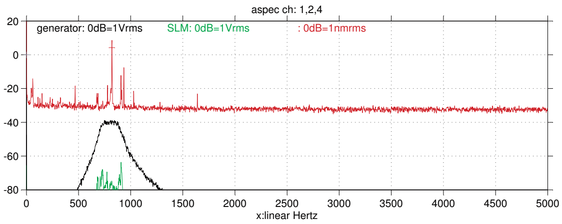
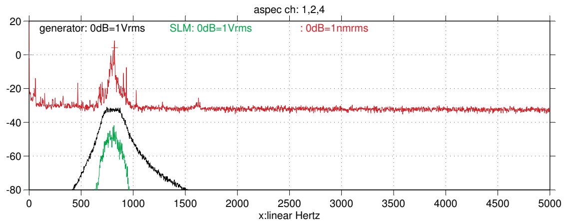
6 *Extrapolation of measured peak-to-peak (pp) values for different frequency bands to get the permissible sound level for the specified performance limit.*



7a



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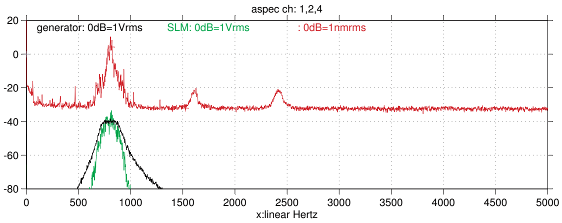

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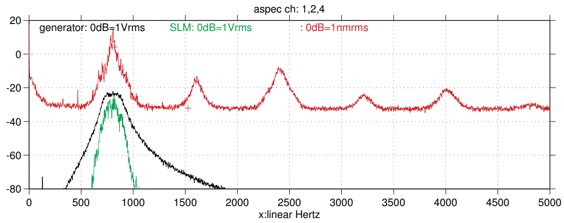


7d

7 *Specific SPL in 800 Hz one-third octave band. Unscaled generator signal in black, unscaled SPL in green, scaled system response in red.*
(a) 55 dB, linear system response.
(b) 80 dB, linear system response.
(c) 90 dB, linear system response.
(d) 100 dB, with harmonics clearly present due to nonlinear system response.

Nonlinear system response

During testing, it is important to remember that the relationship between acoustic excitation and system response may not be linear. The system response consists of the summation of individual responses to many excitations, of which the acoustic excitation is only one component. In Figure 11, an SPL leading to a displacement level of 1 nm increases with frequency except for the 800 Hz one-third octave band. Figure 7 shows the results of the measurements in the 800 Hz one-third octave band. At a background SPL of 55 dB, the system has a clear response in the 800 Hz band, which is not caused by the acoustic excitation. This response will offset the true acoustic responses at elevated SPLs so that the relationship between SPL and displacement becomes nonlinear.

Besides offsets due to non-acoustically induced response signals, the system can exhibit nonlinear behaviour as well. One advantage of using white noise filtered at different frequencies is being able to detect system nonlinearities which will lead to the presence of harmonics in the measured system output. Figure 7 clearly shows the build-up of harmonics in the response, indicating that in the 800 Hz one-third octave band the system is forced into a nonlinear regime during the test.

Statistical properties of bandpass-filtered white noise

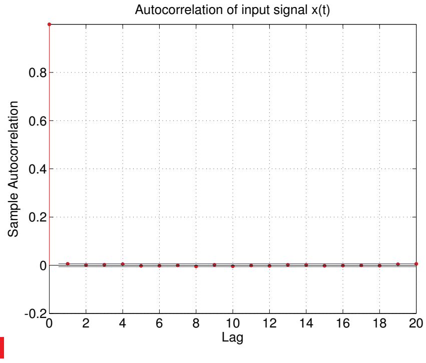
An important point to note about a signal prepared by adding up Gaussian white-noise filtered signals at different frequency ranges is that statistical properties of such a signal remain Gaussian. The power spectral density of such a signal is:

$$PSD_y(\omega) = PSD_x(\omega)\left(H_1(j\omega)^2 + H_2(j\omega)^2 + H_3(j\omega)^2 \ldots\right)$$

Here $PSD_x(\omega)$ is the power spectral density of the input signal $x(t)$ and $H_n(j\omega)$ is the frequency response function of the n^{th} one-third octave filter. The $PSD_y(\omega)$ of output signal $y(t)$ is shaped in contrast to $PSD_x(\omega)$ of the white-noise input signal $x(t)$, resulting in a non-zero time correlation which contrasts with the zero-time correlation of white noise as shown in the autocorrelation plots in Figure 8.

The total of the filtered white-noise signals however results in a signal $y(t)$ which does have a Gaussian amplitude distribution like the white-noise input signal $x(t)$ from which it is derived, as shown in Figure 9.

These results are important when the error criterion due to acoustic excitation is defined in peak-to-peak terms and not in RMS. An RMS to peak-to-peak relationship is then needed to interpret performance specifications in terms of measured results. These relationships vary with the type of signal used. For white noise and one-third octave filtered white noise, the peak-to-peak value is approximately 6σ, for a sinusoid $2\sqrt{2}$ times its RMS value. When you know the peak-to-peak to RMS relationship of one-third octave filtered white noise, you can overcome the apparent disadvantage of this signal compared to white noise or swept sine.



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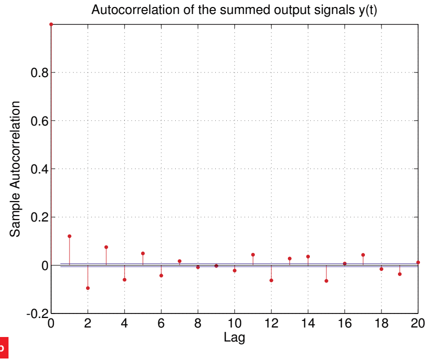


8b

Continuing the discussion above, the same white-noise characteristics can also be observed in the signal obtained by adding the individual responses to such input signals at different frequency bands, as long as the assumption of linearity for the system holds. That way the frequency range of interest can be covered, while making use of the advantage offered by frequency-separated input signals.

Therefore, with output specifications described usually in peak-to-peak terms because this is a more intuitive representation of a signal compared to RMS value, final conclusions about the system design falling within the performance limits across the full frequency range of interest can be made by using relationships that describe statistical properties of white noise. PSDs of individual outputs can be added over the frequency range. The RMS value derived from the PSD distribution can be used to calculate a peak-to-peak value of system response to an acoustic signal that is a combination of all the frequency bands used separately for testing.

Instrumentation

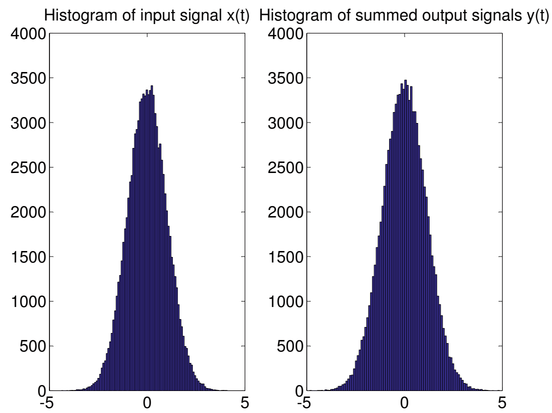
The list of instruments required to carry out acoustic testing includes a programmable signal source needed to produce a filtered white-noise signal for the frequency bands specified as standard frequencies for one-third octave measurements. A set of speakers is required to generate sound waves and an amplifier is used to vary the sound pressure level. A sound level meter and a calibrator are required to ensure that the sound level around the system that is being tested is uniform. Finally, a signal analyser is required to check the time- and frequency-domain distributions of the input and output signal.

Conclusions

We have presented a measurement method to quantify the acoustic vibration sensitivity of precision positioning equipment. Acoustic disturbances and their influence on precision machinery have been discussed.

8 Autocorrelation plots
(a) White noise input signal x(t).
(b) Autocorrelation of total filtered output signal y(t).

9 Distribution of input and summed filtered output signal.



9

The factors determining the choices made for experiment settings, including excitation signal, response analysis strategy and instrumentation, have been presented in detail. The frequency-dependent behaviour of the system as well as the expected nonlinearities are good reasons to use filtered white noise as an excitation signal. The system is overdriven to separate the influence of background noise and acoustic excitation, and measurements are made at sufficient sound pressure levels to be able to make a reliable extrapolation to nanometer level. The ability to detect system nonlinearity or other sources of disturbance allows the separation of the influence of acoustic disturbance on the system from other sources of disturbance.

