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- THEME: (BIO)MEDICAL PRECISION
- DESIGN PRINCIPLES IN COLLIMATOR AT 35 G
- MOTION FEEDFORWARD TUNING FOR HYSTERETIC PIEZO ACTUATORS
- THE NEW NORMAL – REPORT OF EUSPEN'S VIRTUAL INTERNATIONAL CONFERENCE 2021

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The cover image (featuring the construction of a CT-scanner collimator) is courtesy of Philips Engineering Services. Read the article on page 15 ff.

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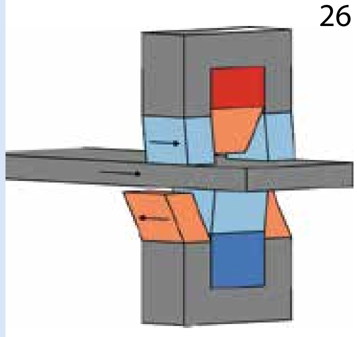

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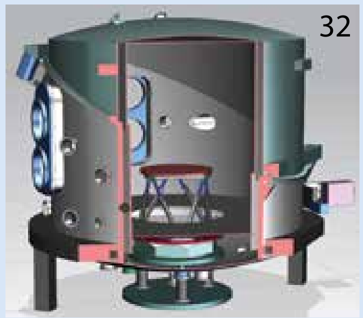

FEATURES

INTERNATIONAL PRECISION FAIR 2.0

This year will see the 20th edition of the Precision Fair. In fact, this anniversary should already have been celebrated in 2020, but for obvious reasons the fair had to be postponed by a year. For the first time, the Brabanthallen in 's-Hertogenbosch (NL) will be the venue. It marks a good time to look back and to look forward.

It all started with research undertaken in 1998 by consultancy firm Berenschot into 'the importance and possibilities of precision technology in the Netherlands'. This was supported by TNO, Mikrocentrum and of course DSPE (then still NVPT), and resulted in the IOP (Innovation-oriented Research Programme) Precision Technology. Triggered by the promising start of the Plastics Fair (*Kunststoffenbeurs*) in 1999, Henny Spaan suggested Mikrocentrum to organise a Precision Fair (*Precisiebeurs*) as well. The first edition was in October 2001 and the fair has grown gradually to its present size.

Due to various outstanding companies, precision technology has undergone an incredible development in the Netherlands over the last twenty years. Clearly, all of these companies operate and compete in an increasingly international environment. What is the impact of this on trade fairs? Most likely, the Precision Fair will also have to adapt, including becoming more international, although there are already a number of international exhibitors and visitors at present. An increased international focus was already topic of discussion about a decade ago.

In 2012, I visited CERN, the well-known particle accelerator in Geneva (CH) that became world famous in 2013 for its discovery of the Higgs boson. As a result, a large CERN delegation visited the Precision Fair in 2012, joined in subsequent years by several other Big Science organisations. This all resulted in close cooperation with various Big Science projects, with several Dutch companies benefitting. As an example, in 2020 the revenue of Dutch companies involved with CERN exceeded the annual funding of CERN by the Dutch government for the first time. Hopefully, this will be repeated if the Einstein telescope (for gravitational waves) is realised in the south of the Netherlands.

How might things develop over coming years? I personally believe that this really is the moment to transform the Precision Fair from a mainly local trade fair into a truly international trade fair. In fact, the Precision Fair is already unique, not just in the Netherlands, but also abroad. Other trade fairs include precision technology topics, but probably none of them to the degree present at the Precision Fair. In general, we should not fear international competition, but embrace it.

The larger venue of the Precision Fair, the introduction in 2019 of an annually changing partner country, and close cooperation with international organisations like euspen and DSPE will all facilitate international expansion. In addition, Mikrocentrum's experience, the existing involvement of precision technology companies, and the spirit of close cooperation over the entire Dutch precision technology sector could be the driving forces in achieving this. Perhaps travel restrictions may still limit such ambitions in 2021, but certainly in the next few years the Precision Fair could further increase its relevance to a level uncommon for the Netherlands.

