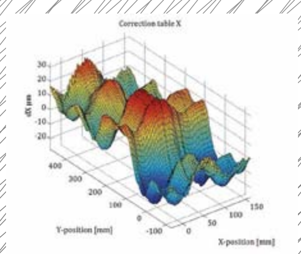
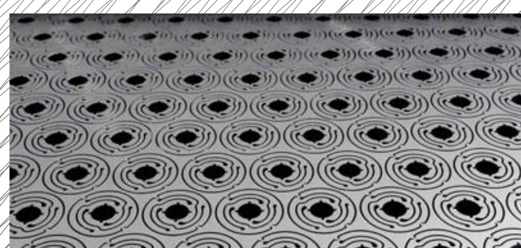
DSPE MIKRONIEK

2017 (VOL. 57) ISSUE 3

PROFESSIONAL JOURNAL ON PRECISION ENGINEERING

- THEME: **FLEXURES AND MECHANISMS**
- **EUSPEN CONFERENCE 2017** REPORT
- **PLACEMENT ACCURACY** IMPROVEMENT
- PRECISION **SURFACE FINISHING**





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

PUBLICATION INFORMATION

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

DSPE
YOUR PRECISION PORTAL

Publisher
DSPE
Annemarie Schrauwen
High Tech Campus 1, 5656 AE Eindhoven
PO Box 80036, 5600 JW Eindhoven
info@dspe.nl, www.dspe.nl

Editor
Hans van Eerden, hans.vaneerden@dspe.nl

Advertising canvasser
Gerrit Kulsdom, Sales & Services
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
Drukkerij Snep, Eindhoven
+31 (0)40 – 251 99 29, info@snep.nl

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

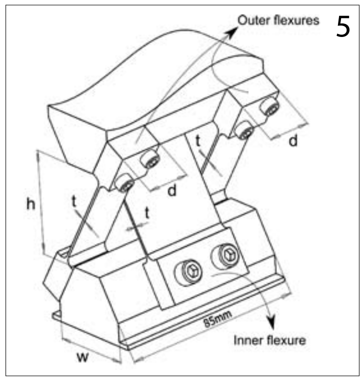
Mikroniek appears six times a year.

ISSN 0026-3699

The main cover photo (featuring a deployable solar array) is courtesy of Prof. L.L. Howell, Brigham Young University Compliant Mechanisms Research group. Read the article on page 13 ff.

IN THIS ISSUE

ISSUE 2017 3



FEATURES

EDITORIAL

FLEXURE FUTURE

In precision mechatronics, flexure mechanisms have become commonplace but developments haven't stopped. Therefore, this issue of Mikroniek is devoted to recent trends in flexures, or rather compliant mechanisms, as their family name has come to be, usually defined as those mechanisms that move due to deformation. They lend themselves very naturally for high precision as they lack friction and backlash, and no lubrication is needed, which is beneficial in hostile environments such as vacuum, underwater or in the human body. On the other hand, their design has some inherent complications: there is always mechanical stress involved in any motion, and the behaviour is dependent of the load case. This implies that kinematics (motion) and kinetics (load case) must be treated simultaneously and that the concept of degrees of freedom fades in compliant mechanisms, because they behave differently for any load case. Many efforts have been undertaken to arrive at workable definitions of mobility, for instance by defining compliance ellipsoids of the point of interest.

Over time, various configurations of wire and leaf flexures, also known as compliant architectures, have been identified that are less affected by the above complications. While their design principles remain of vital importance, there are several drivers for renewed interest in this field. Increased computer power resulted in desktop tools for the analysis of compliant structures right from the drawing board. Although non-linear phenomena like buckling and large deflection remain very tricky, a first impression of linearised behaviour is now at our fingertips. More important is the development of new modelling theory which supports the synthesis of compliant mechanisms directly.

A simple example is so-called pseudo-rigid-body modelling (PRB), where virtual joints emulate the effect of distributed deflection. This results in models with very few parameters, and provides a portal to the large domain of known linkages. Another new modelling approach is the freedom and constraint topology method (FACT), which is based on spatial kinematics and its duality with statics. This method allows one to find the solution space for a given motion or load task, rather than a single solution, giving more freedom to the designer. Also topology optimisation (TO) is maturing and becoming accessible, while the irregular shapes that tend to come out can now be produced by additive metal manufacturing, a promising combination. Interestingly, TO results oftentimes appear organic, providing a link to biomimicry and bio-inspiration, which is very topical.

The drive for miniaturisation has revived interest in methods for manufacturing compliant mechanisms from flat layers of material, i.e. compatible with MEMS technology. Effort into so-called lamina-emergent mechanisms (LEM) has led to a hype in engineering origami and pop-up where spatial compliant structures are created that are hard to produce otherwise. Generalising the idea of origami has also given rise to the development of shell mechanisms, i.e. spatially curved compliant structures, and methods for their synthesis helping the designer create and understand these complex shapes.

Actuation of compliant mechanisms is always a challenge, typically solved by ensuring that part of the mechanism motion is compatible with a given actuator. Avoiding this challenge, and exploiting the large deforming surface, distributed actuation and sensing technology is under investigation where besides piezo layers also polymer-based types are used for driving the mechanism or reducing the adverse effects of undesired degrees of freedom.

Clearly, a lot is going on in compliant mechanisms, with many promising directions for more than incremental progress being explored and included in modern educational curricula.

Just Herder
Professor of Interactive Mechanisms and Mechatronics, Delft University of Technology
j.l.herder@tudelft.nl

LARGE-STROKE FLEXURE HINGES

Large-stroke flexure hinges inherently lose support stiffness when deflected, due to load components in compliant bending and torsion directions. To maximise performance over the entire range of motion, a topology optimisation suited to large-stroke flexure hinges has been developed to obtain an optimised design tuned for a specific application. This method was applied to two test cases, which has resulted in two hinge designs of unmatched performance with respect to the customary three-flexure cross hinge.

MARK NAVES, RONALD AARTS AND DANNIS BROUWER

Introduction

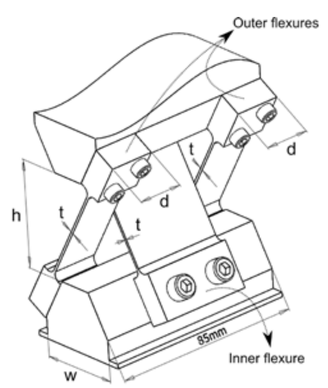
In high-precision manipulators, flexure-based mechanisms are often used for their deterministic behaviour, which is due to the absence of friction, hysteresis and backlash. However, when designing flexure hinges, designers face a trade-off between flexibility for motion in certain desired directions, and stiffness to constrain motion for guiding in the remaining directions. Typical flexure hinges have a range of about 10°, beyond which the guiding stiffness and load-bearing capacity decrease dramatically. Consequently, it is not a minor thing to design flexure hinges suited to large-stroke applications. By using a topology optimisation suitable for large deflections, guiding stiffness can be greatly increased for flexure hinges vastly exceeding a 10° range of motion.

Typical structural topology optimisations are often based on density distribution functions, which divide the design domain into a large number of finite elements and employ piecewise constant 'element densities' in each of the finite elements as the design variables. This method shows good results for small deformations. However, when more complex three-dimensional topologies are considered, the design domain becomes very large and topological optimisations can become computationally intensive. Furthermore, geometrical nonlinearities are mostly disregarded, as they significantly increase computational load, and often iterative solvers are required, which have the potential to fail to converge. This makes finite-element modelling currently impractical for optimising three-dimensional large-stroke flexure mechanisms including the required nonlinear effects.

To overcome the limitations of existing optimisation strategies, a new multibody-based topology synthesis method has been developed for optimising large-stroke flexure hinges. This topology synthesis consists of a layout variation strategy based on a building-block approach combined with a shape optimisation in order to obtain the optimal design tuned for a specific application.

Topology synthesis method

The topology synthesis begins with a shape optimisation of an initial reference layout, which is capable of obtaining an acceptable level of performance. For this initial layout, the customary three-flexure cross hinge (TFCH) is used, schematically illustrated in Figure 1.
The goal of this shape optimisation is to obtain the optimal geometrical shape (flexure thickness, width, length, etc.) that will provide maximum support stiffness for the application considered. To obtain the optimal shape, a parameterised description of the flexure hinge is used, where an optimisation algorithm searches for the optimal set of design parameters, taking all constraints into account (in the example given, maximum stress and required stroke).

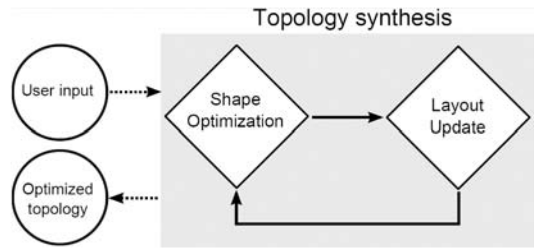


1 *Parameterised model of a three-flexure cross hinge (TFCH).*

AUTHORS' NOTE

Mark Naves, Ph.D. student, and Dannis Brouwer, Professor, are members of the chair of Precision Engineering, and Ronald Aarts, Associate Professor, is a member of the chair of Structural Dynamics, Acoustics & Control, all in the Department of Mechanics of Solids, Surfaces & Systems at the University of Twente, the Netherlands.
Some of this work was presented at the 17th euspen Conference & Exhibition on 30 May - 2 June 2017 in Hannover, Germany.

m.naves@utwente.nl
www.utwente.nl/en/et/ms3



2

The performance of a specific set of design parameters is numerically evaluated with the flexible multibody program SPACAR [1], which uses a series of interconnected nonlinear finite-beam elements. The flexibility of these elements is naturally included in the formulation, owing to a specific choice of discrete deformation modes. Therefore, only a limited number of elements is required to produce fast and accurate results. After the optimal shape of the initial reference is obtained, the layout is updated to improve support stiffness, and the newly obtained layout is re-optimised. In an attempt to find the optimal solution, this process of consecutive shape optimisation and layout update is repeated. This strategy is schematically illustrated in Figure 2.

Building-block approach

In order to obtain the optimal flexure layout, a number of compliant 'building blocks' are defined to synthesise the layout effectively [2]. With each layout update, a building block is replaced or added in order to try to improve support stiffness, based on the typical stiffness properties of each building block and the critical support stiffness from the antecedent shape optimisation. Three building blocks are combined to construct a single flexure hinge: one building block at the inner position of the flexure hinge (in the example, the middle leaf spring of a TFCH); and two identical building blocks at the outer position of the flexure hinge (Figure 1).

The building blocks used to update the layout are a leaf spring (LS), a torsionally reinforced leaf spring (TRLS) and a three-flexure cross hinge (TFCH). Each building block is schematically shown in Figure 3. An overview of the typical stiffness properties at a deflected state of each building block is given in Table 1. Numerical values of the directional support stiffness (defined as the resistance to deformation in a specific direction while motion in all other directions is constrained) for each building block – given a building block width of 20 mm, height of 50 mm, flexure thickness of 0.5 mm, E-modulus of 210 GPa and deflection angle of 0.6 rad – are presented between parentheses. Note that these values are affected by selected geometry and material properties. However, they do provide a proper indication of the typical stiffness characteristics of each building block.

Table 1. Stiffness properties of building blocks in a deflected state.

	LS	TRLS	TFCH
Support stiffness			
x-translation [N/mm]	– (4.1)	– (8.6)	+ (120)
y-translation [N/mm]	– (41)	– (8.2)	+ (290)
z-translation [N/mm]	+ (6,600)	+ (6,700)	– (650)
x-rotation [Nm/rad]	– (48)	+ (1,400)	– (31)
y-rotation [Nm/rad]	– (5.6)	+ (1,300)	– (16)
Motion compliance			
z-rotation [rad/Nm]	+ (13)	– (0.49)	+ (13)

Leaf spring (LS)

The first building block considered is the customary leaf spring (Figure 3a). This element typically has only limited support when considering the stiffness properties in its deformed state, except for translational stiffness in *z*-direction. Furthermore, it provides high compliance in the desired degree of freedom (*z*-rotation).

Torsionally reinforced leaf spring (TRLS)

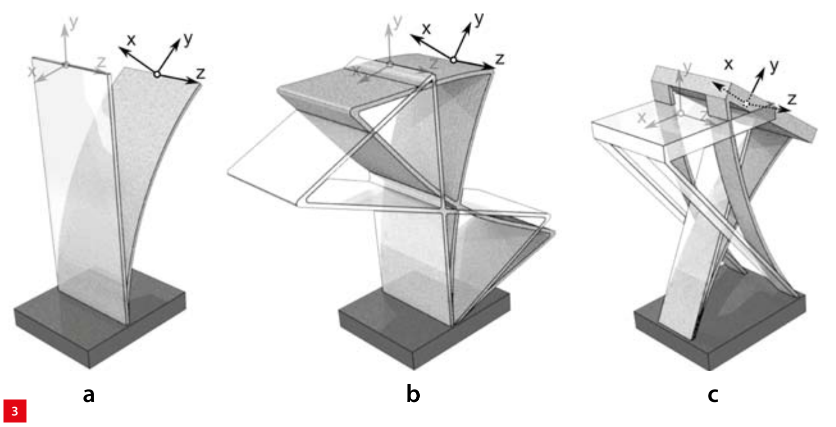
In order to improve torsional stiffness around the *y*-axis and in-plane bending stiffness around the *x*-axis, the so-called torsionally reinforced leaf spring (Figure 3b) is presented, which is inspired by the infinity hinge [3]. This building block consists of a single central leaf spring reinforced with one or more folded leaf springs to improve torsional and in-plane bending stiffness. Motion compliance in the degree of freedom is reduced due to the added folded leaf springs.

Three-flexure cross hinge (TFCH)

The third building block, which aims to increase translational stiffness in *x*- and *y*-direction over the range of motion, is a three-flexure cross hinge (Figure 3c). Two TFCHs can be stacked in series to form the so-called double TFCH (DTFCH), which provides increased translational support stiffness.

2 *Schematic representation of the topology synthesis method.*

3 *Deflected flexural building blocks used to 'synthesise' flexure layout.*
(a) LS.
(b) TRLS.
(c) TFCH



3

Optimisation examples

In order to illustrate the applicability of the suggested method, two optimisation cases will be discussed, aimed at maximisation of directional support stiffness and the first parasitic frequency for a specific mechanism, respectively. Steel was selected as the material, to demonstrate the achievable performance and to facilitate comparison with previous studies [3]. However, this choice does hamper comparison with the experimental validation; see below. For both cases, an allowable stroke of –45° to +45° deflection is considered and the maximum width is bounded to 85 mm. Furthermore, the allowable stress for steel is limited because of deformation to 600 MPa, about one third of the yield stress.

Case 1

The aim is to optimise the support stiffness orthogonal to the axis of rotation (for this case, the vertical support stiffness). The support stiffness for the shape-optimised initial reference layout (the TFCH consisting of leaf springs for the inner and outer building block) decreases to 250 N/mm at a maximum deflection angle, which is less than 1% of the stiffness without deflection. The final optimised layout after two layout updates, consisting of a DTFCH for both the inner and outer building block, shows a minimum support stiffness of 2,100 N/mm over the range of motion, which results in an increase in performance of about a factor eight. Figure 4 displays a prototype resulting from the optimised topology, made of DuraForm PA (Nylon) and manufactured with selective laser sintering (SLS). An overview of the support stiffness for intermediate shape optimisations is given in Table 2.

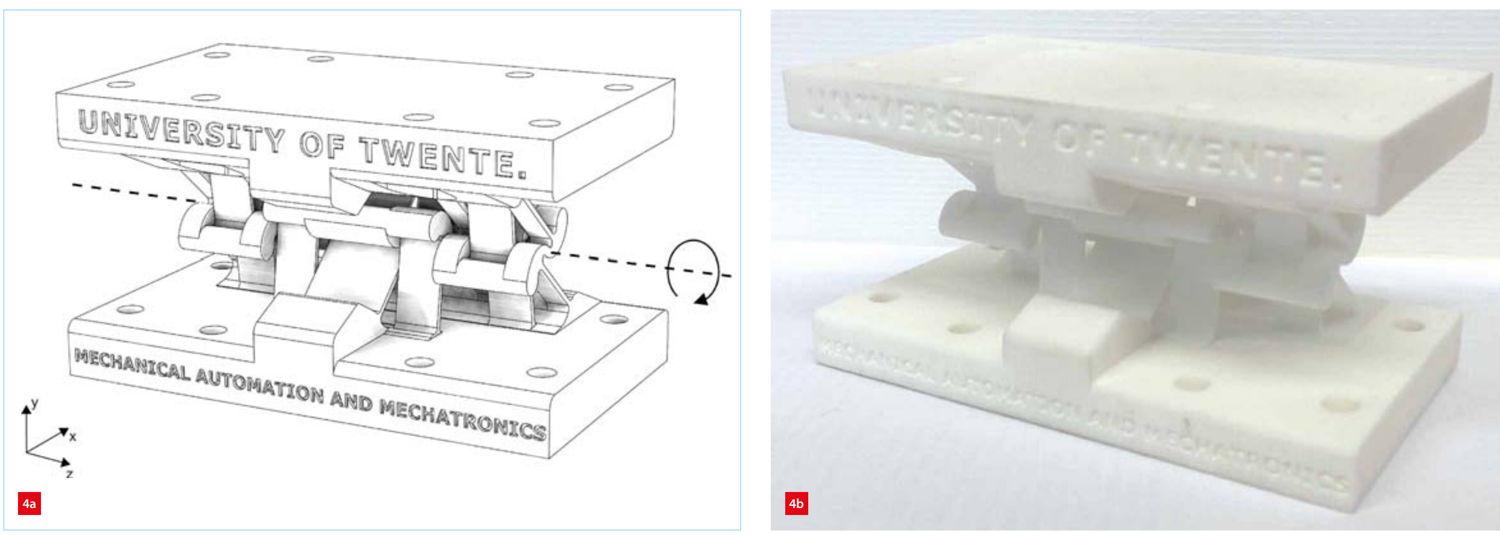
Table 2. Support stiffness for intermediate shape optimisations of Case 1.