The process described was implemented successfully to carry out acoustic measurements on precision engineering equipment.

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ISO 266 – 1997, "Acoustics: Preferred frequencies for measurements".

THE PHYSICS OF MICROMETER STRUCTURES

Microelectromechanical systems, in short MEMS, are small systems embedded in silicon wafers. The ongoing miniaturisation of electronic circuits is making it possible to incorporate a whole range of functionalities. One example of this is the MEMS resonator, a miniature 'tuning fork'. During MEMS production, a wide range of small variations occur which can affect the physical properties of the component. To get a clearer picture of these effects, numerous aspects of the MEMS resonator were simulated using modern FEM software.

HELGER VAN HALEWIJN

MEMS components are a combination of electronic, mechanical and sometimes chemical components, which perform a particular role. NXP Semiconductors in Nijmegen, the Netherlands, developed a MEMS resonator made of silicon material, and special etching techniques in the wafer fab have made it possible to create a miniature resonator or 'tuning fork'. This resonator in the wafer can replace the antiquated quartz crystal, which determines the oscillation frequency in nearly all electronic systems. These old crystals tend to be no smaller than 1 mm^3, which is pretty sizeable and relatively expensive. A MEMS resonator can easily be included in the electronic design of a chip with dimensions of around 10 x 20 x 40 μm^3. In a wafer fab, deposition and etching techniques are used to add a whole range of structures to a chip. As such, creating a MEMS resonator is one of the options.

Quartz crystal is a tried and tested technology, and the frequency of the crystals remains stable for years. If one manufactures the equivalent in the shape of a MEMS resonator, it then has to meet various requirements to generate frequency signals with low noise, a high Q factor and low temperature drift. The MEMS resonator designed by NXP meets all of these requirements.

The manufacturing process for MEMS components causes a range of small variations. For instance, chip depth variations can occur during deposition or layer etching, which can affect certain properties of the resonator.

AUTHOR'S NOTE

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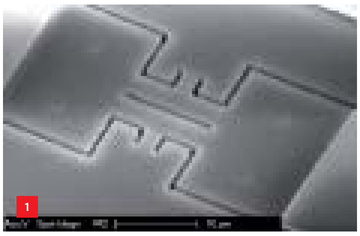
Physixfactor has simulated a series of these types of effects on a so-called dogbone resonator and mapped out the dependency of a few properties. These simulations were carried out using COMSOL's Finite Element Method software. Using this software, a whole range of physical couplings were simulated, e.g.:

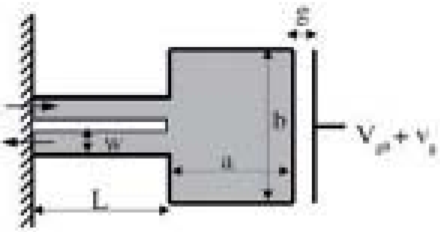
- Nonlinear oscillations
- Anchor losses (or acoustic losses)
- Mode coupling, etc.
- Thermal losses during oscillation
- Resonance drift resulting from temperature fluctuations
- Damping losses resulting from small air leakages in the packaging
- Nonlinear electrical forces driving the resonator
- Influence of the thickness of the oxide layers on the resonator
- Dimensional variations of the dogbone resonator

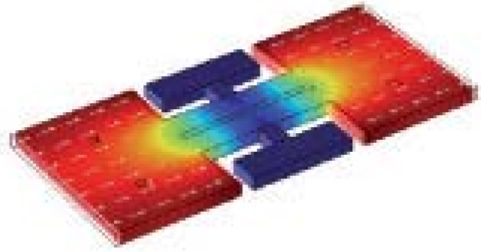
To produce a MEMS resonator that meets the set requirements, one needs to carry out simulations to understand how to dimension the resonator to ensure long-term stable and reliable operation. This will help to draft a set of manufacturing requirements. This article will outline a few simulations in more detail.

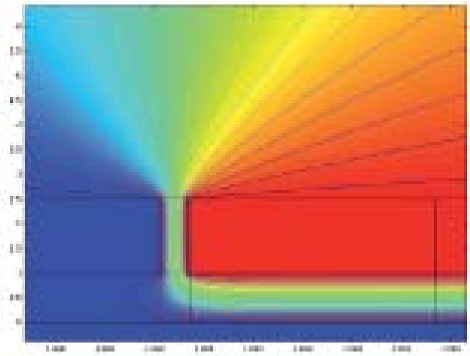
Nonlinear oscillations

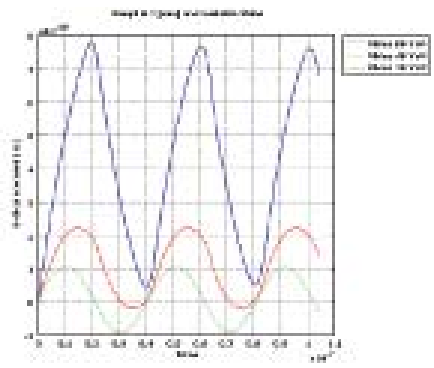
Figure 1 is an SEM photo of the MEMS resonator in question; the scale indicates that the resonator is approximately 40 microns long. The resonator is driven into oscillation using a sinusoidal voltage, and once the











frequency of the electrical signal matches the longitudinal oscillation mode of the resonator, the resonator will be wound up.

A constant bias voltage V_{DC} is applied accross the gap (figure 2) in the material, on top of which is a sinusoidal signal V_{AC}. The time-dependent electrical force across the gap can be written as:

$$F_{el} = \eta V_{AC} \sin(\omega t) + \frac{V_{DC}\eta x}{g} \qquad (1)$$

where η is a constant, reflecting the coupling between the electrical and the mechanical domains, V_{AC} the alternating voltage, ω the angular frequency of the signal, V_{DC} the bias voltage, x the displacement of the resonator and g the gap. The frequency can be calculated from the differential equation of this nonlinear oscillation:

$$f_{res} = \sqrt{\frac{k}{m} - \frac{V_{DC}\varepsilon_o wh}{mg^3}} \qquad (2)$$

Where k is the spring constant of the resonator, m the mass of the vibrating part, ε_0 the dielectric constant, w the width of the gap and h the height of the gap. If the bias voltage varies, this can be used to alter the frequency of the system. Increasing bias voltage causes the frequency of the system to decrease. This can be used to tune the system to the correct frequency, for instance. It should be noted, however, that the resonator being discussed here had a typical resonator frequency of 56 MHz. The orientation of the resonator in relation to the crystal axes in the silicon also plays a role

1 *SEM photo of the resonator.*
2 *Diagram of the dogbone resonator. A sinusoidal signal drives the resonator across the gap g. The forces are not linear; they are heavily reliant on the size of the gap.*
3 *The red parts move symmetrically in relation to each other in the longitudinal mode.*
4 *Fringing of the potential lines across the gap.*
5 *Nonlinear behaviour at V_{DC} = 80 V, blue curve.*

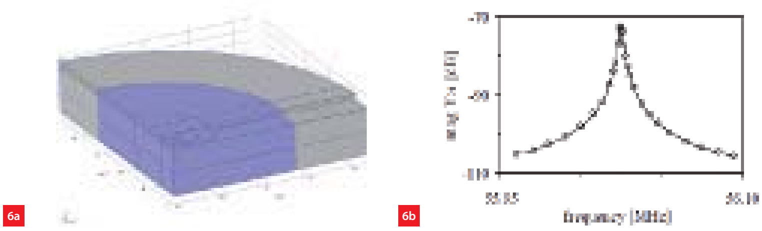
because the Young's modulus in the [100] and [110] directions is different and, moreover, nonlinear; this makes it even more complicated to tune the system [1] [2] [3].

The first time the system is in a state of vibration, the dogbone resonator will oscillate symmetrically in longitudinal mode (see Figure 3). The blue parts will not oscillate, while the red parts will display amplitude, indicated with grey arrows. Figure 4 shows the fringing effect of the electrical potential lines across the gap of the resonator. This gap can be viewed as a condenser, with opposing charges exercising force on each other (see Equation 1).

The 3D structure of the resonator has been programmed into the FEM software and a time-dependent simulation has been carried out to study the nonlinear effects. Figure 4 shows a few oscillations of the dogbone resonator at various V_{DC} values. The nonlinear oscillation at V_{DC} = 80 V is clearly perceptible. The green line is more or less sinusoidal at V_{DC} = 10 V; the blue line is the highly nonlinear oscillation at 80 V. In this case, the FEM simulation is time-dependent and the intervals are approximately 1.5 nanosecond. The amplitude is then nearly 0.1 nanometer.