I would love to see a truly international Precision Fair become a reality in the near future.

Geert Hellings
Advisor and former managing director Mikrocentrum (2003-2021)

SELF-PROPELLING AND STEEERABLE

The design of a self-propelling, steerable needle was inspired by a wasp's ovipositor, a thin, flexible needle-like structure used for laying eggs into larvae hidden inside fruit or wood. The needle's potential medical applications include localised therapeutic drug delivery and tissue sample removal (biopsy). The instrument consists of three or more wires that are moved back and forth inside tissue sequentially. Through friction, a net pulling motion of the tissue towards the actuation unit is generated, resulting in the instrument moving forward inside the tissue. Different sequences of wire actuation can achieve either straight or curved trajectories.

The Delft-based Bio-Inspired Technology (BITE) research group works on the development of innovative technical systems and instruments for minimally invasive surgery and other medical interventions, drawing inspiration from extraordinary biological mechanisms. The group collaborates with academic hospitals, biology groups, veterinary hospitals and companies, and has already brought products to the clinic. BITE output includes surgical knives, tissue puncturing devices, and steerable needles and instruments.

One example is the LaproFlex steerable laparoscopic instrument with ergonomic axial handle, which is now being marketed by spin-off company DEAM (Figure 1). In 2019, the first operation (gynaecological) was performed using the instrument. The technology behind the instrument was already described in *Mikroniek* in 2007 [1]. The LaproFlex has a flexible tip, enabled by an ingenious steering system based on the anatomy of an octopus' tentacle, the so-called cable ring mechanism, which ensures that scissors or a grasper, for example, can be steered in any direction.

Wasp needle-like structure

More recent research on steerable instruments [1] was inspired by the wasp ovipositor, a needle-like structure used by the female parasitoid wasp to drill into wood or fruit and deposit eggs inside living hosts such as larvae. The WASP project was started in 2015, funded by the Netherlands Organization for Scientific Research (NWO), as part of the iMIT programme aimed at developing interactive multi-interventional tools.

The WASP project was focused on medical needles that have to reach their target deep inside a patient's body with high precision. This requires a flexible, steerable needle that can follow complex curved trajectories through complex solid organs while avoiding sensitive structures, such as blood vessels, located along the trajectory between the insertion point and the target site.

AUTHOR'S NOTE

This article was based on an interview with Paul Breedveld, professor of Minimally Invasive Surgery & Bio-Inspired Technology and chair of the Bio-Inspired Technology (BITE) research group in the department of Biomechanical Engineering at Delft University of Technology (NL), and on publications from his group, in particular the Ph.D. thesis by Marta Scali [1].

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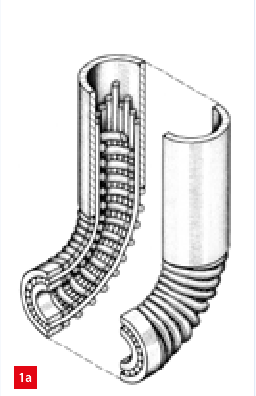
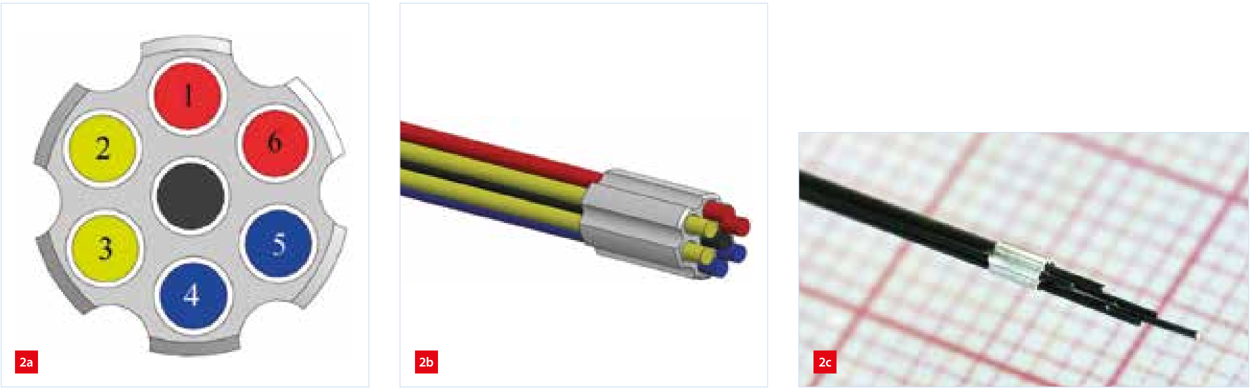