Iteration	Outer building block	Inner building block	Minimum support stiffness (45° deflection) [N/mm]	Maximum support stiffness (0° deflection) [N/mm]
1	Leaf spring	Leaf spring	250	88,000
2	Leaf spring	DTFCH	800	41,000
3	DTFCH	DTFCH	2,100	63,000

Case 2

An optimisation is performed aimed at maximising the first parasitic frequency of the mechanism presented by Folkersma et al. [4]. In short, the flexure hinge considered for this application is subjected to a mixed load of inertia ($I_{xx} = 3.8\cdot10^{-3}$, $I_{yy} = 3.5\cdot10^{-2}$, $I_{zz} = 3.8\cdot10^{-2}$) and mass ($m = 0.57$ kg), concentrated in the pivot of the joint, where most emphasis is put on the inertial load. Table 3 gives an overview of the minimum parasitic frequency over the range of motion of each optimised layout at each layout update step. The first parasitic eigenfrequency for the shape-optimised initial reference (again the TFCH consisting of leaf springs for the inner and outer building block) decreases down to 10 Hz, which is about 7% of the frequency without deflection. The final optimised layout, consisting of six reinforced leaf springs stacked in series supported by two DTFCHs at either side of the joint, shows a minimal parasitic frequency of 100 Hz, which is an increase of about a factor ten in parasitic frequency. Figure 5 shows a prototype resulting from the optimised topology.

For a step-by-step animation of this optimisation case, see [5] and the Appendix below.



4 *Optimised flexure hinge for Case 1.*
(a) CAD rendering.
(b) Realisation.

Table 3. Frequency of first parasitic mode for intermediate shape optimisations of Case 2.

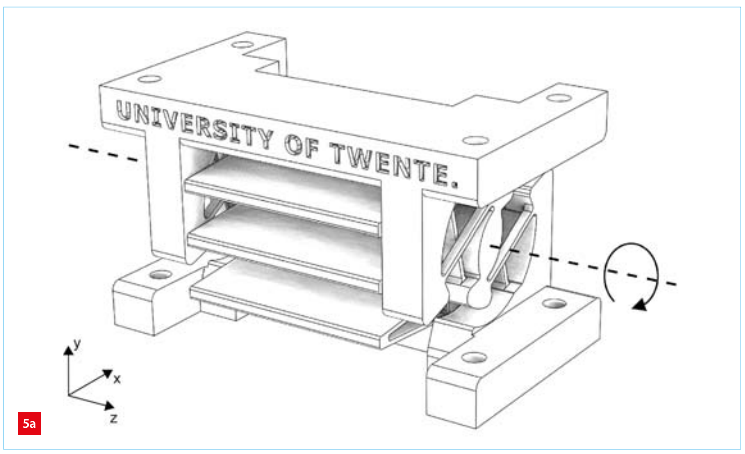
Iteration	Outer building block	Inner building block	Minimum parasitic frequency (45° deflection) [Hz]	Maximum parasitic frequency (0° deflection) [Hz]
1	Leaf spring	Leaf spring	10	150
2	Leaf spring	TRLS (1x)	14	56
3	Leaf spring	TRLS (2x)	39	154
4	DTFCH	TRLS (2x)	43	203
:	:	:	:	:
8	DTFCH	TRLS (6x)	100	132

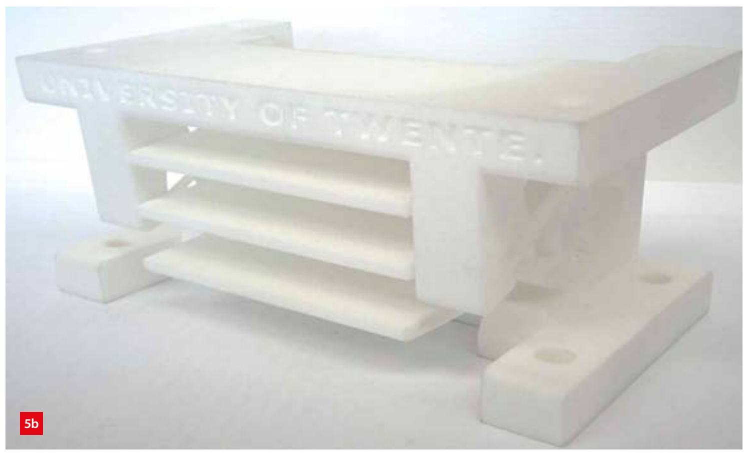
Experimental validation

To validate the models that are used for evaluating the performance of the flexure hinges, an experimental validation has been conducted. For this validation, the optimised flexure hinge of Figure 5 was used. For practical reasons (options like assembling various wire-eroded metal parts or metal 3D-printing are not straightforward), this flexure hinge was made of DuraForm PA and manufactured with SLS. Furthermore, due to the different material properties of Nylon with respect to steel and the geometrical limitations with respect to the sintering process, the flexure thickness is increased to at least 0.7 mm to comply with the SLS Nylon additive manufacturing technology. These experimental changes have been accounted for in the simulations.

To verify the results, a series of measurements were performed to confirm the frequencies of the first four disturbing vibrating modes of interests. Figure 6 shows the measurement set-up for measuring rotational modes around the x-axis. To measure the eigenfrequencies over its entire range of motion, the hinge was held in a deformed state by a wire flexure to prevent any interaction with the considered eigenmodes. These measurements were repeated over the entire range of motion in steps of 5°, where a protractor was used to obtain the deflection angle.

An overview of the experimental results over the entire range of motion is given in Figure 7. The frequency of the first disturbing mode, consisting of a rotation around the x-axis, shows a good agreement with the model results. The second and third disturbing mode, consisting of translations in the x- and y-direction, and the fourth disturbing mode,



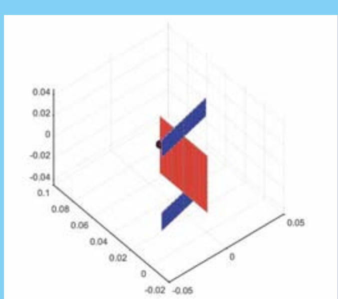


5 *Optimised flexure hinge for Case 2.*
(a) CAD rendering.
(b) Realisation.

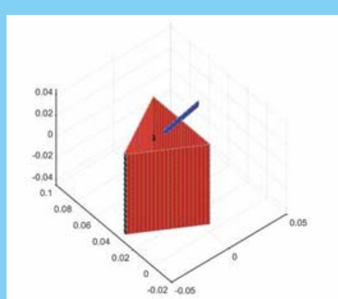
Appendix

Snapshots 'Multibody-based topology synthesis optimisation of a large-stroke flexure hinge' (Source: [5])

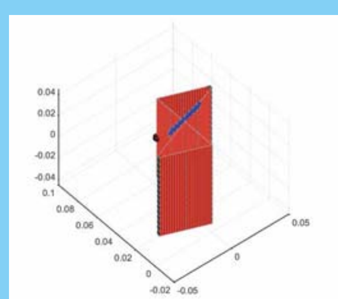
Iteration 1: LS & LS



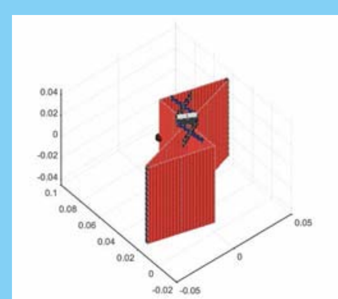
Iteration 2: TRLS (1x) & LS

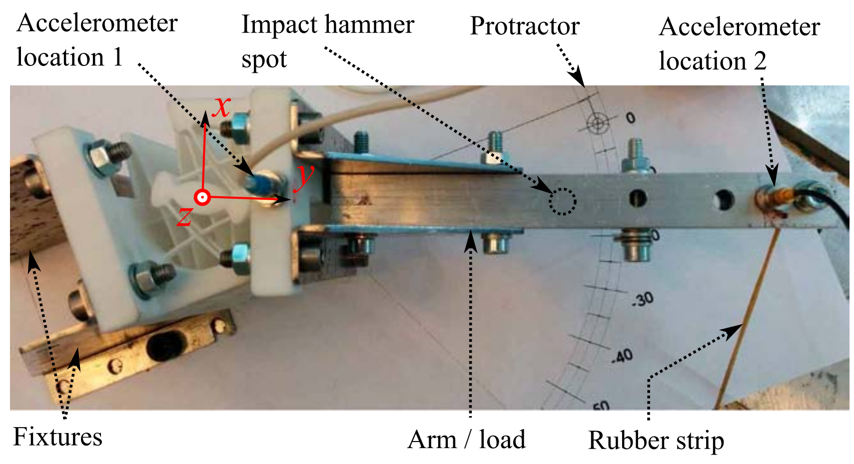


Iteration 3: TRLS (2x) & LS

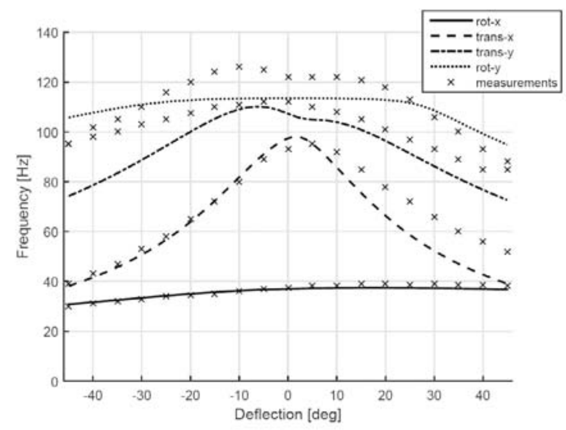


Iteration 4: TRLS (2x) & DTFCH





6



7

consisting of a rotation around the y-axis, shows a slight deviation in frequency. However, these deviations are within an acceptable range and only provide a positive increase in frequency. The deviations with respect to the experimental results can be explained by the interaction between modes with frequencies close to each other and the mixing of eigenmodes. Furthermore, possible inconsistencies in material properties and flexure thickness due to the sintering process can be of influence. The overall trend of the disturbing eigenfrequencies shows good agreement and confirm the models used, although the exact modeshape could only be confirmed for the first vibrational mode.

Conclusion

To effectively optimise topology for large-stroke flexure hinges, a new multibody-based topology synthesis method has been developed that combines a building-block-based layout variation strategy with a shape optimisation method in order to obtain the optimal topology. This method shows good results for optimising flexure hinges vastly exceeding the 10° range of motion and is capable of obtaining optimised solutions in a matter of hours.

The proposed method was used to design two flexure hinges for two selected applications, both of which resulted in a flexure design of unmatched performance. An optimisation case aimed at maximising support stiffness showed an increase in support stiffness of a factor eight with respect to the customary three-flexure cross hinge. In a second case, a flexure hinge was optimised to maximise parasitic frequency, which resulted in an increase in performance of a factor ten.

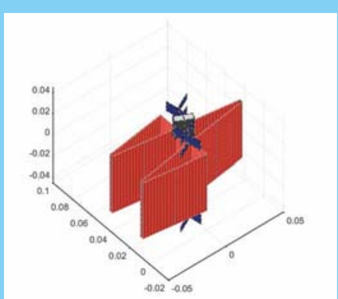
REFERENCES

[1] Jonker, J.B., Meijaard, J.P., "Spacar – computer program for dynamic analysis of flexible spatial mechanisms and manipulators", pp. 123-143 in Schiehlen, W. (ed.), *Multibody Systems Handbook*, Springer-Verlag, Heidelberg, 1990.
[2] Naves, M., Brouwer, D.M., Aarts, R.G.K.M., "Building block based spatial topology synthesis method for large stroke flexure hinges", *Journal of Mechanisms and Robotics*, 9(4), 2017.
[3] Wiersma, D.H., Boer, S.E., Aarts, R.G.K.M., Brouwer, D.M., "Design and Performance Optimization of Large Stroke Spatial Flexures", *Journal of Computational and Nonlinear Dynamics*, 9(1), 2013.
[4] Folkersma, K.G.P., Boer, S.E., Brouwer, D.M., Herder, J.L., Soemers, H.M.J.R., "A 2-dof Large Stroke Flexure based Position Mechanism", *IDETC ASME*, Chicago, IL, USA, Aug. 12-15, 2012.
[5] *www.youtube.com/watch?v=5scbEwPiq6Q*

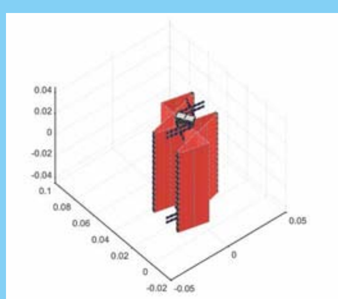
6 *Measurement set-up for testing vibration modes at –20° deflection.*

7 *Experimental validation of the first four parasitic eigenfrequencies.*

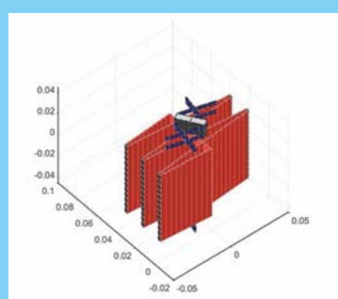
Iteration 5: TRLS (3x) & DTFCH



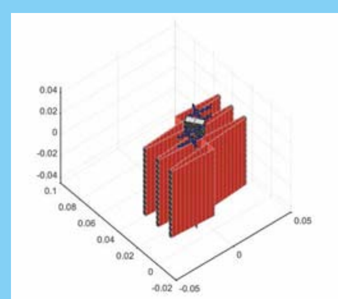
Iteration 6: TRLS (4x) & DTFCH



Iteration 7: TRLS (5x) & DTFCH



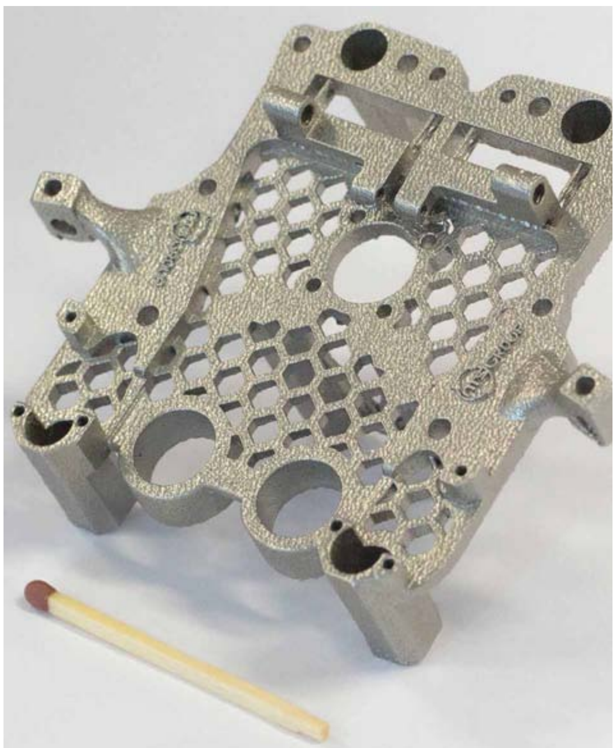
Iteration 8: TRLS (6x) & DTFCH



MONOLITHIC MECHANISMS BEYOND EDM

About four years ago, high-tech system supplier NTS started to invest in 3D printing, or additive manufacturing, by participating in AddLab, a facility which was built on the ambition to develop a broad range of high-end applications for 3D metal printing. Recently, the transition was made from the lab to the fab, AddFab, and NTS strengthened its focus on industrial metal printing. This article briefly describes the challenges involved in printing metal parts with integrated flexures, supported by cases developed by NTS over the last three years.

JEROEN JONKERS



Design principles are widely used in the high-tech industry. Construction elements such as hinges, struts, etc., are nowadays designed to be manufactured using technologies like milling, wire-erosion, sheet metalwork, etc. Additive manufacturing (AM), or 3D printing, however, is not yet commonly used for this purpose, but it turns out to be a very suitable manufacturing technology for this field of application as an alternative to Electric Discharge Machining (EDM). It opens up new design opportunities for multi-DoF mechanisms (DoF = degree of freedom) and optimisation of product mass.

AUTHOR'S NOTE

Jeroen Jonkers is design engineer at NTS-Group, based in Eindhoven, the Netherlands.

jeroen.jonkers@nts-group.nl

Additive manufacturing challenges

NTS is a high-tech system supplier specialised in the development, production and assembly of opto-mechatronic systems, mechanical modules and its critical components. At AddFab [1], NTS uses the AM process called powder bed fusion, which is capable of producing metal parts with mechanical properties close to what is known from bulk material. Powder bed fusion, which uses a focused laser beam to melt thin layers of metal powder, is an excellent process for fabricating metal parts.

Although the process is able to create dense material with predictable properties, thermal variations do induce thermal stresses and shrinkage. The latter makes 3D printing of flexures a challenge. Thermal stresses and shrinkage can result in part deformation which conflicts with the need for defined position and shape accuracy.

When designers select AM as the manufacturing technology for their design, they have considerable influence on both geometrical accuracy and other properties. 3D printing of flexures requires in-depth process knowledge to produce successful designs. In order to have full control over the manufacturing process, designers need to specify supporting structures and laser strategies specifically for the used material, layer thickness and geometry. This extends far beyond the specification of only the end product, so in fact the AM designer has to define the production strategy for the product as well.

Mechanical properties

Over the years the mechanical properties and density of printed products have been tested/monitored and at AddFab this practice is continued. Despite the testing and material knowledge, micro-cracks and notch effects are a matter of concern regarding fatigue strength. The good news is that areas of risk are predictable to a great extent and if required, post-processing can be used to remove defects. It is the nature of the material/AM process combination, but experience has learned that 3D-printed flexures are very usable in applications that undergo a small number of load cycles during the product lifetime. Although fatigue strength is a point of attention, the increased degree of design freedom allows the manufacturing of organic shapes that can avoid stress and strain concentrations which reduces the risk of fatigue, see Cases 2 and 3 below.

Subtractive manufacturing challenges

AM is all about the creation of new starting material. It is great that the technology enables creating parts out of pure functional material but as stated before, thermal stresses can cause deformation. If accurate features and/or surface finishing are required, post-machining will probably be needed. It is nothing new for designers to be aware of all manufacturing technologies involved with the product design. With AM it is easy to manufacture complex-shaped parts and the requirements for post-machining might be overlooked. AM designers need to think ahead and ensure that post-machining is possible after printing and therefore take account of clamping/machining forces, vibrations, tools paths, thread tapping, cleaning, etc.

In conclusion

Although 3D printing of high-tech components with flexures is challenging, it definitely shows promise for the industry. Through the design cases, NTS has gained insight into manufacturability and costs. By having AM in its design and manufacturing portfolio, NTS is well prepared and ready for the next challenges in high-tech systems development.