Anchor losses

The anchors of the resonator fix it to the environment of the chip. If the resonator is in a state of resonance, the anchors will lose energy, and these mechanical losses will contribute to the system's Q factor declining. These losses



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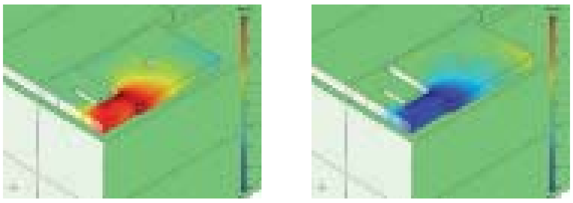

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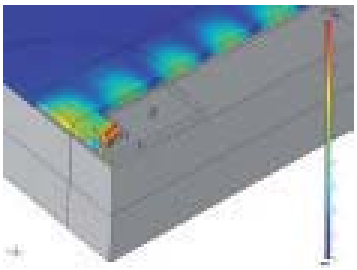

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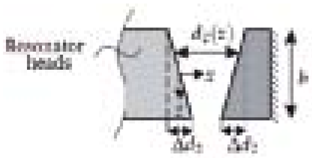

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6 *Calculation of anchor losses.*
(a) Blue is the silicon and grey are the Perfectly Matched Layers which completely absorb the oscillation energy.
(b) Q factor.

7 *Anchor losses due to an oscillation. The yellow-green lobes reflect the amplitudes that occur in the geometry and disappear into the environment via the anchor.*

8 *Asymmetric gap, possible source of mode coupling.*

9 *Temperature variations in the anchor due to high-amplitude oscillation.*
(a) The compression cycle; the red part represents heating (higher temperatures).
(b) The elongation cycle; the blue part represents cooling off (lower temperatures).

have been calculated using the COMSOL software, for which a quarter of the model is enough. The blue parts in Figure 6a are the normal silicon material, while the grey parts are the so-called Perfectly Matched Layers, which completely absorb the acoustic energy. This allows the calculation of the system's Q factor in a time-dependent simulation. Figure 6b shows a diagram of the Q factor around the basic frequency of 56 MHz.

The anchor losses are nicely illustrated in Figure 7 and are highly dependent on the dimensioning of the anchor itself. To map out the effects of the dimensioning, it is important to carry out a minute parametric study for the manufacture of the resonator.

Mode coupling

If the dogbone resonator is not properly dimensioned, and the V_{bias} induces major nonlinear behaviour, mode coupling may occur. It is therefore important that other oscillation modes are not too close to the longitudinal frequency. For instance, it is important that the gap, across which the voltage is driving the oscillations, is nice and even. Current etching techniques are certainly capable of achieving this, but sometimes the gap can taper off too much. The parts that are not as far apart will attract each other more than the parts that are further removed from each other. This asymmetry may cause mode coupling (see Figure 8).

Thermal losses

If the resonator is excited particularly hard and the amplitudes are relatively high, instantaneous heating and cooling off at the anchor will occur (see Figure 9). As a result, the material at the anchor will be subject to a cycle of pressure and axial tension. This goes hand in hand with a cycle of warming up when under pressure and cooling down in the tensile stress phase. This process will be fast at 56 MHz and the warming up and cooling down cycles will offset each other. Nevertheless, a little bit of energy will always be lost; for instance, in the warming-up cycle, a small amount of heat will flow into the surrounding material via the anchor. This loss of energy will reduce the Q factor of the system.

'Multi-physics'

Modern FEM software is capable of simulating many aspects of the MEMS resonator and can, in fact, be regarded as a laboratory in which people can 'measure' or forecast a whole range of product properties. Numerous test runs were performed on the computer, the results of which always translated to the specifications of the factory production processes. A range of variations in the production process could be simulated and understood using the COMSOL software. A sound knowledge of physics is, however, imperative to choose the right simulations to be able to generate the effects that can be observed in practice.

Acknowledgement

Good communication with the development team and the production team at NXP was instrumental to the success of the above project. Thanks go out to Dr H. van der Vlist (NXP, Nijmegen), Dr J. van Beek (NXP, Eindhoven) and Dr Rob Lander (IMEC, Belgium). ■

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MORE INFORMATION

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CONNECTING HIGHER EDUCATION, BUSINESS AND RESEARCH

Fontys University of Applied Sciences has decided to collaborate with regional industry to invest in and develop a new centre of expertise focussing on high-tech manufacturing and materials. Supported by the Brainport ecosystem and the open innovation model, this new centre of expertise will position itself between OEMs and SMEs in the Eindhoven area. It will play a major role in connecting and bringing together different stakeholders from higher education, business and research.

RICARDO ABDOEL AND HENK KIELA

Additive manufacturing is one of the two focus areas of the Fontys University Centre of Expertise.

The Eindhoven region in the south of the Netherlands is the heart of the high-tech industry. Major global companies such as Philips, ASML, Bosch, VDL, FEI, DAF Trucks, NXP and many more develop and produce their equipment in this region in close collaboration with a variety of excellent suppliers and co-makers. The regional companies have understood that collaboration in manufacturing, development and innovation with suppliers is key to retaining a competitive position in the world.
It is clear that a major part of high-tech manufacturing operations will remain in the Netherlands and Europe for a number of reasons. This fact has raised a strong regional interest in innovative manufacturing technology.
Manufacturing complex parts and assemblies in relatively small quantities (high mix, low volume) is typical of the Eindhoven region. To improve competitiveness, the high-tech industry needs manufacturing techniques that support:
- the manufacture of more optimised and integrated complex mechanical and mechatronic parts at a lower integral cost;
- the design of built-in functions in high-end parts;
- the use of 'new' materials like titanium; and
- the flexible automation of low-volume manufacturing and assembly operations.

Fontys University of Applied Sciences is fully aware of the dynamics and significant (economic) potential of the high-end and high-tech manufacturing industry. Fontys plays an important role in the regional innovation system as an industry partner and it is leading the way in education in advanced manufacturing technologies. As such, Fontys has decided to collaborate with regional industry to invest in and develop a new centre of expertise focussing on high-tech manufacturing and materials. Supported by the

AUTHORS' NOTE

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Fontys University and partners will invest in a physical manufacturing lab, called objeXlab.

Brainport ecosystem and the open innovation model, this new centre of expertise will position itself between OEMs and SMEs in the Eindhoven area.
This new development will boost cooperation and partnerships on many different levels, helping to fulfil our stakeholders' different needs. In general, this model of public-private partnership will contribute to our government's goals and Brainport's human capital agenda.

Focus on emerging technologies

Research areas have been chosen in consultation with the high-tech industry. The Centre of Expertise will focus on two main areas:
- Additive manufacturing in metal and polymers
- Adaptive robotics/agro-robotics

The following topics will support these areas:
- High-precision engineering and tooling
- High-precision manufacturing
- Advanced materials

Fontys University and partners will invest in a physical manufacturing lab, called objeXlab, with high-tech and state-of-the-art production, test and measurement equipment. The lab will not only function as a research lab for students, professors and trainees, it will also be a demonstration lab for suppliers, customers and other companies interested in participating in applied research in the above-mentioned areas.

Additive manufacturing

The manufacturing world is currently seeing a major shift from traditional milling and turning operations (subtractive manufacturing operations) towards additive manufacturing (AM) methods. There are currently a lot of major developments ongoing in industrial AM (3D printing) for manufacturing functional high-end metal parts for leading industries in the aerospace, medical and automotive sectors. There are significant technical challenges, however. AM is introducing a more radical and innovative design process that will push the boundaries of design and development, thereby expanding manufacturing capabilities.

The impact on supply chain (local versus outsourcing), cost-effectiveness and time-to-market, as well as the ability to engineer and design complex forms with built-in functionality will open up a whole new perspective in manufacturing.

The Fontys University Centre of Expertise will team up with high-tech companies (OEMs and SMEs) to conduct research into new types of materials and material properties for AM, thermal engineering aspects of the 3D printed products and machines, machine parameters (variable speed, laser power, product volume and quality, etc.), and the operation of 3D metal printers in relation to increased productivity (printer throughput) and repeatability. This will make it possible to test and measure the performance of 3D printed objects in terms of durability, as well as allowing dynamic non-destructive and destructive tests. Developing test beds at the lab will enable 3D printed objects to be benchmarked against products manufactured according to traditional methods. Rules of design can be developed as can techniques to design complex functional objects, using meshing to produce a lightweight product and saving energy and material by only utilising material where needed.