1a


1b

The LaproFlex steerable laparoscopic instrument.
(a) Concept of the patented cable ring mechanism, shown in cross-section as two halves that have been pulled apart for clarity [2].
(b) Commercial version marketed by DEAM, which developed the ergonomic axial handle.



First design of an ovipositor-inspired needle.
(a) Cross-section of the flower-shaped ring, with a central hole to which the central wire is glued and six peripheral holes through which the six other wires can slide back and forth.
(b) Initial position of the wires.
(c) Prototype, showing the tip of the needle with the ring, and some of the wires moved forward.

The wasp's ovipositor is a needle-like structure composed of three longitudinal, interlocking segments that can be actuated individually and independently of each other by musculature that is located in the abdomen of the insect. The propagation of the ovipositor through a substrate is achieved by a push-pull mechanism, in which one of the elements is pushed while the other two are pulled. In this way, the wasp steers the ovipositor along curved trajectories inside different substrates without a need for rotatory motion or global axial push. Inspired by the anatomy and the steering mechanism of this needle-like structure, the aim was to develop an ultra-thin, self-propelled, steerable needle.

Design

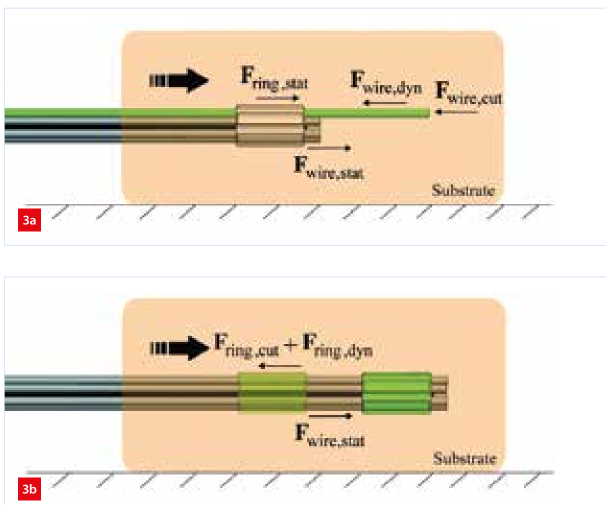
In the first design ([3], the second item), superelastic nickel NiTi wires were used for the segments. Interlocking these turned out to be challenging. In a wasp, the ovipositor segments are interlocked by a jigsaw-puzzle-like structure, which allows them to slide along each other and thus avoid separation. Miniaturisation of such a complex interlocking mechanism was not feasible from a manufacturing perspective.

Therefore, the designers took a step away from nature and decided instead to interlock the wires externally, using a ring with holes through which the wires are fed (Figure 2). The ring was given a flower shape to reduce resistance during propulsion through the substrate. The ring has a central hole to which the central wire is glued and six peripheral holes through which the six other wires can slide back and forth. The first prototype had a diameter of 1.2 mm at the tip and 0.75 mm along the body, while the NiTi wires were 0.25 mm in diameter and 160 mm long, and the flower-shaped ring was 2.0 mm long.

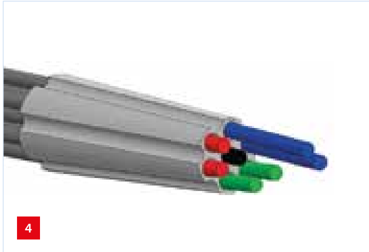
Forward motion

Each proximal end of the six movable wires is connected to a miniature stepper motor, in which a leadscrew-slider mechanism converts rotational motion into linear motion. The needle is moved forward through the substrate firstly by pushing the six wires one by one (or two by two), followed by pulling on all six wires simultaneously, which advances the interlocking ring and the central wire into the substrate.