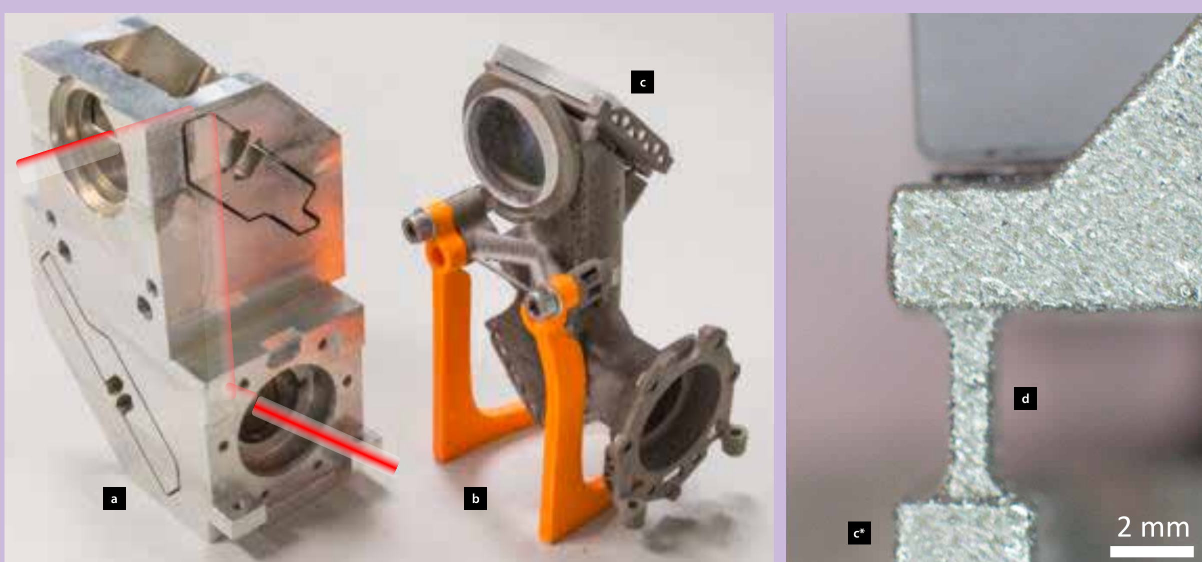
REFERENCES

[1] "From AddLab to AddFab – KMWE, NTS-Group and Machinefabriek de Valk continue 3D printing collaboration", *Mikroniek* 56 (5), pp. 32-34, 2016.

INFORMATION
WWW.NTS-GROUP.NL
WWW.ADDFAB.NL

Case 1: Model conversion (2014)

The function of the original part is to align a laser beam by means of two adjustable mirrors on flexure tilt mechanisms. The goal was to make a printable version and therefore avoid the need to make the hinges by means of wire erosion (which is time-consuming, hence expensive, and for complex products presents a real risk of rejection due to wire break). For the AM part (b), the goals were set to have a comparable surface roughness at the mirror interfaces and mechanical properties of the hinges. By adding only the functional material the AM part is printed from 90% (!) less material compared to the starting situation for the conventional (subtractive) process.



a *Original part with illustrated beam path.*

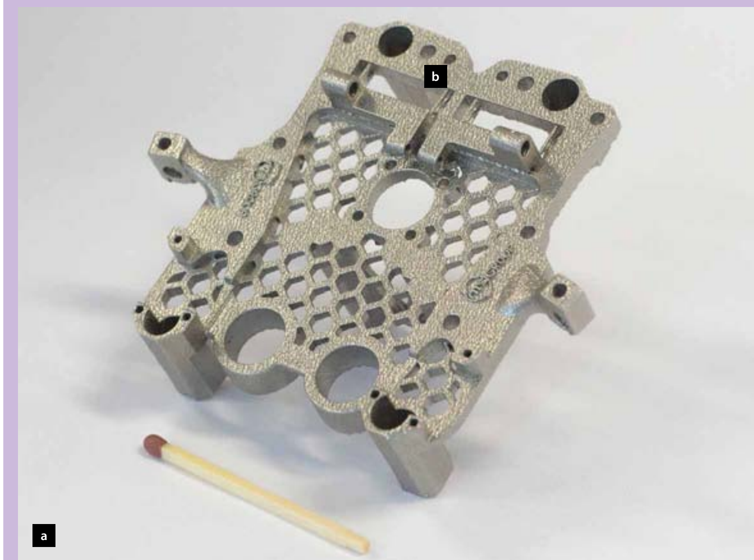
b *AM conversion.*

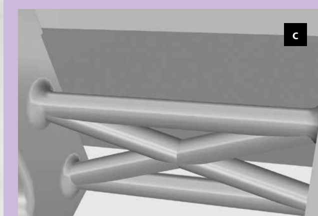
c/c* *Detail of leaf spring.*

d *Leaf spring, thickness 1 mm.*

Case 2: Assembly to mono (2015)

The 3D-printed part originally was a 10-part assembly belonging to an optical column. The printed part contains two adjustable features which function as end-stops (b). By using struts in a parallelogram construction (for the sake of stiffness), the end-stops can translate in a defined direction. The benefits of 3D printing are not only the reduction of the number of individual parts, but also cutting costs on assembling, adjusting, cleaning and logistics. The cost savings are estimated at 40%. With respect to quality, according to a 3D scan deviations from nominal geometry are within +/– 0.2 mm. This is acceptable and only limited post-processing remains, such as thread tapping, and making accurate interfaces.





a *3D-printed monolithic frame.*

b *Location of details c and d.*

c *Struts for adjustable end-stop (CAD), note the fluent shape transition between strut and body material.*

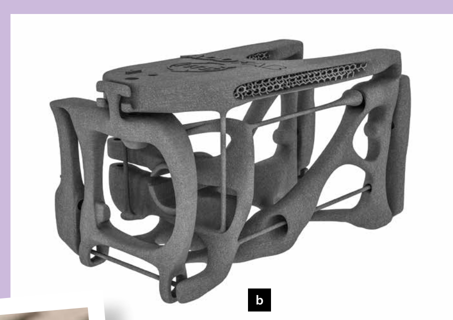
d *3D-printed struts (round 0.3 mm); see matchstick head for size comparison.*

Case 3: AM design from functional concept (2016)

One of the projects needed a 4-DoF mechanism (x, y, tip, tilt) to align a sensor. The conceptual design consists of a sensor mount (d) supported by six struts which are individually adjustable, thereby avoiding a stacked mechanism. Conventionally this would be built from multiple machined parts, the struts would be cut from wire and glued or soldered in. Instead, this was translated to an AM design. Challenges were the manufacturing of struts (50 mm long, 1 mm thick) in different build orientations and the build efficiency.
This design approach turns out to be cost effective because there is no assembly and adjustment involved. Taking into account the savings on (bulk) material as well, it was calculated that compared to conventional production using aluminium and steel parts AM is favoured for series of up to ten. In the case of comparing with more difficult-to-machine materials like titanium, AM is the first choice even for much larger series.

Design highlights are:
- Monolithic.
- Topology-optimised design.
- Integrated stroke limiting.
- Organic shape transitions to avoid stress and strain concentrations at joints.
- Hinges and struts applied at different build angles.
- Pre-printed threaded holes for push/pull screws.

In order to build a part (first time right) with this complexity, customised support structures and scan strategies have been applied.



a *Conceptual design.*

b *AM design.*

c *Printed part as built.*

d *Sensor mount.*

INSPIRATION FROM FOLDING PATTERNS

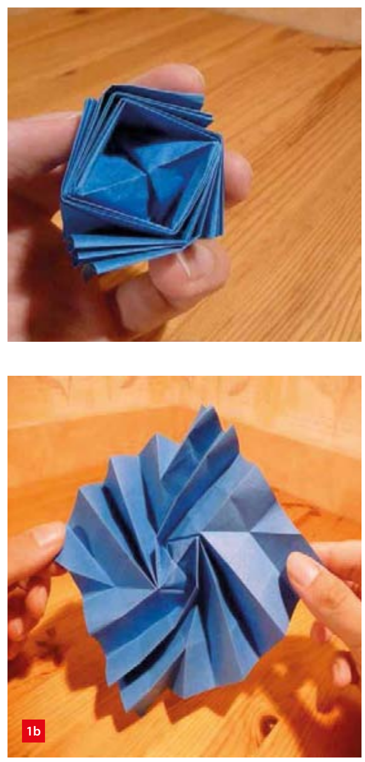
Origami is generally associated with decorative art, not the engineering world. For some time now, however, engineers have been using the gigantic database of origami folding patterns as inspiration for designing deployable mechanisms that can be fabricated efficiently from a flat sheet material. Most of these mechanisms do not contain springs, because by introducing springs, the advantageous planar properties of the design are lost. Yet there is a trick.

JELLE ROMMERS, GIUSEPPE RADAELLI AND JUST HERDER

Taking inspiration from origami for products is not new. Think about stiff sandwich panels with an origami-inspired core, or the clever way in which a paper roadmap can be unfolded in a single movement by pulling two corners apart. More recently, there has been a growing interest in origami from a mechanism design perspective. Paper is then replaced with more common engineering materials, while in the mechanisms, the often ingenious kinematics of the folding patterns are exploited. The paper models are usually constructed from a flexible material, with the creases becoming 'hinge lines', which means they can be categorised as a subset of compliant mechanisms. Compliant mechanisms are popular in precision engineering owing to their highly deterministic behaviour, which is due to the absence of friction and backlash; advantages which also apply to origami mechanisms.

Examples of origami mechanism designs include a solar array that can be stowed in a square satellite and deployed in space (Figure 1), or a stent that can be deployed in the desired place in an artery (Figure 2).


1a


1b

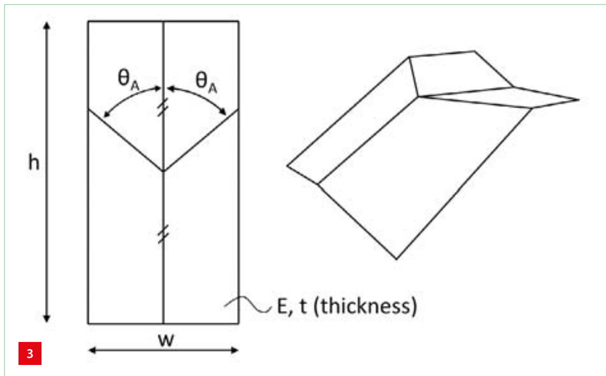
1 *An origami-inspired solar array that can be stowed in a square satellite and deployed in space [1].*
(a) Design by the Brigham Young University Compliant Mechanisms Research group [2].
(b) Unfolding principle.

AUTHOR'S NOTE

Jelle Rommers (Ph.D. candidate), Giuseppe Radaelli (post-doc) and Just Herder (professor) are in the Precision and Microsystems Engineering (PME) department of Delft University of Technology, the Netherlands.

j.rommers@tudelft.nl
www.pme.tudelft.nl

2 *Origami-inspired stent that can be deployed in an artery [3].*



3 *The common 'reverse fold' origami pattern and design variables.*

The main advantages of origami mechanisms are:

- An ability to deploy from a flat state.
- A planar fabrication method, which can reduce fabrication cost. This also makes the mechanisms suitable for the planar fabrication processes in the micro-domain. Additional fabrication steps could be integrated; for example, printing an electrical circuit on the mechanism.
- No assembly step. Again, in the micro-domain where assembly is difficult, this is an important advantage. In this case the term 'responsive origami' is used, where the hinges are designed to react to some external impulse, like heat, and the mechanism then folds itself into the desired state.

Origami mechanisms can be compared to general mechanisms by regarding the facets (panels between the hinge lines) as links or bodies, connected by revolute joints. Viewing the mechanisms in this way, one could argue that origami mechanisms are missing one fundamental attribute: springs. But introducing regular helical springs into an origami mechanism would result in most of the afore-mentioned advantages resulting from its planar nature being lost. In this regard, it would seem that it is impossible to design origami mechanisms with springs. But there is a trick.

Compliant Facet Origami Mechanisms

In most current origami mechanisms, the facets are designed as very stiff elements, and flexibility is primarily seen as an unwanted side-effect. However, this property can be used to the designer's advantage. Flexible facets can function as springs, without losing the advantages of the planar nature of the origami mechanisms. We call these mechanisms Compliant Facet Origami Mechanisms (COFOMs) [4].

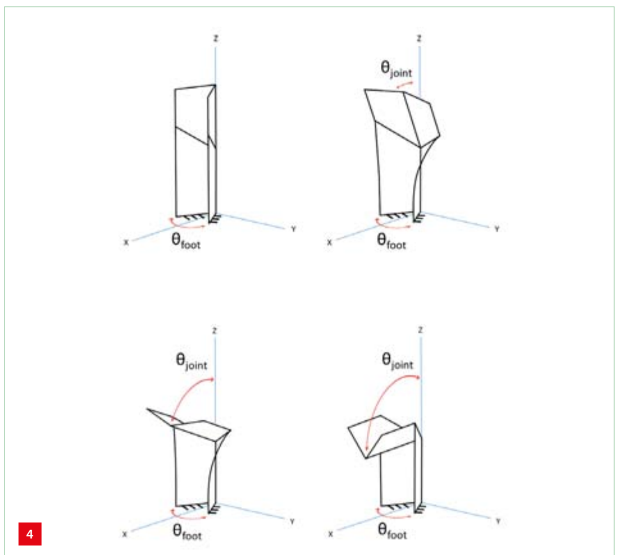
Figure 3 shows a very common origami mechanism segment, called the 'reverse fold' in origami terminology. In Figure 4 this mechanism is shown clamped at the lower facets. When the facets are rigid, the mechanism has zero degrees of freedom (DoFs). But bending the lower facets provides two additional DoFs, allowing movement in the direction θ_{joint} and the y-direction. The bending facets act as springs. In the direction θ_{joint}, this results in a bi-stable behaviour, in which the mechanism snaps to the positions in the top left and bottom right of Figure 4. The mechanism can be viewed as a joint with angle θ_{joint} and a certain reaction moment curve. The main focus of our research is in how this moment curve can be manipulated by changing the design of the mechanism.

Design tool

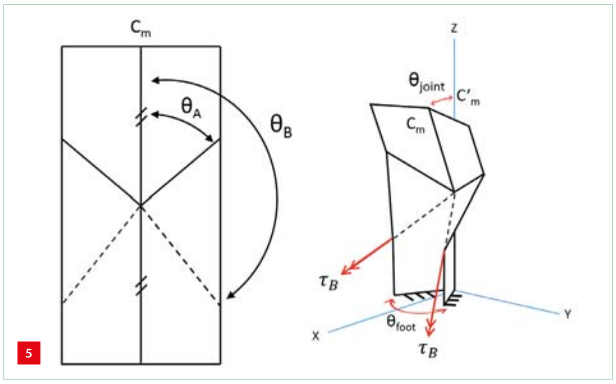
The goal is to create a design tool in which a desired moment curve can be given as an input. The tool will output the values of the design variables (Figure 3), which result in the closest approximation of this desired curve. The challenge here is to come up with a model of the mechanism with a low computational cost. With such a quick model, an optimisation algorithm can be used to select the optimal design by rapidly computing the moment curves of a multitude of designs and selecting the best-performing one.

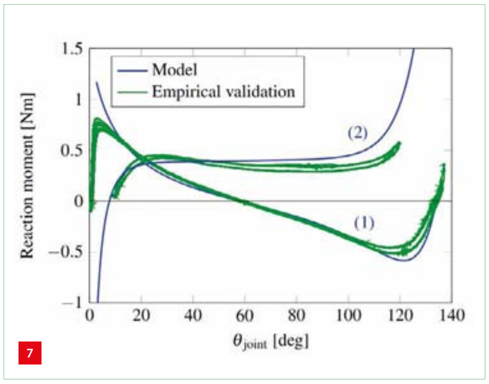
Model

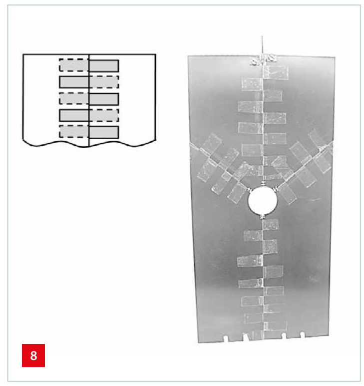
The main challenge in constructing such a quick model is the large deformation of the lower facets. The solution used is to model a bending facet by dividing it into two rigid ones, introducing a 'virtual hinge line' with a torsion spring, shown dashed in Figure 5. From this model, the moment curve can be calculated using kinematic relations.



4 *The 'reverse fold' mechanisms with the lower facets forced to bend, introducing spring forces.*







5 *Modelling the bending of the lower facets.*

6 *The performance of the model is tested by varying design variables from the 'standard design'.*

7 *Moment curves of two example designs; see text for further explanation.*

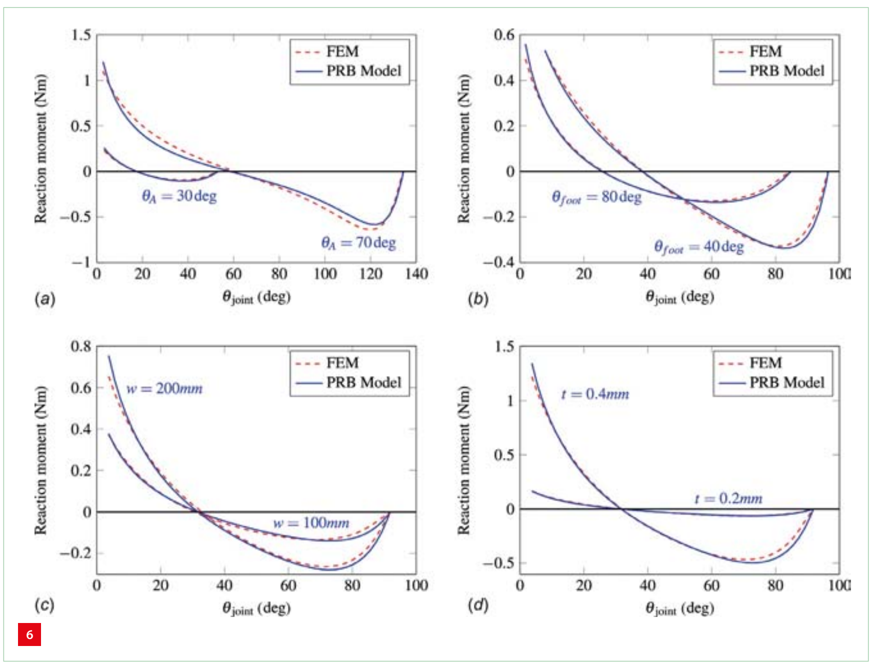
8 *Spring steel mechanism used for empirical validation. Hinge lines are made using alternating Mylar tape. ng forces.*

This model is a semi-spatial version of the Pseudo-Rigid Body (PRB) theory from Howell [5], which is used to approach bending a beam in 2D. Just as in this theory, the position of the virtual hinge line and the stiffness value of the torsion spring are obtained by fitting on existing data, in our case from finite-element analysis and experiments. In order to do this, a 'standard design' of the mechanism is defined. After obtaining the two values, they are fixed, and the model is compared to an (empirically validated) finite-element model (FEM). Figure 6 shows this comparison where the design variables are varied from the standard design.