Besides research, the lab will offer companies the opportunity to use 3D printers for functional prototyping and low-volume manufacturing. In this way, the 3D print lab at Fontys University will operate as an extended research facility for a range of companies and organisations. Lux Research predicts that the 3D printing industry will grow to a €6.1 billion market by 2025 (€562 million in 2012). Prototyping and small-volume manufacturing will become a €0.8 billion market by 2025.

Adaptive robotics/agro-robotics

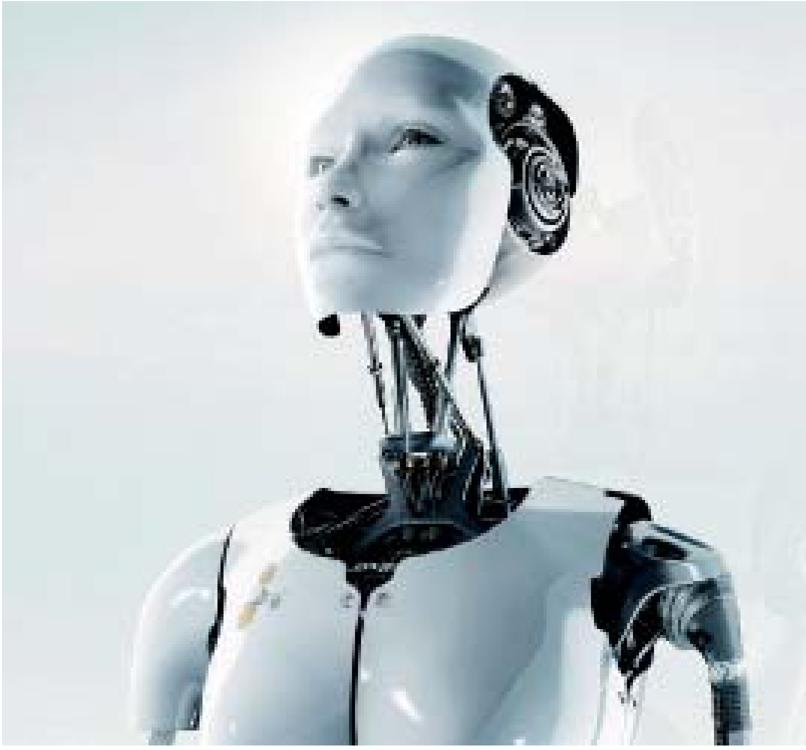
Robots have been part of many factories for more than fifty years. These robots have mainly been used in mass production manufacturing for repetitive tasks such as welding and assembly. These robot systems have made a major contribution to improved and consistent quality. This type of robot has, however, been operating in a protected environment where humans are not allowed for safety reasons.

The high-tech industry with a high-mix, low-volume production also requires:
- collaborative robotics in assembly operations where humans and robots work together;
- flexible robots to handle parts and semi-finished products requiring flexible programming, robust gripping, vision and path planning;
- intrinsically safe robots in an environment shared with humans; and
- robots that are easy to integrate and easy to reprogram for a new task in the manufacturing chain.

Robot technology and the developments in automation have evolved over the past few years, mostly driven by robot developments in research programmes at various universities around the world. Until now, only a limited amount of this knowledge had been applied to industrial robotics. In fact, these research programmes have provided a lot of knowledge on the topic of safe collaborative robots in scenarios in which robots work alongside humans. Adaptive robots exchange information between systems and machines, as well as with other robots and their environment (machine-machine interaction), but they can also adapt to a specific behaviour, task or function. In the near future, every modern factory will be capable of operating intelligent robots with an array of sensors to allow the robot controllers to execute the robots' tasks in a flexible and safe manner. The robots will be controlled and moved in such a way that the robots will assist human operators and will work alongside humans (human-robot interaction). Robots must be able to sense and observe humans, for example, by means of image processing technologies (e.g. text, graphics, facial expressions, etc.) but also gestures. If a person suddenly moves into the moving range or trajectory of a moving robot, the robot will immediately recalculate its path without operations being disturbed.

This development in robotics is perfectly in line with the so-called new industrial revolution, also called Industry 4.0, where the real world will connect to a virtual world (digital manufacturing). It is here that artificial intelligence and augmented reality will play a major role.

The mechatronics and robotics lab of the Centre of Expertise will create a living lab for collaborative robotics and conduct research to build knowledge on how to develop and design safe, low-cost, flexible robotics (e.g. mobile bases, arms and grippers, control systems, vision, integration aspects), for different applications in the medical, care, agriculture and manufacturing sectors. This will be achieved by using standard components and modifying these for a specific purpose and by adding functionality using intuitive programming and modular exchangeable (3D printed) parts.



Research at the Fontys University Centre of Expertise will address, among many other topics, the issue of intrinsically safe collaborative robotics.

A challenging aspect alongside the complexity and high precision of the architecture of the robot is the use of open-source platforms such as ROS (Robot Operating System) and its successor ROS Industrial to develop multi-vendor, independent, self-teaching robots. This research will help gain a better and deeper understanding of how this technology of intrinsically safe collaborative robotics can be adopted and implemented in production companies for economic benefit while delivering more flexible, on-demand and customised low-volume products.

All interested parties are invited to join the new Centre of Expertise at Fontys University in exploring the endless possibilities available and to ensure that high-tech manufacturing continues to develop to meet the ever-increasing demands for smarter, faster, more environmentally-friendly, smaller and integrated products and processes to serve our needs now and in the near future. ■

MUCH MORE THAN JUST BALL BEARINGS

In 1907 Sven Wingquist sketched the world's first self-aligning ball bearing (see Figure 1). His invention resulted in the foundation of the company Svenska Kullagerfabriken. He would never have thought that 100 years later one of the engineers of his company – now known around the world as SKF – would succeed in detecting a 2-μm deep groove in a rolling element of a heavily loaded sub-sea bearing. He did this not by visual inspection, but during operation by transmitting a high-frequency signal through an ultra-thin, kilometers-long glass fibre.

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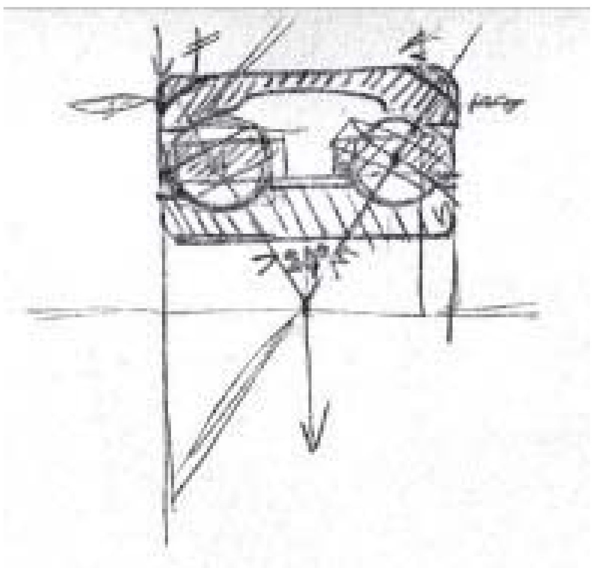
FRANS ZUURVEEN

Nowadays, such self-aligning bearings conform to generally accepted engineering standards. At the start of the 20th century, however, ball bearing failure caused by shafts misaligning was a huge engineering problem. Factories had one common shaft providing a variety of machines with mechanical power via cumbersome leather belts. Steam engines transmitted driving power to such shared power-dividing shafts. Years before this problem was solved with electric motors for every machine, Sven Wingquist's invention could easily cope with misalignment of such driving shafts.

SKF soon became a flourishing ball bearing provider, and in 1914 it had already set up in the Netherlands. This means that SKF Regional Sales and Service, based in Nieuwegein, will be celebrating its 100th anniversary this year. Besides having a sizeable sales department, this SKF office is also home to ERC, a large engineering and research centre. A prime example of the research done there is the work that Stathis Ioannides did in the 1980s. His team studied how roller elements work, the forces they generate and the effects of lubricant and cleanliness. This study saw bearing life significantly extended. In 1989, his New Life Theory was incorporated into the SKF catalogue, making predictions for bearing life much more realistic.