Figure 3 shows the forces acting on the needle during the forward motion. In the first phase, the sum of the dynamic friction force ($F_{wire,dyn}$) and the cutting force ($F_{wire,cut}$) on the wire(s) moving forward should be smaller than (or equal to) the static friction force on the stationary wires and the interlocking ring ($F_{wire,stat}$ and $F_{ring,stat}$, respectively). In the second phase, the ring moves forward if the cutting and the dynamic friction forces on the advancing interlocking ring ($F_{ring,cut}$ and $F_{ring,dyn}$, respectively) are smaller than (or equal to) the static friction force between the wires and the substrate ($F_{wire,stat}$).



Schematic representation of the two-phase forward motion mechanism of a needle with six peripheral wires and one central wire. The thick arrow represents the motion of the wires and the ring. See text for further explanation.
(a) First, one wire is pushed forward at a time (green).
(b) After all six peripheral wires have been moved forward one by one, they are pulled back simultaneously, resulting in advancement of the ring and the central wire inside the substrate.



Steering of the needle is facilitated by specific actuation schemes and the use of a conical interlocking ring. The blue and green wires have been given an offset with respect to the red wires. Then all the wires are moved over the same stroke consecutively, thus maintaining the bevel offset required for steering.

Experimental set-up.
(a) Close-up of the wires emerging from the actuation unit, which contains seven miniature stepper motors.
(b) The actuation unit mounted on an aluminium platform and the gelatine phantom on the cart that can move along a duct.

Steering

A bevel at the needle tip can help to achieve steering. Each needle wire has a flat tip, but bevel asymmetry can be created at the needle tip as a whole. This is done by inducing a bevel offset between pairs of adjacent needle wires. In this way, various bevel angles can be created and steering can be achieved by specific actuation schemes for the individual wires/wire pairs (Figure 4). The steering effect is further enhanced by the use of a conical interlocking ring. This was introduced to counter the observed phenomenon of bifurcation: the effect that wires tend to separate from each other during operation, thus limiting steerability.

Experiments

An experimental set-up (Figure 5) was built consisting of an actuation unit mounted on an aluminium platform, which was provided with a duct to guide a lightweight aluminium cart mounted to four passive (i.e., not driven) wheels in order to move along a straight path with low friction. The cart was used to carry a tissue-mimicking gelatine phantom, in which the needle was to be inserted. The wires were moved back and forth sequentially inside the phantom, generating a net pulling motion of the phantom towards the actuation unit, and resulting in the needle moving forward inside the phantom. Different sequences of wire actuation were used to achieve both straight, curved and S-shaped trajectories. A camera positioned above the cart took photos of the initial insertion and final position of the needle during the experiments (Figure 6).

Conclusion

The ovipositor-inspired needle is the world's thinnest self-propelled, steerable needle. In following prototypes, further

Image of the final position of a needle after insertion.
The deflection shows that steering, i.e. deviation from a straight course, could be achieved.

Follow-up

Another project involved the design of a self-propelling device ([3], the first item) for locomotion through the large intestine (colon). This device (Figure 7) contains a miniature electric motor connected to a cylindrical cam. Six sliders are placed around the cam and move forward and backwards following a path defined by the cam. In each step, one slider moves forward while the others remain stationary relative to the environment, generating a smooth, continuous motion at approximately 1/6 of the speed of a moving slider; see the video [V1]. The mechanism allows for a simple, robust construction that can be miniaturised easily.

Experiments were carried out with various flexible 3D-printed structures attached to the outer surface of each slider to generate direction-dependent friction to further enhance grip. Tests in plastic tubes showed fast, fluent self-propelled motion; see the video [V2].

From April this year, a new project funded by NWO has been running, in which needle technology is being developed for prostate interventions under MRI guidance; this is a collaboration with the AUMC in Amsterdam (NL).