It is important to note that the model has not been refitted on this data. The model has a good accuracy, given the large variation of the design variables, and is orders of magnitude faster than the finite-element model, due to the fact that it is a closed-form analytical expression. Therefore, it is very suitable for use in an optimisation procedure.

Example designs

Figure 7 shows the moment curves of two example designs. The model output is empirically validated by constructing and measuring the resulting mechanisms using spring steel plates of 0.3 mm thickness, joined by Mylar tape in an alternating pattern to form the hinge lines (Figure 8).



Curve 1 shows a design with a snap-through behaviour. Around a joint angle of 60°, the mechanism is in an unstable state, where it tends to snap to the first and last position in Figure 4. It exhibits a large range of 'negative stiffness', i.e. the slope of the moment curve is negative. Combining this with normal positive stiffness from other elements (e.g. a bending beam), the force-deflection characteristics can be manipulated to a large extent.

Curve 2 shows a design where the tool was used to create a mechanism that exhibits a constant moment in a certain range. In this mechanism, the stiffness of the real hinge lines is taken into account. The positive stiffness from these hinge lines, combined with the negative stiffness resulting from the bending of the facets, creates the roughly constant moment curve.

Conclusion

Engineering origami is an exciting and still-emerging field. Applications mainly seem to be in the micro-domain due to the planar fabrication process, although spacecraft and medical applications also benefit from its deployable characteristics. Exploiting the flexibility of the facets, a spring-like behaviour can be incorporated in these mechanisms without losing the planar nature that makes these mechanisms so fascinating. ■

REFERENCES

[1] Zirbel, S.A., Wilson, M.E., Magleby, S.P., and Howell, L.L. (2013), "An Origami-Inspired Self-Deployable Array", *ASME Paper* No. SMASIS2013-3296.

[2] *compliantmechanisms.byu.edu/node/892*

[3] Kuribayashi, K., Tsuchiya, K., You, Z., Tomus, D., Umemoto, M., Ito, T., and Sasaki, M. (2006), "Self-Deployable Origami Stent Grafts as a Biomedical Application of ni-Rich Tini Shape Memory Alloy Foil", *Mater. Sci. Eng.* A, 419(1), pp. 131-137.

[4] Rommers, J., Radaelli, G., and Herder, J.L. (2017), "Pseudo-rigid-Body Modeling of a Single Vertex Compliant-Facet Origami Mechanism", *Journal of Mechanisms and Robotics*, 9(3), 031009.

[5] Howell, L.L. (2001), *Compliant Mechanisms*, Wiley, New York.

MODEL-SIMULATION CROSSTALK

In the semiconductor back-end industry, there is always the need for higher placement accuracy and higher output. This article describes Kulicke & Soffa's approach to realising accuracy and output improvements in its Hybrid machine platform, which employs up to six high-accuracy robots. It outlines how a detailed system accuracy model was developed to verify the actual placement accuracy, and how Monte Carlo simulation was used to combine all model parameters and predict the system accuracy for any improvement of submodules.

RENÉ BOUMAN

Introduction

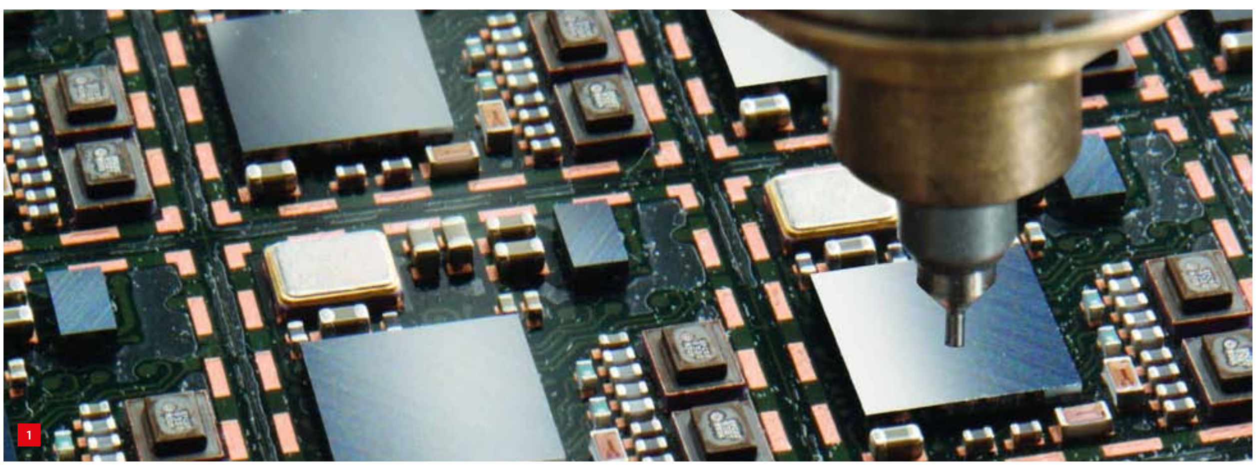
Kulicke & Soffa (K&S) is a leading provider of semiconductor packaging and electronic assembly solutions. K&S Eindhoven (formerly Assembléon) specialises in advanced surface-mount technology (SMT) and the emerging advanced packaging markets in the back-end industry (Figure 1). Since Assembléon's acquisition by K&S in early 2015, the company has been investing heavily in new developments for the benefit of the back-end industry. These include not only many new software features that are continuously being developed, but also the higher placement accuracy (5 µm) and higher output that are required for the new generation of flip chips.

Machine concept

K&S's Hybrid machine has a unique parallel placement concept (Figure 2). These machines can be fully equipped with 20 compact robots that can reach up to 120,000 component placements per hour. This high output with placement accuracy down to 25 µm is achieved by performing vision on the fly, which measures the outline of the component. This alignment method is perfectly suited for passive components like resistors and capacitors. Active components with small bumps like flip chips, however, require placement accuracy down to 10 µm. Here, up to six high-accuracy robots can be used, shooting up to 25,000 flip chip placements per hour. In this case bumps are measured by performing a stop-and-go movement above a static camera. Each robot has a single placement head and a single nozzle, which gives full process control of the pick, align and place action.

Board and component alignment

The substrate (a PCB or other type of carrier upon which the components are placed) contains a number of markers where component positions are referred to, called fiducials. After the substrate has been inserted into the machine and positioned under one of the placement robots, the locations of the fiducials are measured with the downward-looking board alignment (BA) camera. The exact location of the substrate

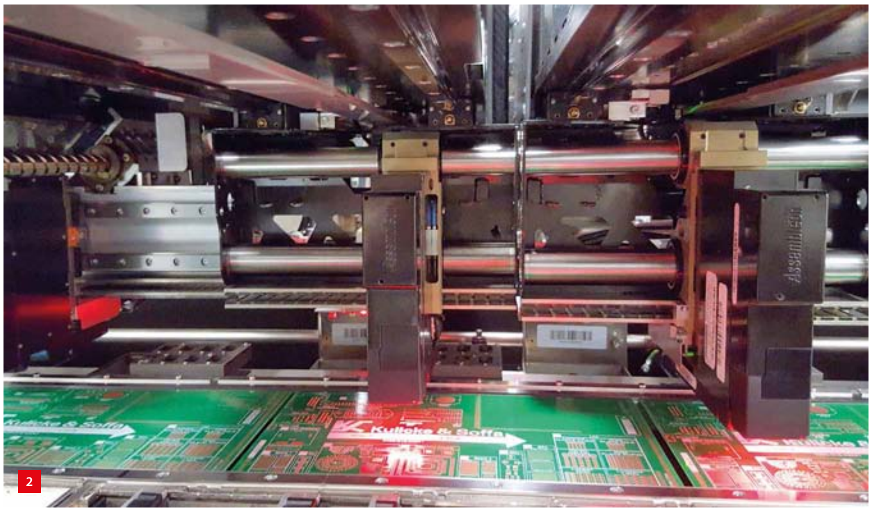


1 *Typical back-end application with passive and active components.*

AUTHOR'S NOTE

René Bouman is a systems engineer in the R&D department of Kulicke & Soffa in Eindhoven, the Netherlands. His focus is on continuous accuracy improvements in the Hybrid machine platform.

rbouman@kns.com
www.kns.com



relative to the placement robot is hereby determined. By measuring multiple (at least three) fiducials, the properties and deformations of the substrate are determined. (Besides position, also orientation, stretch in both directions and angularity are measured.) Once the substrate is aligned with the robot coordinate system, the robot then picks up a component from a wafer or tape feeder and moves it to the upward-looking component alignment (CA) camera.

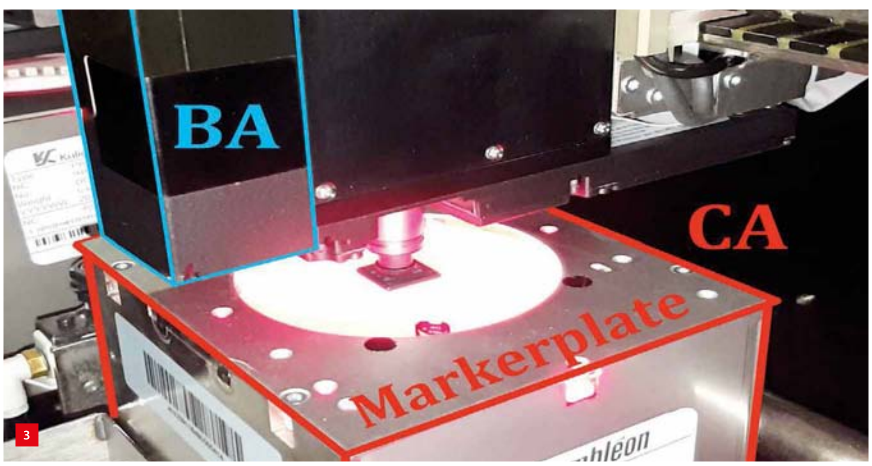
The CA camera contains a glass plate with accurate markers. The camera will measure the component with respect to four markers on the glass plate. The position and orientation of the component relative to the markers are hereby determined. Simultaneously with the image capture by the CA camera, the BA camera also measures one of the markers on the camera glass plate, which is called a closed-loop measurement (Figure 3).

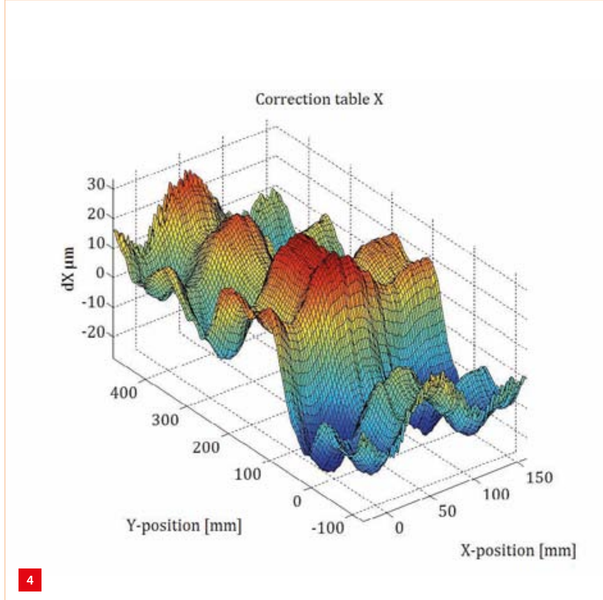
The positions of the various markers on the glass are accurately known, and therefore the position in the robot coordinate system of the component that is to be picked up. The measured pick offset is calculated and the component is accurately positioned relative to the fiducials

2 *Standard and high-accuracy robots placing in parallel.*

3 *Closed-loop measurement of a component using the BA and CA cameras simultaneously.*

4 *Example of a correction table for the error in X-direction as a function of XY-position.*





on the substrate. Since the deformations in the robot and in the substrate are not completely linear, a local fiducial is needed to eliminate small offsets in the placement position.

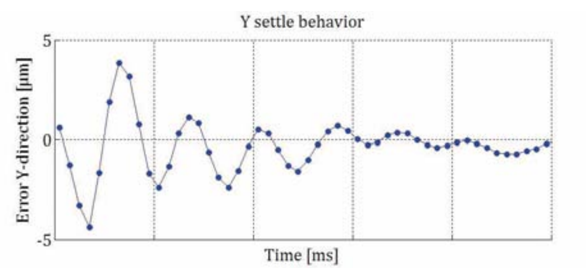
Correction table

Due to this method of location and correction, robots do not require absolute accuracy – relative accuracy is enough. One requirement, however, is that positions between two fiducial measurements remain stable. Thermal drift is compensated for by regularly measuring the fiducials. This keeps the substrate aligned with the robot coordinate system.

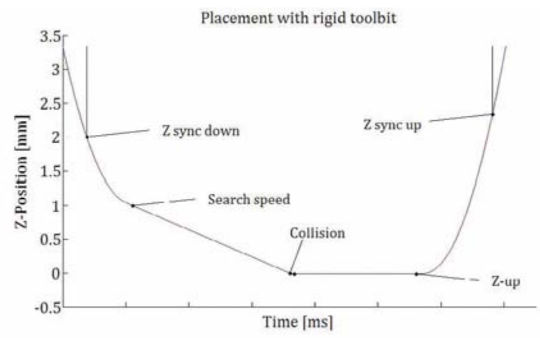
However, the robots are not perfect: their axes are not orthogonal and their guides are not completely straight. Therefore, all robots are calibrated on a calibration device containing a glass plate with a large number of accurate markers. By measuring the position of all the markers in the robot's field of work, a 2D correction table (Figure 4) can be determined for each robot.

Blueprint test

The current placement accuracy of a high-accuracy robot is 10 µm. To close the gap towards 5 µm, multiple areas need to be improved. Identifying the biggest contributors to loss of placement accuracy requires a system accuracy model. As further development will require using an existing robot, this robot's accuracy blueprint should be well known. In addition to a theoretical model, real measurements are used to quantify error budgets for all steps in the pick & place process. For each newly assembled robot, data is collected by running multiple low-level tests that measure the reproducibility of all vision measurements, robot and placement head settling, and hysteresis.



5



6

5 *Reconstruction of settle behaviour by multiple time-delayed measurements.*

6 *Typical Z-motion profile during component placement.*

7 *Hybrid machine with a combination of compact and high-accuracy robots with tape- and wafer-feeding.*

The current blueprint tests are completely automated and take 45 minutes to complete. A simple scripting language is used to control machine axes and vision cameras. In this way, no complex machine software has to be built, so process engineers with basic programming skills can easily create new tests.

Figure 5 shows the result of a settle behaviour test. The test consists of repeatedly moving the BA camera on the robot to a fiducial, whereupon the fiducial is measured at an incremental time step. Because robot dynamics are highly reproducible and vision measurements are performed in real time, the settle behaviour can be reconstructed without using a test set-up with extra sensors. Once all the low-level tests have been completed, the test results are compiled into a report. If a test does not meet the criteria set, then action can be taken before starting factory release tests.

Accuracy model

The blueprint test data is also used in a Monte Carlo simulation to predict the system accuracy in customer applications. The recipe for an application is decomposed in all required XYZRz-movements, and fiducial and component measurements. For each step, samples are taken from the blueprint test data. For example, a fiducial measurement error is a combination of the XY-settle time and hysteresis error for the movement towards the fiducial and the reproducibility of a fiducial measurement. The simulated application accuracy can be decomposed in individual error contributions to show which areas have the largest impact on system accuracy.

Hysteresis

This accuracy model has already been used successfully to push the latest robot upgrade, by replacing the re-circulating ball bearing in X-direction with an air bearing. Although this change substantially improved the reproducibility and hysteresis behaviour, the X-movements still exhibit hysteresis due to the cable slab connected to the X-stage.

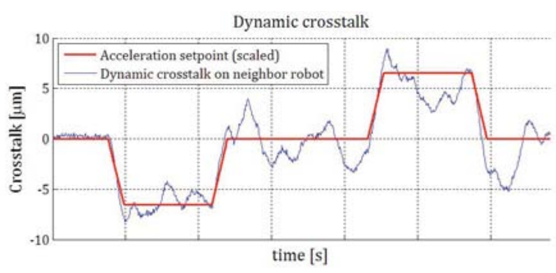
Based on the accuracy model, a 50% reduction of the cable slab hysteresis is still required to meet the overall placement accuracy of 5 µm.

Currently two improvements are being explored. The first is reducing hysteresis by small changes in cable routing and material. The second is creating a hysteresis model that takes the movement direction and distance-dependent correction into account. A general hysteresis model can be created based on the blueprint hysteresis test data. The Monte Carlo simulation can be used to predict the accuracy improvement for each individual robot when the blueprint data is corrected with the hysteresis model.

Placement effects

A current blind spot in the accuracy model is the final step in a pick & place cycle: the placement process. The placement is the period between ‘Z sync down’ and ‘Z sync up’, where XY-movements have stopped (Figure 6). The Z-axis is slowed down to search speed, where motor current

7



8

is monitored to detect a collision. After collision, the vacuum that is holding the component at the nozzle is switched off and the placement force is built up.

The moment between the first contact of the component with the substrate and the force build-up is only a few milliseconds. In this short moment, placement offsets are introduced if the component and the substrate are not planar. The direction and magnitude of the placement offset depends on the friction properties of the nozzle, the component and the substrate, and the size of the nozzle and the component. Experiments are conducted to create an empirical model that predicts the placement offset based on the above-described physical properties.

The accuracy model is used to create a planarity budget for different machine modules, like substrate transport, XY-robot and placement head. A combination of tighter mechanical tolerances, improved adjustment procedures and newly introduced adjustment interfaces should lead to a final component-to-substrate planarity that is a factor 10 improvement on the current situation.

Output improvement

A major advantage of the Hybrid machine concept is that multiple robots can place in parallel (Figure 7). Up to six high-accuracy robots can be positioned on a machine base. The reaction forces due to the high robot acceleration on the machine frame will cause dynamic crosstalk on neighbouring robots (Figure 8).

Currently, the robots' acceleration is lowered in order not to become dominant in the accuracy budget. This results in an output loss of up to 40% for the machine configurations with multiple high-accuracy robots. When the accuracy of the high-accuracy robot has improved to 5 µm, accelerations will need to be lowered even more. Since the biggest selling-point here is the combination of high accuracy and high output, the goal is to lower the effects of dynamic crosstalk without compromising on output.