Lifecycle

The earliest recovered example of a rolling element bearing is a wooden ball bearing supporting a rotating table. It was found in the wreck of a Roman ship, dating back to 40 AD. Famous engineer and artist Leonardo da Vinci also described and drew ball bearings. Modern steel ball bearings, and roller bearings in general, should be viewed as real precision technological products. But SKF is not the only one manufacturing exactly round rolling elements and precisely fitting inner and outer race rings. Today, SKF has to cope with lots of skilled competitors. That's why a few decades ago SKF decided to go one step further and provide general solutions for problems related to motion (see Figure 2).



1 *A page from Sven Wingquist's sketch pad.*

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Nowadays, SKF helps to manage the lifecycle of production means relating to motion in one way or another. This lifecycle involves specification, design and development, production and testing, installation and implementation, functioning and monitoring, and maintenance and repair. This philosophy resulted in five SKF business units: Bearings and Units, Seals, Lubrication Systems, Mechatronics and Service.

The Bearings and Units business unit is all about SKF's core competence of course (see Figure 3). For the Seals, Lubrication Systems and Mechatronics business units, third parties have been integrated into the global SKF group. Today, the group consists of 140 manufacturing sites in 28 countries with about 45,000 employees.

One example of the involvement of the different business units is the monitoring of large bearings in wind turbines. Conventionally, such bearings simply used to be replaced after failure. Nowadays, sensors monitor each bearing by transmitting sensor output to a central monitoring site. If an excessively high vibration level is detected, the automatic lubrication system responds by injecting more lubricant.

2 *Some of SKF's solutions for problems related to motion.*
3 *An SKF precision bearing unit consisting of four angular contact bearings for supporting radial loads as well as axial loads in two directions.*
4 *A large dragline bearing with integrated sensors. A mechatronic system ensures equal directions for the hoist arm and operator view.*

Another example is the moving system in a dragline (see Figure 4). The large bearings supporting the operator cabin and the hoist arm are fitted with angular sensors. Signals from these sensors are transmitted to a mechatronic system, which ensures that operator view and hoist arm always point in the same direction. Such slewing bearings may have a diameter of up to 2 m. Very often they have been exclusively designed and manufactured according to special customer specifications.

Integrating sensors in roller bearings

The problem with the integration of angle-encoding sensors in a standard bearing is realising a reliable and robust unit in a limited space. Relatively small bearings need only 6 mm of extra axial space to accommodate a Hall sensor and an additional permanently magnetised ring. Figure 5 shows such ready-to-mount units. Each sensor ring has at least 32 and at most 80 permanent magnetic pole pairs. The Hall sensor generates a block-shaped output signal with the same number of pulses per revolution. Such units can be installed at either side of an electric motor to acquire a position-feedback actuator. Figure 6 shows a complete hermetically sealed IP67 unit with life-long lubrication. The unit also contains an integrated electronic circuit to amplify and convert signals, but also to determine the direction of rotation.

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5 *Small bearings with a magnetised ring and a Hall sensor requiring only 6 mm of extra axial space.*
6 *A hermetically sealed IP67 bearing with a Hall sensor unit.*


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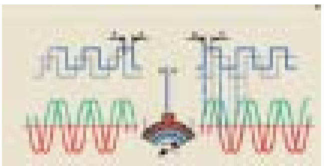
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7 *A sensor-integrated unit for absolute angle detection.*
8 *The principle of absolute angle detection with two square-pulse signals with a π/2 phase difference.*
9 *An SKF CASM unit as a valuable alternative to a pneumatic cylinder.*
10 *Comparing the energy balances of a pneumatic cylinder and a CASM driving unit.*
11 *SKF planetary roller screws.*

Sensor-integrated units for greater diameters are available with absolute angle detection (see Figure 7). The integrated incremental sensor is highly resistant to electro-magnetic disturbances (EMC) and conforms to protection class IP67 as well. The resolution amounts to 5,632 pulses per revolution. Figure 8 illustrates the operation principle. The speed sensor generates two square-pulse signals with a $\pi/2$ phase difference, which means the direction of rotation can be determined. Incremental or absolute position output in binary format is available thanks to the integrated electronic circuit.

Servo actuators

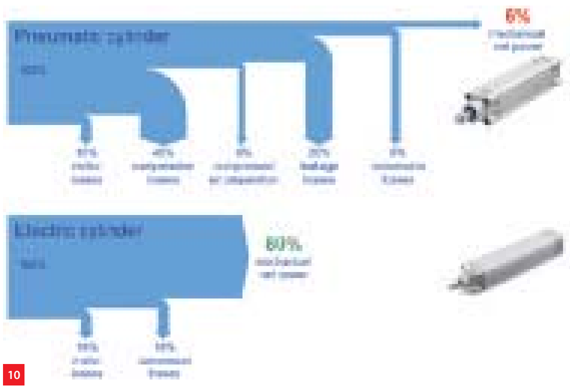
SKF CASM units (component actuator servo modular) are an excellent alternative for the well-known pneumatic cylinder. Therefore, another name for this SKF product is 'modular electric cylinder'. Coupled via an adapter to a servomotor, such a unit is practically interchangeable with a pneumatic cylinder according to ISO 15552 (see Figure 9). However, SKF's electric alternative is more flexible and more energy-efficient and delivers better controlled movements with higher precision and repeatability. The units do not need to be serviced thanks to life-long lubrication. A pneumatic cylinder has a mechanical efficiency of only 6%, whereas a CASM driving system has a mechanical efficiency of up to 80% (see Figure 10).

SKF uses several principles for translating the rotary motion of a driving motor via a screw into an output linear motion. The least sophisticated mating device is a sliding nut, resulting in rather high friction and energy loss. But the device most widely used is the well-known ball recirculating nut, which gives less friction. As such, a highly accurate ball screw forms the basic element in a CASM unit.

The most sophisticated rotation-translation conversion mechanism is a planetary roller screw. This gives a low amount of friction, can be backlash-free and delivers the highest positioning precision and resolution (see Figure 11). Roller screws are well suited for heavy loads, high rotational and linear speeds and high accelerations. In terms of manufacturing difficulty, these real precision products are comparable to planetary gear systems.

In a planetary roller screw, the threaded surface of the rollers transmits the load from the nut to the shaft. This load-transmitting area is substantially larger than in a ball screw, which explains the higher loadability. Roller screws are applied in EMC actuators (electro-mechanical cylinders) for high-end applications.

Recirculating ball screws are also used in SKF telescopic pillars (see Figure 12). They provide an aesthetic solution to



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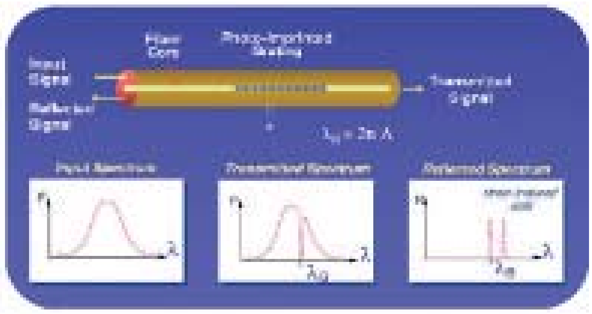

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resolve lifting problems in human-friendly constructions, e.g. infant care systems. Figure 13 illustrates the application of an SKF telescopic pillar in a table for positioning ophthalmic equipment, providing a better performance of eye examination tools.

Remote sensing of bearing performance

The monitoring of heavy-loaded sub-sea bearings was a challenging task for specialists working for the SKF System and Product Development group. The monitoring concerned the bearings in a 4 MW twin-screw pump, operating several kilometers below sea level and used for transporting a mixture of oil, water and gas. Given the obvious impossibility of inspecting the pump bearings locally, a remote sensing system had to be developed that used optical strain gauges.

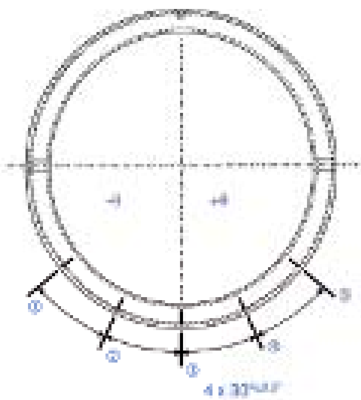
Optical strain gauges are an alternative to conventional strain gauges, which are based on strain-dependent changes in ohmic resistance. The optical ones consist of an optical fibre in which a periodic structure has been scribed.