Ovipositor-inspired design of a self-propelling device.
(a) The device has six sliders on its perimeter. One slider at a time moves forward while the others remain stationary relative to the environment, generating a smooth, continuous motion.
(b) Experiments were carried out with various flexible 3D-printed structures attached to the outer surface of each slider to generate direction-dependent friction to further enhance grip.

miniaturisation of the needle to diameters below 0.5 mm was realised. The novel bio-inspired steering and propulsion mechanism enables the design of extremely long and thin needles that can be used to reach targets deep inside the body without a risk of buckling and with the possibility of correcting the trajectory.

When the central wire is removed, a hollow needle is created [4]. This can be used for the transportation of substances, applying the same motion mechanism in a reverse manner, i.e. not needle with respect to external substrate, but internal substance with respect to needle.

Steering, however, has remained a challenge, because the needle exhibits torque. The thinner the needle, and hence the individual wires, the lower the torsional stiffness. Sensors in the needle tip will be required for real-time control of steering. As glass fibres have already been used as 'wires', the fibre Bragg grating sensing principle is a likely candidate. In this way, high-tech photonics will meet bio-inspired design.

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[3] *www.bitegroup.nl/self-propelled-devices*

[4] Sakes, A., Steeg, I. van de, Kater, E.P. de, Posthoorn, P., Scali, M., and Breedveld, P., "Development of a novel wasp-inspired friction-based tissue transportation device", *Frontiers in Bioengineering and Biotechnology*, 8:575007, 2020.

VIDEO

[V1] *www.bitegroup.nl/wp-content/uploads/2020/07/Ovipositor-Device_IMG_9725.m4v*

[V2] *www.bitegroup.nl/wp-content/uploads/2020/07/Ovipositor-Device_IMG_9839.m4v*

THE NEXT STEP OF PROJECT MARCH

Project MARCH, a non-profit student team from Delft University of Technology (NL), is driven by the vision that using exoskeleton technology can improve the quality of life for people with paraplegia. An exoskeleton is a motorised robotic harness that enables them to stand up and walk again. Each year, Project MARCH develops a new version, to both stimulate technological innovation in exoskeletons and challenge students to think of new solutions. The sixth team's goal was to develop an entirely new exoskeleton with which the team's pilot could walk a route through the city of Delft in a dynamic way. This was achieved last month.

Introduction

Each year, a new Project MARCH team is composed from Delft University of Technology (TU Delft) students of various backgrounds and years of study. The team then takes from September until the end of the following summer to develop a new exoskeleton. Every time, their design choices and project development are thoroughly documented, with a lot of attention paid to the handover of the project from one team to the next. Recently, Project MARCH settled in its new location in RoboValley, "a future-of-work fieldlab where robot developments and the study of social processes can occur simultaneously", on the TU Delft campus.

Project MARCH VI's goal was to develop an entirely new exoskeleton, with which the team's pilot could walk a route through the city of Delft in a dynamic way. 'Dynamic' here means that the movement of the exoskeleton is controlled using live information about the environment, instead of pre-programmed movements. On this route, the pilot, who is a person with paraplegia, will come across various obstacles such as bridges, pavers and ramps.

The design of MARCH VI (Figure 1) was presented March 2021; see the video [V1]. The biggest challenges for this sixth version were to provide the exoskeleton with dynamic walking control, improve its user-friendliness and make it suitable for outdoor use. Some of the main design choices are highlighted below.

Mechanics

Frame

The frame of the exoskeleton (Figure 2), similar to the bone structure of the human body, consists of a backplate, hip structure, upper leg bone, lower leg bone, lever arm and footplate. Together these parts are the force-bearing structure of the exoskeleton. Safety plays a major role here, because the frame has to be strong enough to carry the weight of the pilot.