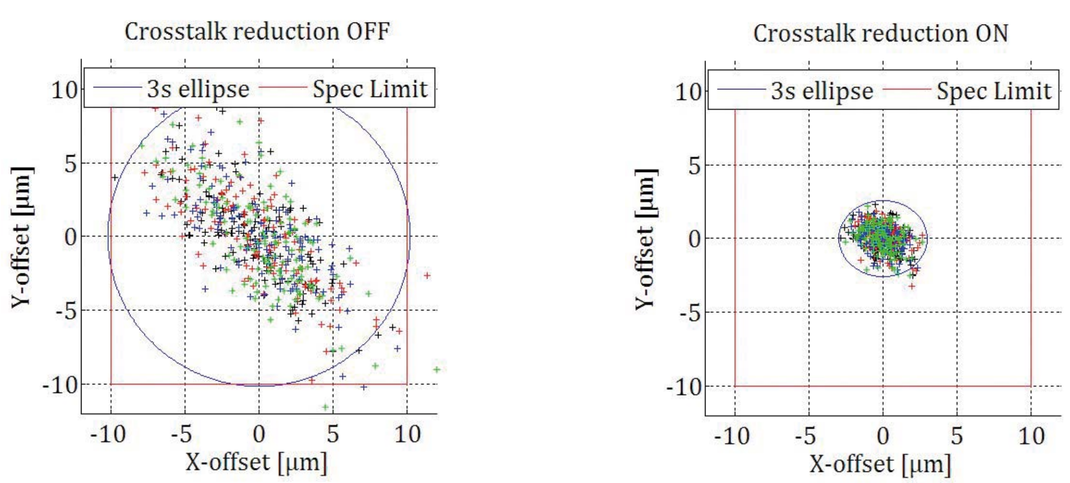
Crosstalk reduction

In addition to stiffness improvements in the machine frame, investigations of dynamic crosstalk reduction have been started. A feasibility model has been built and the first test results are positive (Figure 9).

In the coming months, the reduction in dynamic crosstalk and the increase in machine frame stiffness will be completed, leading to the first customer introduction at the end of this year. An additional advantage of dynamic crosstalk reduction is the improved settle behaviour. The combination of shorter settle times and the use of higher accelerations is expected to reduce the output loss of 40% for the current maximum machine configuration to almost zero. ■

8 Acceleration forces resulting in dynamic crosstalk on a neighbouring robot.

9 Improvement of placement accuracy when dynamic crosstalk reduction is applied.



9

DANCES WITH WAVES

The 2017 euspen International Conference & Exhibition was held in Hannover, Germany. Once again the event provided a pleasant and vibrant atmosphere for sharing knowledge and for meeting precision engineers and nanotechnologists from all over the world. One of the highlights was the keynote address by Professor Karsten Danzmann of the Albert-Einstein-Institute Hannover on the detection of gravitational waves.

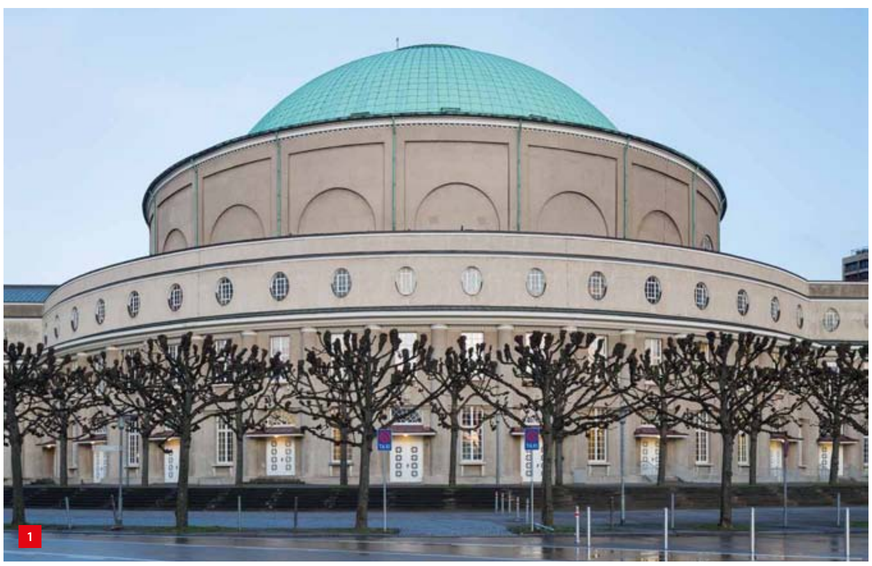
EDITORIAL NOTE

Input for this report was received from Arjo Bos (Eindhoven University of Technology), Mark Naves (University of Twente), Dishi Phillips (euspen) and Adrian Rankers (Mechatronics Academy). Their support is acknowledged.

From 29 May to 2 June, euspen (European Society for Precision Engineering and Nanotechnology) organised its 17th annual International Conference & Exhibition at the Hannover Conference Centre (HCC) in Hannover, Germany (Figure 1). The event attracted some 380 participants and featured four tutorials, two workshops, three keynote speeches, 38 oral presentations and 190 poster presentations. While the numbers were slightly below those of the 2016 conference in Nottingham, UK, delegates came from all over the world, with a remarkably large contingent from Asia. The Netherlands were well represented with a significant number of oral and poster presentations and exhibitors, which included companies as well as the Dutch Federation of Universities of Technology.

Presidential address

In his opening statement, president of euspen Prof. Hans Norgaard Hansen demonstrated that "euspen is very much alive", organising a variety of activities of which the conference is the annual highlight. He identified trends where euspen can play an important role, such as the digitisation of industry ("euspen is about knowing what you measure, so that you can trust your data") and big science (facilities like XFEL, the X-Ray Free-Electron Laser, and ESS, the European Spallation Source, which pose serious precision engineering demands), and emerging fields for precision engineering applications, such as biomedical sciences.



1 *Venue of euspen's 17th International Conference & Exhibition, the Hannover Conference Centre. (Photo: Christian A. Schröder/ www.wikiwand.com)*

Norgaard Hansen also mentioned the European certified precision engineering course programme ECP², which was created in collaboration with DSPE and is now gathering international momentum, with course providers and national coordination partners from countries including Germany, Belgium, Italy and the UK.
As a 'cool' proof of euspen keeping up-to-date, the conference had its own new app, which participants could use to communicate with each other, consult the conference programme and vote for the poster awards.

Tutorials and workshops

One of the hidden treasures of the annual euspen event is conference day 0, which features tutorials and workshops. A tutorial on optical measurement technology was presented by Prof. Wolfgang Osten of the Institut für Technische Optik, Universität Stuttgart. He began with some history on optics and optical measurement systems, then moved on to selected basics in geometrical optics and wave optics, including the mathematics. Following this, the tutorial focused on selected technologies that are relevant for a diversity of measurement tasks and surface feature measurements (shape, waviness, roughness and defects). Principles for the solution of typical problems in optical metrology were presented. The tutorial ended with a discussion on challenges to optical metrology, and typical advantages and disadvantages. All in all, it was a very interesting tutorial, for which a bit more time might have been allocated.

The other tutorials were given by Prof. Alex Slocum (MIT) on fundamentals of precision design; Dick Laro (MI-Partners) and Adrian Rankers (Mechatronics Academy) on dynamics and control of mechatronic systems;

2 *Overview of a conference session in the Glashalle of the HCC. (Photo courtesy of euspen)*

and Sven Pekelder and Mark Meuwese (Settels Savenije Van Amelsvoort) on vacuum technology and engineering. The workshops, devoted to ultra-precision spindle technology applications and areal surface metrology, concluded an information-dense, highly educational conference kick-off.

Keynote speeches

The three conference keynote addresses, presented in the Glashalle of the HCC (Figure 2), had a regional origin in common, with presenters from Braunschweig, Hannover and Hamburg, but they covered global subjects. The first keynote, by Prof. Joachim Ullrich, president of the German metrology institute Physikalisch-Technische Bundesanstalt (PTB), was devoted to the revision of the International System of Units (SI). This involves linking units to fundamental constants instead of, for example, physical objects, such as the standard mass which is kept in Paris. The aim of the revision, to be established in 2018, is to assure long-term stability, global availability and increased accuracy of the standards for the various units.

The second keynote, by Prof. Dr. Karsten Danzmann, director of the Albert-Einstein-Institute Hannover, was titled "Gravitational Wave Astronomy: Listening to the Dark Universe". In an enthusiastic manner, he sketched the history written by the detection of a gravitational wave in 2015 by the two LIGO detectors in the USA, which resulted in a paper in *Phys. Rev. Lett.* with over 1,000 authors from over 100 participating institutes, and also made the cover of the German tabloid *Bild*.

"For thousands of years we could only look at the universe and not hear it; but more than 99% of the universe is dark and will never be visible with electromagnetic radiation. Since September 2015, this has changed: the first detection of gravitational waves from two merging black holes has opened the era of gravitational wave astronomy. From now on we have a new sense and will be able to hear the universe."

The last keynote address was presented on the second day of the conference by Dr. Harald Sinn, group leader X-ray Optics, European XFEL, on high-precision mirrors and metrology. He talked about the ultra-high form accuracy and short-term heat load sustainability required for the European XFEL. XFEL's mirrors are currently the flattest in the world, having profile errors of two nm peak-to-valley deviation from an ideal surface over 1 m length. Consequently, optical metrology is a key technology and has to be pushed to its limits to obtain this single-nm accuracy.

Presentations

The conference programme comprised nine sessions, of which seven included oral and poster presentations and two were posters-only. There was a strong focus on manufacturing and machining, and only one session was devoted to mechatronics & control. From a Dutch viewpoint, there might have been more. The following is an overview.

Precision Machine Development

Talking of big science, Ivo Hamersma of IBS Precision Engineering presented the development of an automated assembly machine for the particle tracking system of the ALICE detector upgrade at CERN. IBS built a series of machines to challenging requirements, including a 5 μm positioning tolerance of the chips. The chips have to be joined to a flexible printed circuit with about 70 inter-

connects per chip, and have to undergo multiple measurements, functional tests and inspections during the assembly process.
In May 2016, the first machine was delivered to CERN. By the end of 2016, six additional machines were produced and delivered to institutes worldwide, and the eighth machine is underway. In this way, IBS has helped CERN and its partner institutes take the next step in unravelling the mysteries of quark-gluon plasma physics.

In contrast, a very 'concrete' subject was presented by Christoph Hahm (Technische Universität Ilmenau): "Strength enhancement of precision concrete parts by sol-gel surface coating". He proposed the use of precision concrete for machine-base frames, offering a reliable alternative to natural stone (granite). Concrete parts can withstand a high compressive load, but very little tensile load. By using an organofunctional sol-gel silane surface coating, researchers are trying to increase concrete's endurance strength.

Advances in Precision Engineering and Nanotechnology
Mark Naves (University of Twente) presented a large-stroke 3-DoF spherical flexure joint, designed with the aid of an adapted Nelder-Mead optimisation algorithm and SPACAR software. The flexure was optimised for axial stiffness under a deformed state. The flexure can handle a rotation of 30° in two degrees of freedom (DoFs). The typical movement of the centre of rotation was 1.0 mm, which limits the application in precision systems. See also the article on page 5 ff.

Former euspen president Ekkard Brinksmeier, Professor of Manufacturing Technologies, University of Bremen, was happy to be back in the hall where he had enjoyed a concert by the Swedish pop group ABBA forty years ago. He gave an interesting talk on speeding up ultra-precision manufacturing. This versatile process for generating precision parts and optical surfaces has a major drawback in that it has long machining and set-up times, which have a negative impact on economic efficiency. A collaboration of scientists from Bremen and Hannover has given evidence that manufacturing time can be reduced by up to a factor of ten by implementing high-speed diamond milling, applying automated tool balancing procedures, and using diamond milling tools with multiple cutting edges. The next step will be integrating these individual measures into a common platform.

Revision of SI
Continuing on the first conference keynote address, this session focused on redefining the kilogram. The two accepted methods of measuring the kilogram were discussed. The first is by applying a Kibble balance, an electromechanical instrument that measures the weight of a test object very precisely by the strength of an electric current and a voltage. This was the subject of the presentation by Ian Robinson (NPL, UK). A next-generation Kibble balance was proposed, with the idea of making it available worldwide.

3 *A ^{28}Si sphere used for the dissemination of the kilogram. (Photo courtesy of PTB)*

The second presentation, by Robin Wegge (PTB), was concerned with the dissemination of the kilogram via silicon spheres (Figure 3). The most accurate spheres, the ^{28}Si spheres, are very expensive (~ 1 M€ each). The idea is to compare the density of a ^{28}Si sphere to natural Si spheres (~ 0.1 M€) using a hydrostatic balance to calibrate natural Si spheres and make them available for every country in the world.

Metrology
This session started with a very interesting talk by Michael de Podesta (NPL, UK) about thermal measurements using an acoustic interferometer while humidity is measured simultaneously. Acoustic interferometry can, in some ways, be compared to the method for detecting gravitational waves. The device looked well constructed and reports the average air temperature along a path. The potential application of this technology is the in-situ measurement of the average reflective index of air along a path that is also being measured by a laser interferometer.

Vivak Badami of USA-based Zygo Corporation held a presentation about heterodyne, grating-based encoders for high-precision displacement measurements. They used a single 20 mW laser with multiple encoder read heads, so that the power-dissipating laser could be placed at

a distance. These encoders are able to measure two degrees of freedom. The cyclic error is typically lower than 0.05 nm rms, while the noise level is lower than 0.03 nm rms (at 20 kHz bandwidth).
These systems are typically applied in ASML machines. Calibration needs to be done after the final assembly of the complete machine, as mounting, etc., can change the form of the gratings. In fact, the form accuracy of gratings is harder to control than the flatness of the mirrors used in laser interferometer systems.

Mechanics & Control
The design and realisation of a position actuator (PACT) for the primary mirror segments of the European Extremely Large Telescope (E-ELT) was presented by Arjo Bos, Eindhoven University of Technology. A low-stiffness and cost-effective PACT was proposed and realised, with a voice coil as a fine stage and a coarse stage driven by a DC-motor and a leadscrew. A flexure-based straight guide was applied to minimise hysteresis and friction, based on sharp-folded leaf springs. An off-loading mechanism was integrated into the flexure-based straight guide, to minimise power dissipation during operation. These PACTs constitute an essential element in the world's largest optical and near-infrared telescope, which will become operational in the next decade.

To conclude

Accompanying the oral presentation programme, the poster sessions featured a variety of themes, from mechatronics & control and non-mechanical manufacturing processes to revision of the SI and metrology to applications of precision engineering in biomedical sciences. The prizes for best poster, determined through app voting, were awarded to:

1. Berend Denkena, et al. (Leibniz Universität Hannover), "Experimental investigation of an electromagnetic linear guide for ultra-precision high performance machining".
2. Berend Denkena, et al. (Leibniz Universität Hannover), "Mass production for micro end mills".
3. Julian Cedric Porsiel, et al. (Technische Universität Braunschweig and PTB), "The synthesis and metrology of colloidal semiconductor nanocrystals".

A series of scholarships were awarded by Heidenhaim to students to help them cover the costs of attending events such as the euspen Conference and expand their horizons concerning where their future careers in precision may lead them (Figure 4).

As always, the conference featured a variety of social events. This year the welcome reception was at the Hannover Zoo, in the Gasthaus Meyer barn to be precise, a half-timbered house in the regional style dating from 1669. The football challenge between a UK and an all-stars team, on a Hannover 96 pitch, ended 1-2; it was a friendly match and everybody had great fun. The student networking dinner, sponsored by ASML, also was an enjoyable meeting.

The exhibition running alongside the conference comprised some 35 international companies and institutions in precision engineering. On Friday, five technical tours were organised, to PTB, Volkswagen Commercial Vehicles, GEO600 (a ground-based interferometric gravitational wave detector located near Hannover), the Hannover Centre for Production Technology (PZH), and MTU Maintenance at Hannover airport, the world's largest independent provider of maintenance services for aircraft engines and industrial gas turbines.

4 *A series of scholarships were awarded by Heidenhaim to help students expand their horizons in precision engineerng. (Photo courtesy of euspen)*

Overall, the successful 17th euspen International Conference & Exhibition was a very informative, international and inspiring event. The 18th edition will be held 4-8 June 2018 in Venice, Italy. ■

INFORMATION
WWW.EUSPEN.EU/EVENTS/17TH-INTERNATIONAL-CONFERENCE-EXHIBITION

FROM MEDICAL IMPLANTS TO GASOLINE DIRECT INJECTION SYSTEMS

Photo-etching is nowadays seen as a leading manufacturing solution for numerous precise, complex and feature-rich applications where traditional processes fail to deliver. This article analyses its use in the manufacture of flexures in various industry sectors.

ALBERT TSANG

AUTHOR'S NOTE

Albert Tsang is the Technical Manager at Precision Micro, Birmingham, UK.

albert.tsang@precisionmicro.com
www.precisionmicro.com

Photo-etching allows for the mass manufacture of uniform parts, and can easily handle the demands of large production runs, with speedy start-up of digital tooling, and high throughput. However, due to the low set-up and tooling costs, it is equally well suited to prototype production. It not only copes well with difficult geometries, but also allows design engineers enormous flexibility, facilitating the tweaking of designs right up to the point of manufacture – ideal for spring and flexure prototyping.

Many industry sectors take advantage of photo-etching's ability to mass-produce hugely intricate, thin metal parts at a fraction of the cost of using alternative metal machining technologies. Unlike in other processes, the cost of (digital) tooling for photo-etching does not increase as part complexity increases, which stimulates innovation, as design engineers focus on optimised part functionality rather than cost.

1 *Photo-etching is suitable for almost any metal, including those hard-to-machine such as titanium.*

Photo-etching can work to extremely exacting tolerances (down to 0.025 mm), and is able to produce parts with different geometries at the same time on a single metal sheet. The process is also agnostic to the metal being processed, and can be applied to hard-to-machine titanium (Figure 1), and also to metals that would be either too conductive, too fragile, or too thin to be formed using stamping or laser cutting.

As no hard tooling is used in photo-etching, there is no distortion or stress on the metal being processed. In addition, parts produced by photo-etching are completely uniform, and also burr-free. Burrs are eliminated as metal is dissolved away uniformly and evenly until the desired geometries are achieved, and because of this there are also no uneven edges or other imperfections often associated with alternative processes.