12 *SKF telescopic pillars.*
13 *An ophthalmic table with an SKF telescopic pillar.*
14 *The principles of an optical strain gauge based on Bragg's law.*
15 *Strain measuring at five points in a groove in the outer ring.*
16 *The sensorised bearing (on a pedestal) with two grooves for optical strain gauges.*

Incoming light with a Bragg wavelength of $\lambda_b = 2n\Lambda$, where Λ is the period of grating, is reflected, while all other wavelengths are being transmitted (see Figure 14). When connecting the structured part of the fibre to the outer bearing ring, a change in the strain causes a variation of the grating period and thus a change in the wavelength of the reflected light in the fibre.

The major advantage of this method of strain detection is that the strain-dependent signal can be transported across large distances, in this particular case about 10 km. Another advantage is the integration of more than one strain measuring point in one fibre by applying successive gratings with different periods. Figure 15 illustrates the measurements at different places in the circumference of the outer ring. Figure 16 shows the sensorised bearing.

Careful analysis of the transmitted signal, using the SKF @ptitude Monitoring Suite, identified the geometrical deviations in the roller elements of one of the bearings. The suite is a digital platform enabling the efficient saving, handling and processing of large quantities of complex conditional machinery and plant information. Later demounting and microscopic inspection of the bearing showed that the monitored geometrical deviations were minor cracks that were only 2 µm deep.



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To conclude

The various research activities at the ERC laboratory in Nieuwegein clearly show that SKF delivers much more than just ball bearings. These activities range from heavy-loaded dragline slewing bearings to the detection of minor micrometer cracks in remote sub-sea bearings. It is also worth noting that these scientific activities of an originally Swedish company are performed in the Netherlands. ■

INFORMATION
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A ROBOT AT YOUR BEDSIDE?

Over 300 people attended the 3TU.Innovation & Technology conference on 6 December 2013 at which the three Dutch universities of technology (TUs) showed the technological progress being made from working together in the various 3TU.Research Centres. The event featured showcases at the 'Technology Fair', interactive workshops, debates on actual and future challenges, and lectures on high-tech & healthcare and energy & mobility. The lectures covered topics such as self-driving cars, gas transport and robots.

EDITOR'S NOTE

This report was based on input from the 3TU.Federation and professor Stefano Stramigioli.

Henk Nijmeijer, professor of Dynamics and Control at Eindhoven University of Technology, addressed the future of motorists. Increasingly, developments are pointing towards drivers having to relinquish some of the control of their car and ending up in an autonomously driving car or even in a 'train' of cars.

Bendiks Jan Boersma, professor of Turbulence at Delft University of Technology, demonstrated that research into turbulence can help save energy costs. Adding certain polymers to turbulent flows through pipes reduces flow resistance. Although it is not possible to add polymers to gas pipes, using fibres should work. From numerical simulations and experiments, Boersma deduced that the reduction in flow resistance may be considerable.

Over 300 people attended the 3TU.Innovation & Technology conference on 6 December 2013. (Photos: Rien Meulman)

Robots

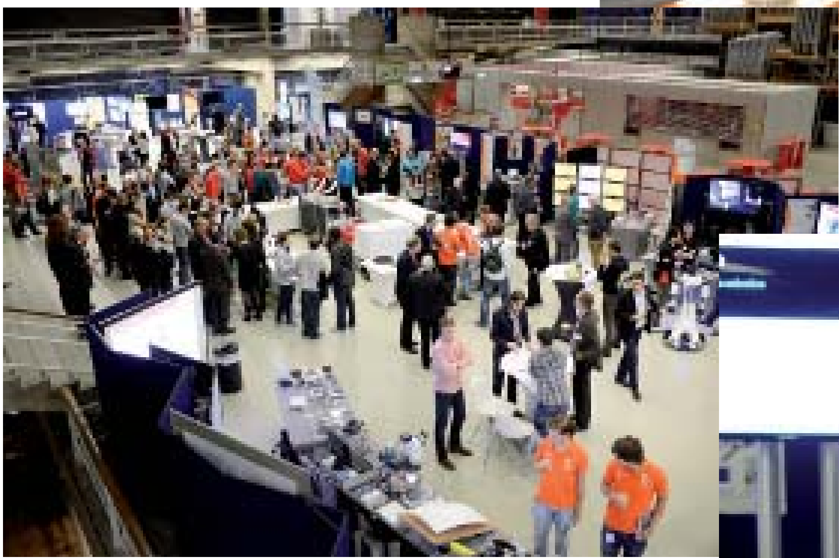
Stefano Stramigioli, professor of Advanced Robotics at University of Twente, talked about robotics as the "new technology wave to solve real challenges and create new opportunities". Robotics experts agree that in medical applications robots may offer new and innovative solutions, be they in prosthetics, rehabilitation or surgical systems, or in quality improvement and/or cost reduction.

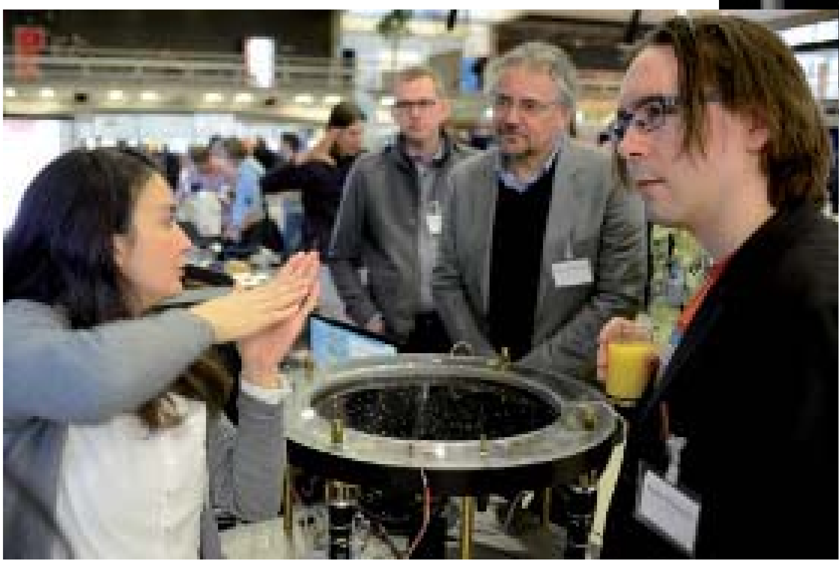
As an example, Stramigioli introduced the 3TU project on the robot Bobby, which provided new insights on mobile care applications. Bobby is a robot that cares. This care robot can talk, play games, check whether pills were really swallowed, and warn a doctor when necessary. In the next few years, robots like Bobby may be a reality in the health care sector – a potential solution to the imminent problems of ageing and staff shortages. The technology is available and development costs continue to fall.

Another interesting robot application concerns inspection: dangerous or unpleasant activities that are currently being performed manually. In some cases, human inspectors can be replaced by systems that are operated remotely or that can operate semi-autonomously, thereby eliminating tasks that might endanger people.

According to Stramigioli, the added value of 3TU research is "strength in unity". "The combination of the Dutch TUs is stronger than any other individual university of technology. I expect the 3TU research on robots to enter practice quickly. The same core technology can be applied in various areas. From that perspective, I foresee a huge potential for inspection robotics. That's why we are running several projects in this field." ■

Professor Stefano Stramigioli talking about the potential of robotics for healthcare and inspection applications.





Impressions of the 3TU.Innovation & Technology conference on 6 December 2013 in Eindhoven, the Netherlands.

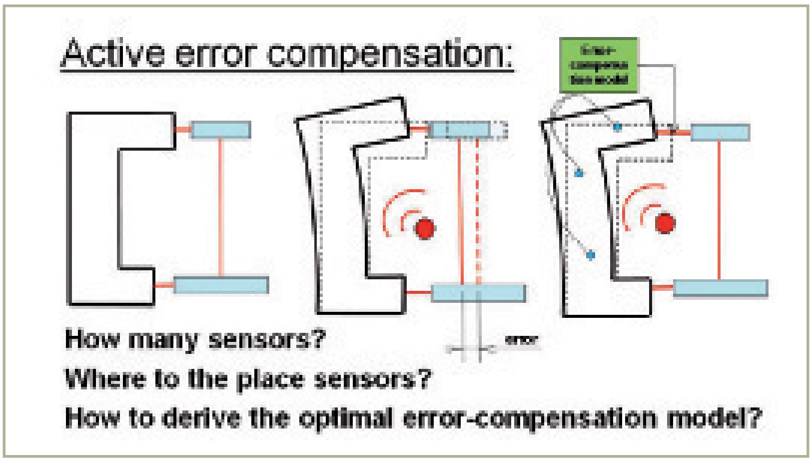
INFORMATION
WWW.3TU.NL

HOT TOPIC THERMO-MECHANICS — SPECIAL INTEREST GROUP AND WEBSITE LAUNCHED

As the field of thermo-mechanics is becoming increasingly important in precision engineering, DSPE, together with engineers in thermo-mechanics, decided to address this hot topic. On 3 December 2013, during the Precision Fair, DSPE vice president Pieter Kappelhof presented the Thermo-Mechanics special interest group (SIG) and the website developed by this SIG.