Titanium

Precision Micro put its 50 years of experience in photo-etching to use for high-tech engineering applications of flexures including medical implants, automotive fuel injection and satellite cryogenic coolers. One recent flexure contract with a global medical implant manufacturer required that the flexure be made from titanium, the material of choice for many medical device OEMs due to its lightweight, strength and corrosion properties.

Difficulties in processing titanium effectively (an issue for a range of metal manufacturing processes) have been overcome by Precision Micro. Today, it is the only company in Europe offering a stand-alone, accredited titanium etching process for etching clean, stain-free titanium parts with the surface finish required, for instance, in implantable applications.

The implantable titanium flexure that Precision Micro is delivering requires very tight tolerances, and demands a focus on the precise thickness and biocompatible nature of the metal – all attributes of the photo-etching process. The raw material composition and the thickness variation over the surface of the etched part have a direct impact on its performance as it is in direct contact with the human body. It is vital that parts delivered to the client are absolutely clean, and the etching needs to be very homogenous.

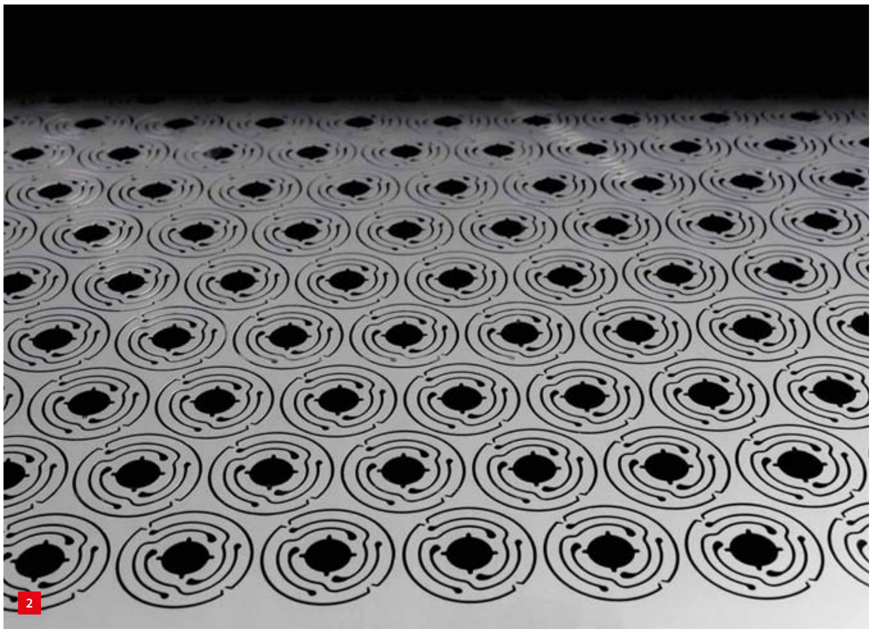
Automotive

Precision Micro also has extensive experience supplying flexures to automotive clients, today supplying flat springs to three of the five key global gasoline direct injection (GDi) systems manufacturers, including a five-year agreement with Continental to supply it with flexures. It is currently producing more than 1,000,000 GDi flexures each month (Figure 2).

Etching is considered the best method for producing such automotive flexures. It is particularly suited to working with high-performance spring steels, and the burr- and stress-free nature of the process means that springs actuate longer and more reliably, which is vital in safety-critical and exacting environments such as in GDi systems.

Conclusion

In flexure applications – in common with many others that Precision Micro work on – the overall integrity of the metal parts is vital, and the fact that photo-etching induces no degradation in the metal being processed is a huge advantage. Add to this the exacting tolerances that can be achieved using photo-etching, and the fact that it can be applied to virtually any metal, and it is unsurprising that the process is being seen as the 'go to' technology for the manufacture of precision metal parts. ■



2 *Photo-etched flexures used in gasoline direct injection systems.*

MACHINING AND SURFACE FINISHING ARE CONVERGING

Today, the production of precision parts is characterised by highly demanding specifications with regard to tolerances and surface quality. Innovative, advanced processes for deburring, surface finishing and shaping are making it possible to improve quality and productivity, as well as economic efficiency.

DORIS SCHULZ

AUTHOR'S NOTE

Doris Schulz is a journalist. Her agency, based in Korntal, Germany, specialises in PR solutions for technical products and services. This article was commissioned by DeburringEXPO.

www.schulzpressetext.de

In addition to the actual manufacturing processes, more and more attention is being focused on intermediate and downstream processes such as deburring and surface finishing for the production of high-quality components. On the one hand, this is targeted at burr-free components and workpieces with defined edges and fillets or a surface finish which minimises friction, wear and noise, and increases performance and service life.

On the other hand, manufacturing steps for precise shaping are required as well, and in this respect machining and surface finishing are converging to an ever greater extent. Innovative, advanced process are available which can be matched to the task at hand with high levels of productivity and economic efficiency, and which deliver reliable, reproducible results.

ECM of metallic workpieces

In the case of electrochemical machining (ECM), which is used in the fields of aviation and aerospace, the automotive industry, toolmaking, medical technology, microsystems engineering, the energy industry and other sectors – for mass production as well – metal is anodically removed from the surface of the workpiece. This procedure makes deburring possible in difficult-to-access areas such as internal bore intersections and pockets, and also permits burr-free shaping processes.

1 *In the case of ECM, a charge exchange takes place between the cathode and the anode (component) in an aqueous electrolyte solution, by means of which the workpiece is accurately machined in a targeted fashion. (Source: EMAG ECM)*

The machining tool, namely a cathode, and the component (as an anode) are connected to a generator which serves as a direct voltage source for the machining process. The component is machined highly accurately, independent of the metal's amorphous structure, by means of the charge exchange which takes place between the cathode and the anode in an aqueous electrolyte solution (Figure 1). This makes it possible to produce even very small, thin-walled contours, fillets, ducts, slots and wash-outs in workpieces made of practically any conductive metal. Since processing is contactless, the tooling is neither subject to wear due to the machining process, nor is it exposed to thermal or mechanical influences.

The characteristics and the shape of the tool holder determine where and how much material will be removed from the workpiece. Generator power is selected depending on the size of the surface to be machined at any given point in time, and also determines the speed at which material is removed and the achievable degree of surface roughness. Newly developed generators reach R_a values of 0.1 µm and better, depending on the initial state. Beyond this, they also prevent so-called stray machining which may lead to worse machining results at the anode's peripheral areas.

Precision ECM

As far as the actual processes are concerned, ECM and precision ECM (PECM) are both based on exactly the same principle. Essential differences include the distance from the cathode to the workpiece, and the use of an oscillating cathode in the PECM process. Similar to electrical discharge machining (EDM), this makes it possible to produce extremely accurate

3D shapes, contours and structures with very high levels of surface quality. R_a values of down to 0.03 µm can be achieved (Figure 2). As compared with the EDM process, machining is more accurate with regard to component dimensions and tolerances, and it doesn't result in any thermal influences.

Significantly reduced machining time is a further advantage of the PECM process as opposed to conventional manufacturing. Comparisons, for which a component was produced by means of a conventional process involving spark erosion, milling, drilling, grinding, deburring and lapping, as well as a PECM process with subsequent grinding, reveal a 90% reduction in pure manufacturing time. In addition to shaping, the PECM process is also used for microstructuring of surfaces, for example in order to optimise tribological properties.

ECM for AM

Components produced by means of additive manufacturing (AM) processes have already established themselves in various industry sectors such as aviation and medical technology. However, poor surface finishes after 3D printing, as well as blobs which remain on the part after removing the support structure, are still a great challenge. The new Coolpulse ECM process has been specially developed for, amongst other applications, surface finishing of 3D-printed, metallic components. It makes it possible to improve both micro- and macrostructures on internal and external surfaces in a single process, and specified surface characteristics can be reproducibly obtained with short cycle times. Furthermore, support structure remnants and surface defects can also be removed, which may result from 3D printing processes.

Abrasive flow machining

Abrasive flow machining (AFM) is used primarily for processing difficult-to-access workpiece areas and internal surfaces of high-quality components made of metal and ceramics, which cannot be processed by means of conventional procedures. Typical applications include rounding, polishing and deburring, as well as geometry optimisation and the minimisation of surface tension. The workpiece(s) is/are clamped for processing in one or more fixtures at the AFM machine (Figure 3).

The processing medium – abrasive particles which are matched to the respective task with regard to type, size and concentration and are embedded in a polymer mass of defined viscosity – is caused to flow through or over the area(s) of the component(s) to be processed in alternating directions at a defined pressure level by means of hydraulically powered pistons. The grinding medium functions like a liquid file. Process parameters are continuously monitored in order to assure reproducible results.

The AFM process makes it possible to improve surface roughness by a factor of five to eight as compared with initial surface condition (Figure 4). It's used, for example, in the automotive, plastics and aluminium industries, as well as in tool and mould making for the processing of, amongst other workpieces, impression dies, tablet moulds and deep-drawing dies. AFM has proven its worth in other sectors as well, including medical technology, aerospace and textile machinery manufacturing. AM of metallic components in modern industrial production is opening up an additional range of applications for AFM.

2 *Shaping of the vane contours and surface finishing (roughness at the front and sides) are completed in a single process step. (Source: Extrude Hone)*

3 *Schematic diagram of an AFM machine. (Source: Fraunhofer IPK)*

4 *With the help of AFM, surface roughness can be improved by a factor of five to eight as compared with initial surface condition. Surface tension is reduced at the same time. (Source: 4MI)*

5 *This stream finishing system with pulse drive, which is integrated into mass production in the automobile industry, is used for fully automated deburring, rounding and smoothing of cam shafts. Reduction of peak-to-valley height, for example from 0.2 to 0.1 µm, is accomplished in less than one minute. (Source: OTEC)*

Barrel finishing

Surf, stream and pulse finishing processes involve barrel finishing solutions for individual part processing which can be easily integrated into automated production lines (Figure 5). These new developments permit highly accurate, reliable deburring, edge rounding, smoothing, grinding and polishing of high-quality, geometrically complex components such as machine cutting tools and implants, as well as motor, gearbox and turbine components. These are tasks which usually had to be completed manually in the past by means of time-consuming, costly processes because no automated solutions were available.

The effects of pulse finishing are based on ideally matched relative motion between the processing medium and the workpiece. For example, the workpiece is secured in a clamping collet and accelerated to a speed of up to 2,000 rpm, decelerated and accelerated again in a rotating bowl within a very short period of time. Interaction with the inertia of the processing medium – i.e. due to the different speeds of the workpiece and the abrasive particles – results in targeted grinding action with accurate deburring, even in areas which have previously been inaccessible for barrel finishing, for example cross-holes in hydraulic components.

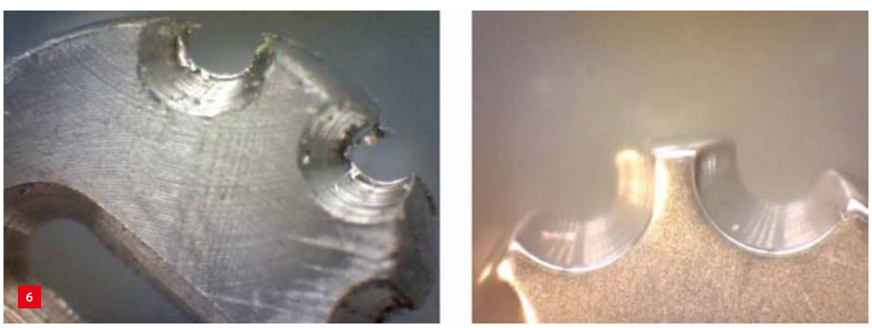
Polishing with plasma

Like electropolishing, plasma polishing is an electrolytic process, but it works with high voltage and an electrolyte based on a salt solution which is considered ecologically harmless. This process results in the formation of a plasma after the anodically polarised metallic workpiece has been immersed into the electrolytic bath. The plasma coats the workpiece, thus resulting in reduced roughness, as well as the removal of organic and inorganic contamination with just a minimal loss of mass. Depending on the material specification, material abrasion typically lies between 2 and 8 µm per minute and achievable roughness values are below 0.01 µm. The geometric shape of the component remains nearly unchanged.

DeburringEXPO

As the trade fair for deburring technologies and precision surface finishing, the DeburringEXPO provides a platform for users from all industry sectors. The second DeburringEXPO will take place at the Karlsruhe Exhibition Centre, Germany, on 10-12 October 2017. The exhibition portfolio includes equipment, systems and tools for belt grinding, brushing, abrasive flow machining, vibratory grinding, blasting with solid and liquid media, abrasive water-jet blasting, magnetic-abrasive deburring, ultrasonic deburring, chemical bath deburring, ECM, electron beam machining, TEM, mechanical deburring, buffing, polish honing, electrolytic polishing, plasma polishing, laser polishing, immersion and brush polishing, as well as measuring, test and analysis systems, and technical literature.

WWW.DEBURRING-EXPO.DE



6 *With the help of plasma polishing, for which an electrolyte consisting of 98% water and 2% salt is used, burrs as well as milling marks and material upturns have been removed and smooth, homogeneous surfaces have been obtained (photo on the right; the change in colour is due to different light conditions for the two photos). (Source: Plasotec)*

BEYOND TRADITIONAL PRECISION APPLICATIONS

The second Gas Bearing Workshop, held in late March in Düsseldorf, demonstrated that there are numerous opportunities for gas bearing applications beyond the traditional precision domain. One requirement for fulfilling the potential of gas bearing technology is standardisation, in teaching, calculations, performance specifications and measuring procedures. The applications may be exotic, the format for their technical characterisation should be standard.

JOS GUNSING

AUTHOR'S NOTE

Jos Gunsing is founder/owner of MaromeTech, a technology & innovation support provider, based in Nijmegen, the Netherlands. In his capacity of DSPE board member he acted as chair of the programme committee for the Gas Bearing Workshop 2017 and wrote this report on behalf of the programme committee, which included Farid Al-Bender (KU Leuven), Ron van Ostayen (TU Delft), Wolfram Runge (Beuth Hochschule für Technik Berlin), Ronald Schnabel (VDE/VDI-GMM) and René Theska (TU Ilmenau).

jos.gunsing@marometech.nl

The second Gas Bearing Workshop was held on 27 March 2017, in Düsseldorf, Germany, and attracted some forty participants (Figure 1). The workshop was organised by the VDE/VDI-Society Microelectronics Microsystems and Precision Engineering (GMM) from Germany and DSPE from the Netherlands. Partners in support of the workshop were the Bond van Materialenkennis (a Dutch network of experts in the area of material technology), the Consulate-General of the Netherlands in Düsseldorf, and NRW.International (the international business portal of North Rhine-Westphalia).

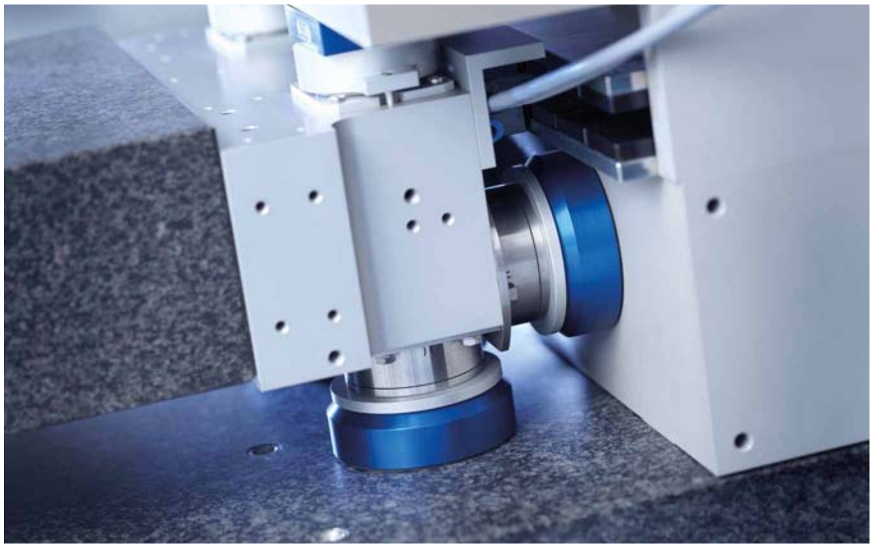
After the second Gas Bearing Workshop had been opened by VDE/VDI-GMM director Ronald Schnabel, Hans van den Heuvel, consul of the Netherlands in Düsseldorf, expressed his satisfaction with the German-Belgian-Dutch cooperation to gather gas bearing specialists from these and other countries. "High-precision applications are important niche products to keep our economies very much alive!"

Keynote

The keynote was then presented by Henny Spaan (IBS Precision Engineering), who gave an inspiring introduction into the subject of air bearings beyond traditional precision applications. After showing traditional application examples of porous bearings in semicon and coordinate measurement machines, Spaan presented examples in medical devices (enhancing image resolution and reducing sound in a CT scanner), testing of micro-satellites and satellite solar panels under simulated zero-gravity conditions, and flat panel display handling (huge panels carried with tight fly-height control down to 5 µm height accuracy).

Spaan also showed exotic applications, such as a special rotary pendulum work of light art for the Glow festival in Eindhoven, the Netherlands, which would have been impossible to realise without air bearings. Another topic was controlling the shape of very thin substrates with the aid of gas bearings, which was carried out in an experimental test set-up. Air bearings in vacuum,

1 *Impression of the Gas Bearing Workshop 2017 on 27 March in Düsseldorf, Germany, with the chairman of the day, Wolfram Runge. (Photos courtesy of Ronald Schnabel)*



2 *Applications of air bearings in measurement machines. (Photos courtesy of IBS Precision Engineering)*

for example in lithography, or applied as a barrier between two gas pressure levels in, for example, oil-free turbines closed a wide range of non-conventional gas bearing applications.

Concrete

Christoph Hahm (Technische Universität Ilmenau) presented his research work with respect to air bearings being built in concrete as a mechanically stable, low-thermal-expansion and precisely manufacturable material without a need for subsequent finishing. It can be cast in a mould with a very high surface quality so that it can be used as an alternative to granite and/or polymer tables. Of course, compensating (using Ansys FEM analysis) the deformations due to the thermal effects during the curing of the concrete and determining the deformations afterwards can help to optimise the results for small series production. Currently, roughness values of 20 μm can be obtained.

Standardisation

Gas bearing pads from different vendors seem very similar. However, no DIN regulations are available, so every customer comes with its own requirements. Is standardisation possible and advantageous? A lively panel discussion on the pros and cons of standardisation in gas bearings took place between Wolfram Runge (Beuth Hochschule für Technik Berlin), who also acted as chairman of the day, Norbert Steffens (Hexagon Metrology) and Werner Schwarz (Mikrotechnik).

The gas bearing market is not small but very diverse, even in quasi-standard coordinate measurement machines which are produced in considerable numbers. A lot of discussion was devoted to the use of standardisation to the customer. Starting with standardisation in teaching and calculation methods may already help to come up with some sort of standardised understanding of gas bearing design and behaviour. Such a way of working could be compared to the approach of rolling bearings, with their Hertzian contacts, friction and fatigue. The same standardisation plea applies to performance specifications and measuring procedures.

Low pressure

Jack van der Sanden (ASML) talked about gas bearing stability in low-pressure environments. Important topics are stiffness estimation in the high-frequency domain and stiffness/damping as a function of frequency. A potential danger at high frequencies is the instability of the gas bearing. The assumption of isothermal compression is made when modelling the bearings. The measurements take place in a low-pressure set-up; this is necessary to take account of the gas laws for a compressible medium. Both measurement and simulation yielded good results while showing a sufficiently large overlap.

Semiconductor metrology

Bradley Engel (Physik Instrumente) discussed air bearings in semiconductor metrology. He showed a lot of examples in process metrology, e.g. for wafer processing, large gantries, etc. Especially interesting were his examples of a 3-degree-of-freedom spherical air bearing and a dual or triple wedge air bearing to adjust z-heights of equipment in a frictionless manner. In the latter application, the potential accuracy may be limited unless the height is directly measured in the position feedback loop.

High-speed rotations

Marius Nabuurs (KU Leuven) spoke about tilting pad journal air bearings (Figure 3) for high-speed applications like turbo-compressors: micro gas turbines, typically with a rotating mass under 1 kg, rotational speeds above 100,000 rpm and a high-temperature environment where low frictional losses are a must. The tilting pads provide a solution to overcome the destabilisation effect in conventional (full, rigid) journal air bearings where the aerodynamic pressure profile is not symmetric with respect to the load vector (Figure 3a). The freedom of the pad to tilt eliminates the misalignment between load and film reaction vector, thereby reducing the undesirable cross-coupling between terms in the stiffness matrix and thus pushing the onset speed of instability to much higher limits.

For research purposes a monolithic, spark-eroded prototype has been designed and built (Figure 3b). With a maximum rotational speed of 220,000 rpm being realised, yield stress at the shaft propeller blades is now the limiting factor, and not the (in)stability of the bearing.Tests with a 600 mgmm imbalance have been carried out to see how the tilting pad air bearings deal with that: the imbalanced-whirl amplitude remained below 7 µm. The tilting pad air bearing was also able to cope with the thermal and centrifugal growth in shaft diameter. It therefore offers a robust gas bearing solution for rotating equipment that would become hot at extremely high speeds.

Automotive

Michael Mayer (Robert Bosch) spoke about the potential and challenges for future Bosch products fitted with gas bearings. In general, the trends in automotive are downsizing, high power density, lower material cost, better efficiency and oil-free solutions. In the automotive industry, turboblowers are the most obvious candidates for air bearing applications. Product cost in combination with the required performance is the dominant factor.

Potential problems:
- high power loss with ordinary fluid bearings;
- robustness gap variations;
- (rotor) dynamic instability;
- positioning inaccuracy/poor damping;
- lack of technological maturity of the critical manufacturing processes of 100,000+ per year series;
- availability (i.e. lack of) of design tools;
- scarcity of available experts.

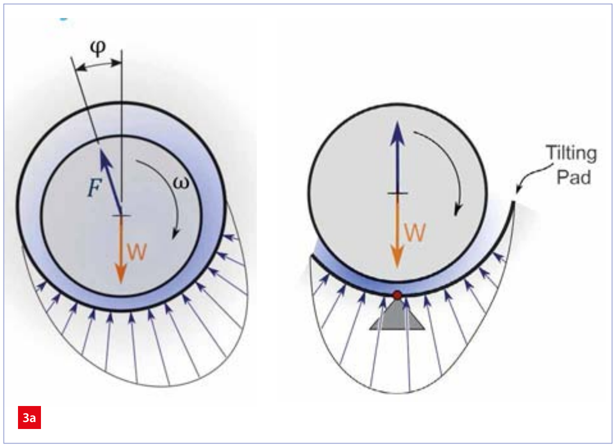
Alternatives which may be applied:
- herringbone groove journal bearing pad;
- foil bearing;
- externally pressurised bearing;
- tilting pad bearing.

Although the potential is increasing, Robert Bosch is reluctant to use gas bearings in automotive applications, because they are not mature enough and know-how and design tools are still lacking.

Wrap-up

Nevertheless, the scope is widening. Additive manufacturing with 'built-in' control of porosity may play a role in extending the possibilities of applying gas bearings. Harsh environments are also areas that are typically suitable for gas bearings. After interesting presentations and panel discussion, Wolfram Runge expressed his wish to hold a subsequent workshop in 2019. Having seen such a wide variety of gas bearings and an even wider range of applications, and despite the remarks by Robert Bosch with respect to automotive applications, he had every reason to be optimistic about the future of gas bearings. ■

3 *Tilting pad bearing. (Images courtesy of KU Leuven)*
(a) Principle: compensating for the effect that due to aerodynamic action the pressure profile is not symmetric with respect to the load vector w.
(b) Top view of the realisation.
(c) Exploded side view of the design.



3a

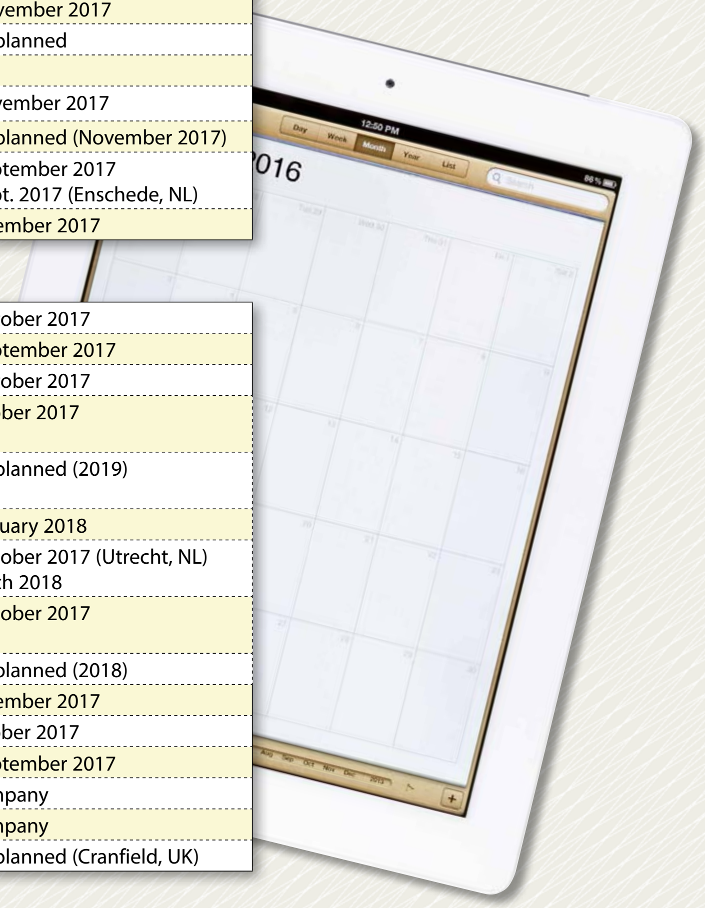

3b


3c

INFORMATION
WWW.GAS-BEARING-WORKSHOP.COM

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date (location, if not Eindhoven, NL)
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	2 October 2017
Mechatronics System Design - part 2 (MA)	5	HTI	9 October 2017
Design Principles	3	MC	25 September 2017
System Architecting (Sioux)	5	HTI	30 October 2017
Design Principles Basic (SSvA)	5	HTI	to be planned
Motion Control Tuning (MA)	6	HTI	15 November 2017
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	7 November 2017
Actuation and Power Electronics (MA)	3	HTI	14 November 2017
Thermal Effects in Mechatronic Systems (MA)	3	HTI	to be planned
Summer school Opto-Mechatronics (DSPE/MA)	5	HTI	-
Dynamics and Modelling (MA)	3	HTI	27 november 2017
Summer School Manufacturability	5	LiS	to be planned (November 2017)
Green Belt Design for Six Sigma	4	HI	20 September 2017 26 Sept. 2017 (Enschede, NL)
RF1 Life Data Analysis and Reliability Testing	3	HI	6 November 2017
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	31 October 2017
Applied Optics	6.5	MC	14 September 2017
Machine Vision for Mechatronic Systems (MA)	2	HTI	11 October 2017
Electronics for Non-Electronic Engineers – Basics Electricity and Analog Electronics (T2Prof)	6	HTI	9 October 2017
Electronics for Non-Electronic Engineers – Basics Digital Electronics (T2Prof)	4	HTI	to be planned (2019)
Modern Optics for Optical Designers (T2Prof)	10	HTI	19 January 2018
Tribology	4	MC	31 October 2017 (Utrecht, NL) 6 March 2018
Basics of Design Principles for Ultra-Clean Vacuum Applications (SSvA)	4	HTI	30 October 2017
Experimental Techniques in Mechatronics (MA)	3	HTI	to be planned (2018)
Advanced Motion Control (MA)	5	HTI	6 November 2017
Advanced Feedforward Control (MA)	2	HTI	4 October 2017
Advanced Mechatronic System Design (MA)	6	HTI	22 September 2017
Finite Element Method	5	ENG	in-company
Design for Manufacturing – Design Decision Method	3	SCHOUT	in-company
Precision Engineering Industrial Short Course	5	CRANF. UNI.	to be planned (Cranfield, UK)



ECP² program powered by euspen

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

WWW.ECP2EU.WPENGINE.COM

Course providers

- Engenia (ENG)
  WWW.ENGENIA.NL
- The High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- LiS Academy (LiS)
  WWW.LISACADEMY.NL
- Schout DfM (SCHOUT)
  WWW.SCHOUT.EU
- Holland Innovative (HI)
  WWW.HOLLANDINNOVATIVE.NL
- Cranfield University
  WWW.CRANFIELD.AC.UK

Content partners

- Dutch Society for Precision Engineering (DSPE)
  WWW.DSPE.NL
- Mechatronics Academy (MA)
  WWW.MECHATRONICS-ACADEMY.NL
- Settels Savenije van Amelsvoort (SSvA)
  WWW.STTLS.NL
- Sioux
  WWW.SIOUX.EU
- Technical Training for Professionals (T2Prof)
  WWW.T2PROF.NL

Symetrie – Hexapods for metrology and positioning

Founded in 2001 and located in Nimes, France, Symetrie designs and manufactures high-precision positioning & motion hexapods that meet the most specific needs of industries and research laboratories. The company's core competencies lie in mechanical engineering, electronics, control software and tests. Symetrie was co-founded by Olivier Lapierre and Thierry Roux, who came from LNE, the French national metrology laboratory.

Products

For over 15 years, Symetrie has developed a strong expertise in hexapods, which are parallel kinematics systems used to position objects in space following the six degrees of freedom (three translations and three rotations). Symetrie is experienced in choosing and using the most adapted technologies in terms of motors, encoders, joints, materials, et cetera, according to the customer's application and budget.

When the company started, users were looking for resolutions (minimum incremental motion) in the range of 100 to 10 µm. Nowadays, submicronic resolution is common and people are regularly asking for resolutions of several tens of nanometers to meet the ever increasing challenges of space optics, particle accelerators or semiconductor industry. That is why Symetrie's R&D department works every day to improve technologies and control systems.

Applications and examples

Symetrie hexapods offer high resolution, high accuracy, high reliability and stiffness. They are easy to integrate and come with an ergonomic software. They can be found in many areas, such as optics, space, astronomy, universities, naval, defense, automotive, research, synchrotrons, ...

Sample positioning for EUV lithography

TNO has built an EUV (Extreme Ultra Violet) lithography facility to help the semiconductor industry in testing the EUV effects on the materials and components of their future integrated circuits in order to address contamination and lifetime challenges. With high resolution and stiffness, a customised hexapod is positioning the samples via manipulators inside a vacuum chamber in an ISO 5 cleanroom.

1 *Hexapod for EUV lithography. (Credits: TNO)*

Meteosat Third Generation (MTG) satellites

A large and accurate hexapod was designed to calibrate optical instruments that will be onboard of the MTG satellites ordered by the European Space Agency (ESA) for weather forecast. The 1 m diameter hexapod has a linear accuracy of ±0.1 µm over 400 mm and is used by Bertin Technologies as a key part of their Optical Ground Support Equipment.

To achieve higher accuracy on an even larger workspace, Symetrie has recently started a joint laboratory with LIRMM, the Robotics University of Montpellier, France. ■

2 *Hexapod for space optics calibration. (Credits: Bertin Technologies)*

INFORMATION
WWW.SYMETRIE.FR

YPN VISIT TO HEIDENHAIN NEDERLAND

On 30 March, YPN (DSPE's Young Precision Network) paid a visit to Heidenhain Nederland in Ede, the Netherlands, during the Demoweek 2017 (see the report in the April issue of Mikroniek). After a warm welcome in a German-style bar with drinks accompanied by 'Bratwurst und Sauerkraut', Jan Sturre (Sales Manager) started his presentation about the limits and possibilities of optical encoders. He titled it: "Heidenhain broke a barrier".

Sturre started with a short introduction on Dr. Johannes Heidenhain GmbH and its position in the development and manufacturing of encoders and numerical controls for precision positioning tasks. After outlining the theory of different optical encoder principles with their advantages and disadvantages, he got into more detail on digital interpolation. He also discussed the definitions and boundaries of resolution, accuracy and precision. The specifications of Heidenhain encoders distinguish between 'long-wave errors', which can be compensated for to a large extent with calibration, and 'short-wave errors', which will remain in the resulting error after calibration. Part of these short-wave errors are interpolation errors.

Until recently, a rule of thumb when estimating the maximum interpolation error was to use max. 1% of the signal period. Now, Heidenhain has broken that barrier (hence the title of Sturre's presentation) by marketing an ultra-precision encoder system with a signal period of 0.512 μm with an interpolation error of max. ±1 nm (0.2%). Further, Heidenhain can now not only specify the accuracy grade (long-wave error per meter), but also the accuracy within small sections of the range, the interpolation errors, and the estimated error due to noise for every encoder. This gives engineers more insight when determining the possibilities and boundaries of precision for each encoder system.

After this motivating talk, a few case-study demos were shown during a tour. Firstly, the robustness against severe-scale contaminations was shown, by comparing two exposed linear encoder systems on a linear stage guided by ball bearings. Then, a translating stage for machining purposes, driven by a spindle with rotary electromotor, was showcased with an encoder in a co-located (rotary encoder at motor side) and non-co-located (linear encoder at translating stage) arrangement.

Both repeatability and temperature were measured while controlling the position of the stage using the rotary co-located sensor ('indirect') and linear non-co-located sensor ('direct'). The effect of a temperature variation using only a co-located sensor after a minute of operation was visible: micrometer positioning errors were obtained with only a few degrees rise in temperature. Using the linear non-co-located sensor, the measured positional error was zero during temperature fluctuations.

Finally, the 'barrier breaking' encoder was shown in a set-up with a linear stage guided by air bearings. This set-up was able to measure sub-nanometers inflicted by disturbances from the environment, after fixing the moving stage to the stationary world.

This interesting afternoon ended with a Bavarian buffet and time for networking. YPN would like to thank Heidenhain, and in particular Jan Sturre as host of the day, for the hospitality and the inspiring visit.

(report by Arjo Bos and Jordan Bos)

WWW.HEIDENHAIN.NL

Impression of the YPN visit to Heidenhain, with Jan Sturre demonstrating one of the encoder set-ups.

BROAD PROGRAMME FOR THE **DSPE OPTICS WEEK** IN AACHEN

The Optics & Optomechanics week is a unique collaboration by Dutch, German and international organisations. The third edition of the biennial event will be organised on 23-26 September at the RWTH Aachen University, Germany. This week brings outstanding international speakers and lecturers, from semicon to medical, from industry to academia.

The week kicks off on Monday 23 October with the DSPE Optics and Optomechanics Symposium & Fair. As chairman of the day, Jos Benschop, Senior Vice President Technology of ASML, will preside over the presentation of a variety of topics, including packaging and micro-optics, 3D printing of optical components, adaptive optics, thermal effects in optical systems, and complex optical coatings. Speakers come from, for example, Fraunhofer, TNO, Qioptiq and Demcon Focal.

Tuesday 24 October will see the debut of a new activity, Demonstration Day, which brings participants to the Fraunhofer IPT and ILT institutes and the Digital Photonic Production research campus, which was established in Aachen two years ago. The number of participants is limited to 50, so early registration is advised.

The two-day course on Optomechanics will be delivered on 24-25 October by Daniel Vukobratovich, Senior Scientist at Ratheyon, as well as Adjunct Professor in the College of Optical Sciences, University of Arizona, USA. The course is targeted at (systems) engineers, Ph.D. students and technicians and will cover optics and optics mounting alignment, dynamics and thermal as well as material stability.

The three-day course on Optical Design for Imaging Systems, coordinated by Prof. H.P. Urbach from Delft University of Technology, will take place on 24-26 October. The course is a continuation of the European SMETHODS project (SMEs Training and Hands-on practice in Optical Design and Simulation), delivering hands-on training in design and optimisation of optical imaging systems supported by a theoretical introduction.

WWW.OPTICSWEEK.NL (INFORMATION AND REGISTRATION)

■ *Impressions of the DSPE Optics Week 2015 in Delft, the Netherlands.*

Interest in visiting German optics networks in Wetzlar and Aachen?

Last November, members of the German optics network Optence visited the south of the Netherlands to meet the Dutch networks of DSPE and Brainport Industries. This visit was an eye-opener for Optence and inspired them to invite for a return visit to the German regions of Wetzlar and Aachen at the end of September.

The preliminary programme comprises visits to companies such as Befort Wetzlar, Leica Microsystems and Carl Zeiss Sport Optics in the Wetzlar region (25 September); participation in the Wetzlarer Herbsttagung exhibition (26 September), devoted to modern optics manufacturing; and visits in the Aachen region to Aixemtec, Fraunhofer IPT and Innolite (27 September), for example.

To gauge the interest in participating in this visit, an online form can be completed by DSPE and Brainport Industries members. Closing date is 3 July.

WWW.DSPE.NL/CENTRAAL/EVENTS/VISIT-TO-GERMAN-OPTICS-NETWORKS-IN-WETZLAR-AND-AACHEN

UPCOMING **EVENTS**

11-15 September 2017, Ilmenau (DE)

59th Ilmenau Scientific Colloquium

Flagship event of the Technische Universität Ilmenau, organised by the Department of Mechanical Engineering. Topics include Precision Engineering and Metrology; Industry 4.0 and Digitalisation in Mechanical Engineering; Mechatronics, Biomechatronics and Mechanism Technology; Systems Engineering; and Innovative Metallic Materials.