The formation of special interest groups (SIGs) is a recent DSPE initiative. Last year saw the launch of the first SIG, which is dedicated to Optics & Opto-Mechatronics. An SIG is a group of (enthusiastic) professionals working with the same technology or within the same discipline. The objective of an SIG is to initiate activities to promote, present and develop the SIG's given technology or discipline. Activities may include organising conferences, having a

Thermo-mechanics in action: schematic of a thermo-mechanical compensation model for position control. (Source: Philips Innovation Services)



Contents

Introduction
Chapter 1: Basics of Thermo-Mechanics
- 1.1 Temperature, heat and heat capacity
- 1.2 Heat transfer
- 1.3 Principles of thermal deformations
- 1.4 Thermo-mechanical beam equations ('forget-me-nots')

Chapter 2: In Depth
- 2.1 Conduction in solids
- 2.2 Conduction in gases
- 2.3 Thermal convection
- 2.4 Thermal radiation

Chapter 3: Thermo-mechanical design
- 3.1 Material selection
- 3.2 Geometry
- 3.3 Design principles
- 3.4 Passive thermal conditioning
- 3.5 Active thermal conditioning
- 3.6 Compensation
- 3.7 Summary

Chapter 4: Thermo-mechanical modelling
- 4.1 Important variables
- 4.2 Lumped capacitance modelling
- 4.3 Advanced hand calculations
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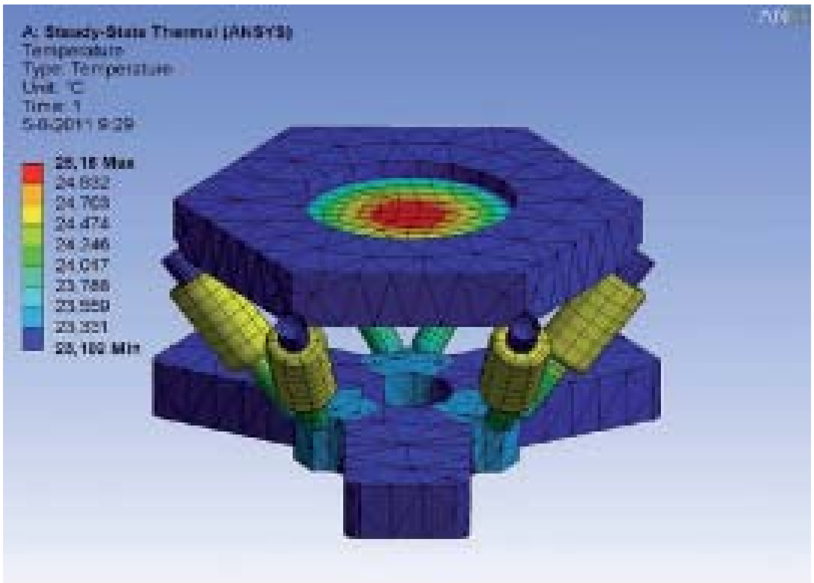
Chapter 5: Sensors
- 5.1 Contactless temperature sensors
- 5.2 Contact temperature sensors
- 5.3 Heat flux sensors

Chapter 6: Measurement
- 6.1 Calibration
- 6.2 Practical information

Chapter 7: Examples
Chapter 8: Miscellaneous



■ *The stability of a hexapod manipulator for positioning optical components is disturbed by various thermal effects. The temperature distribution in the hexapod can be calculated using Finite Element Method simulations. (Source: Ronald Lamers, MI-Partners; see Mikroniek Vol 51(3), pp. 27-33, 2011)*

special issue of Mikroniek published, launching a website, organising educational programmes, developing a road map for research, providing consultancy, networking, etc.

"Now that we have mastered the dynamics of complex systems, thermal effects are becoming the dominant factor in system performance", emeritus professor in Advanced Mechatronics, Jan van Eijk, said to Mikroniek in 2012, when talking about research conducted at Delft University of Technology into thermal effects in precision systems. This issue is often underestimated or not properly understood, hence the need for an SIG and a website, which as Pieter Kappelhof stated on 3 December, will tell you "all you ever wanted to know about thermo-mechanics but were never able to find on the world wide web."

The main purpose of the website is to introduce thermo-mechanics to precision engineers. The second purpose is to act as a starting point for mechanical engineers who want to know how to solve thermo-mechanical problems and get an understanding of how thermo-mechanics affects a mechanical design, using practical tools such as calculators. The website has been developed by engineers for engineers, and if you have any comments, the DSPE Thermo-Mechanics SIG will be happy to receive them (info@dspe.nl).

Acknowledgement
During the launch session on 3 December, DSPE vice president Pieter Kappelhof acknowledged the enthusiasm and hard work of a small group of professionals: Erik de Jong (Mapper Lithography), Evert Hooijkamp (Delft University of Technology), Martin Lemmen (TNO) and Ronald Lamers (MI-Partners), supported by DSPE webmasters Jasper Winters and Peter Giesen (both from TNO). ■

WWW.DSPE.NL/KNOWLEDGE_BASE/THERMOMECHANICS

Calculators

- Lumped mass – steady state
  Calculate the temperature of a model with multiple bodies connected with conduction, convection and radiation couplings.
- Lumped mass – transient
  Calculate the temperature of a model with multiple bodies connected with conduction, convection and radiation couplings. The steady-state temperature situation and the temperature distribution in time can be calculated.
- Radiation – transient
  Calculate the temperature of an enclosure with two bodies. The temperature and the heat flux as a function of time can be plotted.
- Gas conduction
  Calculate the thermal conduction between two bodies, separated by a gap filled with gas.
- Bimetal deflection
  Calculate the deflection of a multi-layer strip due to thermal effects.

Integrated 6D motion

Attocube has developed the six degrees of freedom hexaCUBE positioning system. The system combines extremely stiff design and long travel range with nanometer repeatability in 6D. With the heaxCUBE, attocube aims to provide cost-effective integrated motion solutions for precision machining, optics, semiconductor industry, and research. The hexaCUBE combines six (linear) closed-loop piezoelectric motors with an innovative assembly of high-precision ball joints and linear bearings. The sample platform was designed with an integrated aperture, enabling the ultraprecise alignment of optical and mechanical components.

Compared to other products, the hexaCUBE – according to an attocube press release – offers an improved ratio of system volume to travel range and superior accuracy specifications. With standard dimensions (hexaCUBE 190) of only 190 x 170 x 105 mm^3, travel ranges exceeding ±15 mm in x, y, and z direction and rotations in excess of ±19° around these axes can be achieved. With a repeatability ranging below 50 nm (1 sigma) in xyz and 1 µrad in θ_x, θ_y, and θ_z, the hexaCUBE belongs to the most precise 6D motion systems currently available.

The hexaCUBE offers stiffnesses of 1 N/µm in x/y and 3 N/µm in z, enabling 6D motion of samples weighing up to 700 g. A combination of two ECC100/PRO motion controllers enables the simultaneous operation of all six piezoelectric motors. The intuitive PC software facilitates the closed-loop control of the sample position in 6D, and enables the user to set arbitrary pivot points, and utilise extended programming tools.

WWW.ATTOCUBE.COM

'Wiki for robots'

Last month, after four years of research, scientists from six European research institutes (TU Eindhoven, Philips, ETH Zürich, TU München and the universities of Zaragoza and Stuttgart) presented an online platform through which robots can learn new skills from each other worldwide – a kind of 'Wikipedia for robots'. The RoboEarth platform connects robots by internet, bringing the development of robots that can carry out caring or household tasks a big step closer. RoboEarth was demonstrated using four robots and two simulated hospital rooms. The project was financed by the European Commission.

To enable robots to successfully lend a mechanical helping hand, they need to be able to deal flexibly with new situations and conditions. For example, you can teach a robot to bring you a cup of coffee in the living room, but if some of the chairs have been moved the robot won't be able to find you any longer. Or it may get confused if you've just bought a different set of coffee cups.

"The problem right now is that robots are often developed specifically for one task", said René van de Molengraft, TU/e researcher and RoboEarth project leader. "Everyday changes that happen all the time in our environment make all the programmed actions unusable. But RoboEarth simply lets robots learn new tasks and situations from each other. All their knowledge and experience are shared worldwide on a central, online database. As well as that, computing and 'thinking' tasks can be carried out by the system's 'cloud engine', so the robot doesn't need to have as much computing or battery power on-board."

It means, for example, that a robot can image a hospital room and upload the resulting map to RoboEarth. Another robot, which doesn't know the room, can use that map on RoboEarth to locate a glass of water immediately, without having to search for it endlessly. In the same way a task like opening a box of pills can be shared on RoboEarth, so other robots can also do it without having to be programmed for that specific type of box.

WWW.ROBOEARTH.ORG

HEINMADE on the move

Heinmade has moved to new premises in Veldhoven, the Netherlands, to accommodate for growth and realise in-house cleanroom facilities. Heinmade develops and delivers piezo solutions ranging from single components to servo-controlled multiple-axis motion platforms. Heinmade has built up extensive knowledge of piezo materials and their applications, uses state-of-the-art design and optimisation tools, and relies on in-house manufacturing expertise and capacity.

At the 2013 Precision Fair, Heinmade showcased the design and realisation of an objective stage, as an example of their project approach. This lens focusing device can be used on a variety of microscopes because of its fully configurable, interchangeable threaded adapters with user-specified threads and apertures. The stage incorporates a piezoelectric actuator element. Mechanical amplification is required to translate its 50 µm stroke into the required 400 µm range of motion. High-precision positioning is achieved by closed-loop feedback control using strain gauges in combination with a custom-designed motion controller and voltage amplifier.

The amplification mechanism consists of four pairs of leaf springs, which are under an angle to generate amplification of the piezo motion. Upon expansion of the piezo actuators, all leaf springs become oriented more horizontally, causing the 'moving part' to move downward with an amplified travel, and vice versa. The low-cost strain gauges are bonded directly to the piezo actuator. For higher accuracy, a high-budget capacitive sensor directly tracking the moving part can be incorporated. Another design aspect is the signal-to-noise ratio of the actuator-amplifier combination. The noise level may be required to be better than several millivolts, hence the large dimensions (big amplifier transformers)

WWW.HEINMADE.COM

CPE COURSE CALENDAR

COURSE	CPE points	Provider	Starting date (location, if not Eindhoven)
BASIC			
Mechatronic System Design (parts 1 + 2)	10	HTI	31 March 2014 (part 1) 7 April 2014 (part 2)
Construction Principles	3	MC	1 April 2014 (Utrecht) 6 May 2014
System Architecting	5	HTI	17 March 2014
Design Principles Basic	5	HTI	12 May 2014
Motion Control Tuning	6	HTI	2 April 2014
DEEPENING			
Metrology and Calibration of Mechatronic Systems	2	HTI	to be planned
Actuation and Power Electronics	3	HTI	22 September 2014
Thermal Effects in Mechatronic Systems	2	HTI	10 March 2014
Summer school Opto-Mechatronics	5	DSPE + HTI	16 June 2014
Dynamics and Modelling	3	HTI	28 October 2014
SPECIFIC			
Applied Optics	6.5 6.5	MC HTI	6 March 2014 26 February 2014
Machine Vision for Mechatronic Systems	2	HTI	20 March 2014
Electronics for Non-Electronic Engineers	10	HTI	to be planned
Modern Optics for Optical Designers	10	HTI	12 September 2014
Tribology	4	MC	12 March 2014 (Utrecht) 7 May 2014
Introduction in Ultra High and Ultra Clean Vacuum	4	HTI	to be planned
Experimental Techniques in Mechatronics	3	HTI	15 April 2014
Design for Ultra High and Ultra Clean Vacuum	4	HTI	22 May 2014
Advanced Motion Control	5	HTI	6 October 2014
Iterative Learning Control	2	HTI	12 March 2014
Advanced Mechatronic System Design	6	HTI	27 June 2014

DSPE Certification Program

Precision engineers with a Bachelor's or Master's degree and with 2-10 years of work experience can earn certification points by following selected courses. Once participants have earned a total of 45 points (one point per course day) within a period of five years, they will be certified. The CPE certificate (Certified Precision Engineer) is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills. The certificate holder's details will be entered into the international Register of Certified Precision Engineers.

WWW.DSPEREGISTRATION.NL/LIST-OF-CERTIFIED-COURSES

Course providers

- The High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- Dutch Society for Precision Engineering (DSPE)
  WWW.DSPE.NL

UPCOMING **EVENTS**

11-14 March 2014, Utrecht (NL)

ESEF 2014

The largest exhibition in the Benelux area in the field of supply, subcontracting and engineering. The exhibition programme includes design, machines, tools, software, embedded technology and nanotechnology.

WWW.ESEF.NL

13 March 2014, Delft (NL)

ZIE 2014

The Zuid-Holland Instrumentation Event 2014 is organised by Holland Instrumentation, a network of CEOs/CTOs from high-tech companies, institutes and universities in the Dutch province of Zuid-Holland, aimed at promoting the region's instrumentation industry

WWW.HOLLANDINSTRUMENTATION.NL

19-20 March 2014, Zürich (CH)

Special Interest Group Meeting: Thermal Issues

Euspen's SIG meeting addresses thermal issues regarding machine tools, micro-manufacturing, and semiconductor equipment.

WWW.EUSPEN.EU

15 April 2014, Enschede (NL)

Industrial Laserevent 2014

Research institutes, suppliers and users exchange information on the latest developments in laser material processing. This year's theme is Additive Manufacturing.

WWW.INDUSTRIAL-LASEREVENT.NL

7-8 May 2014, Den Bosch (NL)

High-Tech Systems 2014

The second edition of this event focuses on the high-tech systems industry in all European areas with significant high-tech roadmaps. It entails advanced system engineering and architecture, precision engineering, mechatronics, high-tech components system design as well as advanced original equipment manufacturing (OEM).

WWW.HIGHTECHSYSTEMS.EU

22-23 May 2014, Aachen (DE)

28th Aachen Machine Tool Colloquium

The Aachen Machine Tool Colloquium (Aachener Werkzeugmaschinen-Kolloquium, AWK) has established itself as an important platform for exchanging future perspectives for production technology. The general topic of AWK 2013 is 'Industry 4.0 – The Aachen Approach', focusing on the potential as well as risks of implementing a cross-linked, intelligent production and demonstrating the technical realisation by means of case studies.

WWW.AWK-AACHEN.DE

2-6 June 2014, Dubrovnik (Croatia)

Euspen's 14th International Conference & Exhibition 2014

Topics:

- Renewable Energy Technologies
- Precision Engineering for Medical Products
- Additive Manufacturing for Precision Engineering
- Nano & Micro Metrology
- Ultra Precision Machines
- Ultra Precision Manufacturing & Assembly Processes
- Important/Novel Advances in Precision Engineering & Nano Technologies
- Motion Control in Precision Systems, Nano & Micro Manufacturing

WWW.EUSPEN.EU

11-12 June 2014, Veldhoven (NL)

Vision, Robotics & Mechatronics 2014 / Photonics Event 2014

Colocation of two Mikrocentrum events. Vision, Robotics & Mechatronics features innovations and solutions for vision systems, robotics, motion control, sensors and equipment automation. The Photonics Event focuses on knowledge, design, engineering, manufacturing and application of a key enabling technology for the high-tech industry.

WWW.VISION-ROBOTICS.NL
WWW.FOTONICA-EVENEMENT.NL

16-20 June 2014, Eindhoven (NL)

International Summer school Opto-Mechatronics 2014

Five days of intensive training, organised by DSPE, The High Tech Institute and Mechatronics Academy.

WWW.SUMMER-SCHOOL.NL

2-3 September 2014, Sint-Michielsgestel (NL)

DSPE Conference on Precision Mechatronics

Second edition of conference on precision mechatronics, organised by DSPE and Brainport Industries. The target group includes technologists, designers and architects in precision mechatronics, who (through their respective organisations) are connected to DSPE, Brainport Industries, the mechatronics contact groups MCG/MSKE or selected companies or educational institutes. This year's theme is 'Revolution vs. Evolution', because progress is always a mix of evolution (optimisation) and revolution (disruptive technologies).

WWW.DSPE-CONFERENCE.NL

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  - curing systems: RT and oven heat, UV, microwave, etc.
  - quality control.
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- Development of quality control plans, quality monitoring and suggestions for corrective actions.
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