59th IWK

WWW.TU-ILMENAU.DE/IWK

18-22 September 2017, Braga (PT)

MNE 2017

The 43st international conference on micro- and nanofabrication and manufacturing using lithography and related techniques is devoted to recent progress and future trends in the fabrication and application of micro- and nanostructures and devices. The event will be held at INL – International Iberian Nanotechnology Laboratory.

INL International Iberian Nanotechnology Laboratory

WWW.MNE2017.ORG

---

4 October 2017, Bussum (NL)

15th National Cleanroom Day

Event for cleanroom technology users and suppliers in the fields of micro/nano electronics, healthcare, pharma and food, organised by the Dutch Contamination Control Society, VCCN.

WWW.VCCN.NL

10-12 October 2017, Leuven (BE)

Special Interest Group Meeting: Additive Manufacturing

The 4th in a series of joint Special Interest Group meetings between euspen and ASPE on dimensional accuracy and surface finish in additive manufacturing.

WWW.EUSPEN.EU

10-12 October 2017, Karlsruhe (DE)

DeburringEXPO

Second edition of trade fair for deburring technology and precision surface finishing.
See also the article on page 26 ff.

DEBURRING EXPO

WWW.DEBURRING-EXPO.COM

23-26 October 2017, Aachen (DE)

Optics & Optomechanics Week

A unique collaboration by Dutch, German and international organisations comprising the DSPE Optics and Optomechanics Symposium & Fair on 23 October, Demonstration Day (at the Fraunhofer IPT and ILT institutes and the Digital Photonic Production research campus) on 24 October, and two courses. The Optomechanics course will be given by Daniel Vukobratovich on 24-25 October, and the Course on Optical Design for Imaging Systems is on 24-26 October.

WWW.OPTICSWEEK.NL

24-26 October, Stuttgart (DE)

Parts2clean 2017

International trade fair for industrial parts and surface cleaning.

WWW.PARTS2CLEAN.COM

---

29 October - 3 November 2017, Charlotte (NC, USA)

32th ASPE Annual Meeting

Meeting of the American Society for Precision Engineering, introducing new concepts, processes, equipment, and products while highlighting recent advances in precision measurement, design, control, and fabrication. ASML will deliver the keynote address.

ASPE.NET

November 2017 (exact dates to be set), Leiden (NL)

LiS Academy Summer School Manufacturability

5-Day summer school targeted at young professional engineers with a limited knowledge of and experiences with manufacturing technologies and associated manufacturability aspects.

WWW.LISACADEMY.NL

8-9 November 2017, Glasgow (UK)

Special Interest Group Meeting Micro/Nano Manufacturing

The focus will be on novel methodological developments in micro- and nano-scale manufacturing, i.e., on novel process chains including process optimisation, quality assurance approaches and metrology.

WWW.EUSPEN.EU

15-16 November 2017, Veldhoven (NL)

Precision Fair 2017

Sixteenth edition of the Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum.

Precision Fair

WWW.PRECISIEBEURS.NL

---

23 November 2017, Utrecht (NL)

Dutch Industrial Suppliers & Customer Awards 2017

Event organised by Link Magazine, with awards for best knowledge supplier and best logistics supplier, and the Best Customer Award.

WWW.LINKMAGAZINE.NL

12-13 December 2017, Amsterdam (NL)

International MicroNanoConference 2017

Microfluidics, photonics and nano-instrumentation are main topics of this industry- and application-oriented conference, exhibition and demo event.

WWW.MICRONANOCONFERENCE.ORG

ASML history: architects and money machine

Wim van der Leegte, figurehead of Dutch manufacturing, was presented with the first copies of two Dutch-language books in Eindhoven's Evoluon conference centre on Thursday 8 June. Their titles translate as 'The Architects of ASML' and 'The Money Machine – The Turbulent Youth of ASML'. Both publications from Techwatch Books were authored by René Raaijmakers, publisher at Techwatch and initiator of Bits&Chips. The book presentation was attended by a sizeable number of Philips and ASML veterans and the crème de la crème of the Dutch supply industry.

'Architects' is the 'pop science' edition (640 pages) on the history of ASML and its lithography technology. 'Money Machine' is the management version, purged to a large extent of technical and anecdotal material, and abridged to a 'mere' 440 pages. Furthermore, 'money' refers to both the high margins ASML is making on its machinery and the huge investments it is making in technological development, in the past and at present.

The books cover the origins of ASML, which was founded in 1984, as well as its formative years up till around 1996. Author René Raaijmakers is promising a sequel, though he will have a hard time getting the people he talks with to open up in the way that they did for his first books. Consider the ups & downs in relationships with suppliers and the turbulent development of EUV (extreme ultraviolet) lithography. That history is perhaps still too fresh. It is sure to be an exciting process.

WWW.TECHWATCHBOOKS.NL/ARCHITECTEN

WWW.ASML.COM

NEWS

High-acceleration linear motor

Magnetic Innovations, based in Veldhoven, the Netherlands, has developed a novel limited-stroke actuator design to enable a new generation of high-accuracy stages. The moving-magnet principle was implemented to reduce the disturbance effects of power cables on the moving part and to improve the thermal path of the stator part. The lightweight moving part is directly propelled in the centre of gravity, which strongly reduces all kind of dynamic disturbance forces and torques felt in a high-precision stage. Low K-factor ripple and attraction force ripple enables high dynamic control performance.

The optimised permanent-magnet array and coil assembly yields a high steepness, meaning it causes little dissipation in the coils for high forces. The magnetic design is free of cogging forces and exhibits very little end-effects enabling a functional stroke of 50 mm in X- and Y-direction. The static part is easily connected to a force frame or can function as a balance mass to reduce overall machine disturbance forces. The static coil part can be cooled with forced air cooling, water cooling or heat-pipe technology depending on the required force density. In combination with a suitable amplifier, high peak forces can be generated during servo control.

WWW.MAGNETICINNOVATIONS.COM

New piezo walking drive

If large optics, detectors or camera set-ups in industrial applications need to be positioned with nanometer precision, drive solutions are necessary that not only work with the required precision, but can also withstand the high continuous load. Physik Instrumente (PI) has added PICMAWalk walking drives to its extensive product portfolio for those types of applications.

PICMA® actuators aligned in the shape of a V ensure a reliable and very exact feed motion with a holding force of at least 60 N, 50 N push/pull force, and a velocity up to 15 mm/s. Loads up to 5 kg can be positioned with exact nanometer precision. Runner lengths are variable between 25 and 100 mm. The reliable lift-off behaviour of the actuators in conjunction with exactly matched flexure guides guarantees a long lifetime.

PI's piezo walking drive, with PICMA® actuators aligned in the shape of a V.

WWW.PHYSIKINSTRUMENTE.COM

Next generation of LabVIEW

NI has announced LabVIEW NXG 1.0, the first release of the next generation of LabVIEW engineering system design software. LabVIEW NXG bridges the gap between configuration-based software and custom programming languages with an innovative new approach to measurement automation.

"Thirty years ago, we released the original version of LabVIEW, designed to help engineers automate their measurement systems without having to learn the esoterica of traditional programming languages. LabVIEW was the 'non-programming' way to automate a measurement system", said Jeff Kodosky, NI co-founder and business and technology fellow, known as the 'Father of LabVIEW'. "Now, we have designed LabVIEW NXG from the ground up to embrace a streamlined workflow. Common applications can use a simple configuration-based approach, while more complex applications can use the full open-ended graphical programming capability of the LabVIEW language, G."

WWW.NI.COM/LABVIEW

Automation Technology

Festo BV
Schieweg 62
2627 AN DELFT
The Netherlands
T +31 (0)15-2518890
E sales@festo.nl
W www.festo.nl
Contact person:
Mr. Ing. Richard Huisman

Festo is a leading world-wide supplier of automation technology and the performance leader in industrial training and education programs.

member DSPE

Cleanrooms

Brecon Group
Kroonstraat 6
4879 AV Etten-Leur
T +31 (0)76 504 70 80
E brecon@brecon.nl
W www.brecon.nl

Brecon Group can attribute a large proportion of its fame as a cleanroom builder to continuity in the delivery of quality products within the semiconductor industry, with ASML as the most important associate in the past decades.

Brecon is active with cleanrooms in a high number of sectors on:
* Industrial and pharmaceutical
* Healthcare and medical devices

Connect 2 Cleanrooms BV
Graadt van Roggenweg 328-344
(Blok D)
3531 AH Utrecht
Nederland
T +31 (0)30 298 2112
E info@connect2cleanrooms.com
W www.connect2cleanrooms.nl

Our cleanroom solutions are bespoke and scalable, encouraging efficiency through flexible design. We help organisations reduce failure rates by getting it right first time.

member DSPE

Development

TNO
T + 31 (0)88-866 50 00
W www.tno.nl

TNO is an independent innovation organisation that connects people and knowledge in order to create the innovations that sustainably boosts the competitiveness of industry and wellbeing of society.

member DSPE

Development and Engineering

ACE ingenieurs- & adviesbureau
werktuigbouwkunde en
elektrotechniek BV
Dr. Holtroplaan 46
Postbus 7030, 5605 JA Eindhoven
5652 XR Eindhoven
T +31 (0)40 - 2578300
F +31 (0)40 - 2578397
E info@ace.eu
W www.ace.eu

ACE has developed into a leading engineering and consultancy firm with a strong focus on mechanics and mechatronics. Services include conceptualization, development, engineering and prototyping.

member DSPE

Development and Engineering

Segula Technologies Nederland B.V.
De Witbogt 2
5652 AG Eindhoven
T +31 (0)40 8517 500
W www.segula.nl

SEGULA Technologies Nederland BV develops advanced intelligent systems for the High Tech and Automotive industry. As a project organisation, we apply our (engineering) knowledge to non-linear systems. This knowledge is comprised of systems architecture and modelling, analysis, mechanics, mechatronics, electronics, software, system integration, calibration and validation.

member DSPE

Education

LiS Leidse instrumentmakers School

Leiden school for Instrument-makers (LiS)
Einsteinweg 61
2333 CC Leiden
The Netherlands
T +31 (0)71-5681168
F +31 (0)71-5681160
E info@lis.nl
W www.lis.nl, www.lisacademy.nl

The LiS is a modern level 4 MBO school, with a long history (founded in 1901). The school encourages establishing projects in close cooperation with industry and scientific institutes, allowing for high level “real life” work. Under the name LiS-Engineering and LiS-Academy the school accepts contract work and organizes education for others.

member DSPE

PAO TECHNIEK EN MANAGEMENT

PAO Techniek en Management

De Bouwcampus
TU Delft, gebouw 26
Van der Burghweg 1
2628 CS Delft
Postbus 5048
2600 GA Delft
T +31 (0)15-2784618
E info@paotm.nl
W www.paotm.nl

Electrical Discharge Machining (EDM)

CVT precisie draadvonken

CVT BV
Heiberg 29C
5504 PA Veldhoven
The Netherlands
T +31 (0)497 54 10 40
E info@cvtbv.nl
W www.heinmade.com

Partner high tech industry for wire EDM precision parts. Flexible during day shifts for prototyping. Outside office hours low cost unmanned machining. Call and enjoy our expertise!

member DSPE

terhoek edm & precision solutions

Ter Hoek Vonkerosie
Propaanstraat 1
7463 PN Rijssen
T +31 (0)548 540807
F +31 (0)548 540939
E info@terhoek.com
W www.terhoek.com

INNOVATION OF TOMORROW, INSPIRATION FOR TODAY
Staying ahead by always going the extra mile. Based on that philosophy, Ter Hoek produces precision components for the high-tech manufacturing industry.

We support customers in developing high-quality, custom solutions that can then be series-produced with unparalleled accuracy. That is what makes us one of a kind.
It is in that combination of innovative customization and repeated precision that we find our passion. Inspired by tomorrow’s innovation, each and every day.

member DSPE

Lasers, Light and Nanomotion

LASER 2000

Laser 2000 Benelux C.V.
Voorbancken 13a
3645 GV Vinkeveen
Postbus 20, 3645 ZJ Vinkeveen
T +31(0)297 266 191
F +31(0)297 266 134
E info@laser2000.nl
W www.laser2000.nl

Laser 2000 Benelux considers it her mission to offer customers the latest photonics technologies available.
Our areas of expertise are:

- Lasers, scanners and laser machines for industry and research
- Light metrology instruments for LED and luminaire industries
- Light sources for scientific applications
- Piezo- and stepper motion products for nano- and micro positioning
- Inspection and research grade high speed cameras
- Laser safety certified products

Mechatronics Development

SIOUX CCM MECHATRONICS SOURCE OF YOUR TECHNOLOGY

Sioux CCM
De Pinckart 24
5674 CC Nuenen
T +31 (0)40 2635000
F info.ccm@sioux.eu
W www.sioux.eu

Sioux CCM is a technology partner with a strong focus on mechatronics.
We help leading companies with the high-tech development, industrialization and creation of their products, from concept stage to a prototype and/or delivery of series production.
Commitment, motivation, education and skills of our employees are the solid basis for our business approach

Sioux CCM is part of the Sioux Group.

member DSPE

MTA CREATING MACHINES TOGETHER

Manufacturing Technical Assemblies (MTA) b.v.
Waterbeemd 8
5705 DN Helmond
T +31 (0)492 474992
F +31 (0)492 474510
E info@m-t-a.nl
W www.m-t-a.nl

MTA is an high-tech system supplier specialized in the development and manufacturing of mechatronic machines and systems.
Our clients are OEM s in the Packaging, Food, Graphics and High-tech industries.

member DSPE

Mechatronics Development

MI-Partners
Dillenburgstraat 9N
5652 AM Eindhoven
The Netherlands
T +31 (0)40 291 49 20
F +31 (0)40 291 49 21
E info@mi-partners.nl
W www.mi-partners.nl

MI-Partners is active in R&D of high-end mechatronic products and systems. We are specialised in concept generation and validation for ultra-fast (>10g), extremely accurate (sub-nanometers) or complex positioning systems and breakthrough production equipment.

member DSPE

Metal Precision Parts

Etchform BV
Arendstraat 51
1223 RE Hilversum
T +31 (0)35 685 51 94
F info@etchform.com
W www.etchform.com

Etchform is a production and service company for etched and electroformed metal precision parts.

member DSPE

Micro Drive Systems

Maxon Motor Benelux

The Netherlands

Head Office
maxon motor benelux bv
Josink Kolkweg 38
7545 PR Enschede

South
High Tech Campus 9
5656 AE Eindhoven
T +31(053) 744 0 744
E info@maxonmotor.nl
W www.maxonmotor.nl

Belgium / Luxembourg

maxon motor benelux bv
Schaliënhoevedreef 20C
2800 Mechelen - Belgium
T +32 (15) 20 00 10
F +32 (15) 27 47 71
E info@maxonmotor.be
W www.maxonmotor.be

maxon motor is the worldwide leading supplier of high precision drives and systems. When it really matters! Try us.

member DSPE

Micro Drive Systems

FAULHABER Benelux B.V.
Drive Systems
High Tech Campus 9
5656 AE Eindhoven
The Netherlands
T +31 (0)40 85155-40
E info@faulhaber.be
E info@faulhaber.nl
W www.faulhaber.com

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

Physik Instrumente (PI)
Benelux BV
Hertog Hendrikstraat 7a
5492 BA Sint-Oedenrode
The Netherlands
T +31 (0)499-375375
F +31 (0)499 375373
E benelux@pi.ws
W www.pi.ws

PI is the world's leading provider of nanopositioning products and systems. All key technologies are developed, manufactured and qualified in-house by PI: Piezo components, actuators and motors, magnetic drives, guiding systems, nanometrology sensors, electronic amplifiers, digital controllers and software.

member DSPE

Motion Control Systems

Aerotech United Kingdom
The Old Brick Kiln
Ramsdell, Tadley
Hampshire RG26 5PR
UK
T +44 (0)1256 855055
F +44 (0)1256 855649
W www.aerotech.co.uk

Newport Spectra-Physics B.V.
Vechtensteinlaan 12 - 16
3555 XS Utrecht
T +31 (0)30 6592111
E netherlands@newport.com
W www.newport.com

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

member DSPE

Motion Control Systems

Physik Instrumente (PI) Benelux BV
Hertog Hendrikstraat 7a
5492 BA Sint-Oedenrode
The Netherlands
T +31 (0)499-375375
F +31 (0)499 375373
E benelux@pi.ws
W www.pi.ws

PI is the world's leading provider of nanopositioning products and systems. All key technologies are developed, manufactured and qualified in-house by PI: Piezo components, actuators and motors, magnetic drives, guiding systems, nanometrology sensors, electronic amplifiers, digital controllers and software.

member DSPE

Optical Components

Molenaar Optics
Gerolaan 63A
3707 SH Zeist
Postbus 2
3700 AA Zeist
T +31 (0)30 6951038
F +31 (0)30 6961348
E info@molenaar-optics.nl
W www.molenaar-optics.eu

member DSPE

Piezo Systems

HEINMADE BV
Heiberg 29C
NL - 5504 PA Veldhoven
T +31 (0)40 851 2180
E info@heinmade.com
W www.heinmade.com

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

member DSPE

Piezo Systems

Physik Instrumente (PI) Benelux BV
Hertog Hendrikstraat 7a
5492 BA Sint-Oedenrode
The Netherlands
T +31 (0)499-375375
F +31 (0)499 375373
E benelux@pi.ws
W www.pi.ws

PI is the world's leading provider of nanopositioning products and systems. All key technologies are developed, manufactured and qualified in-house by PI: Piezo components, actuators and motors, magnetic drives, guiding systems, nanometrology sensors, electronic amplifiers, digital controllers and software.

member DSPE

Ultra-Precision Metrology & Engineering

IBS Precision Engineering
Esp 201
5633 AD Eindhoven
T +31 (0)40 2901270
F +31 (0)40 2901279
E info@ibspe.com
W www.ibspe.com

IBS Precision Engineering delivers world class measurement, positioning and motion systems where ultra-high precision is required. As a strategic engineering partner to the world's best manufacturing equipment and scientific instrument suppliers, IBS has a distinguished track record of proven and robust precision solutions. Leading edge metrology is at the core of all that IBS does. From complex carbon-fibre jet engine components to semiconductor chips accurate to tens of atoms; IBS has provided and engineered key enabling technologies.

member DSPE

ADVERTISERS INDEX