The main design theme for the frame was user-friendliness, which was achieved by reducing its weight. To this end, 3D topology optimisation was applied to the design of the back-plate (Figure 3) in order to reduce its size and weight while

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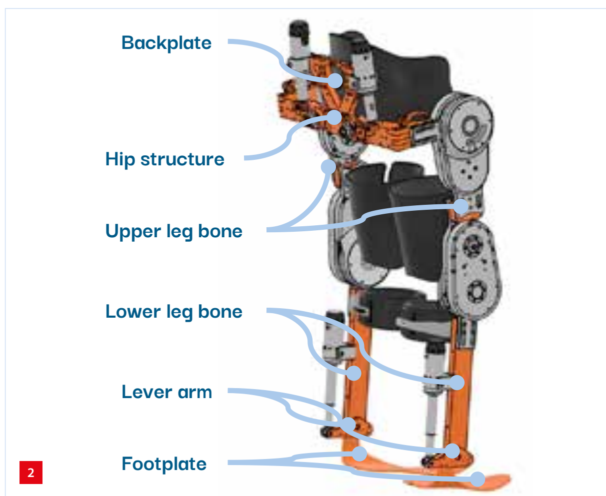
Artist's impression of the MARCH VI exoskeleton. The 'white' version on the right visualises the project's future-based control method.



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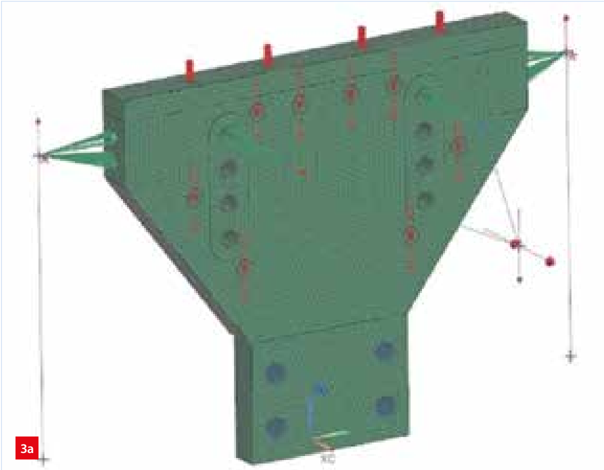
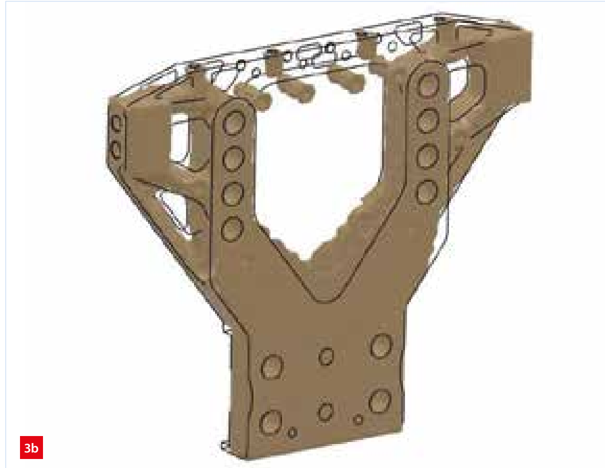
The frame of the exoskeleton.

EDITORIAL NOTE

This article was based on information provided by Project MARCH, in particular a series of blogs about the technical design.

www.projectmarch.nl





Topology optimisation of the backplate design in 3D.
(a) Starting point.
(b) Final result.

maintaining its main function, i.e. to safely absorb all forces that the pilot and various attached parts/modules exert on it.

Another user-friendly design upgrade was the added hinge that allows an exoskeleton leg to be rotated out in order to facilitate the pilot's transfer from wheelchair to exoskeleton (and vice versa). Naturally, after the transfer, the leg has to be turned back in and the hinge secured. A design study to find a safe solution resulted in two concepts: the lever latch and the quick-release. In both concepts, the frame is made up of two parts in which the edges are shaped to fit neatly together, like two parts of a whole, with large overlapping surfaces.

In the quick-release concept, the hinge is fixated with a pin that runs through both frame parts. A clamping mechanism can be added to this pin to not only block the rotation, but also to clamp the frame pieces together to prevent wiggling. In the other concept, a lever latch on top of the frame is used to pull these surfaces together and fixate the hinge. Upon evaluation, the quick-release system (Figure 4) proved to be safer, more user-friendly and easier to implement than a lever latch.

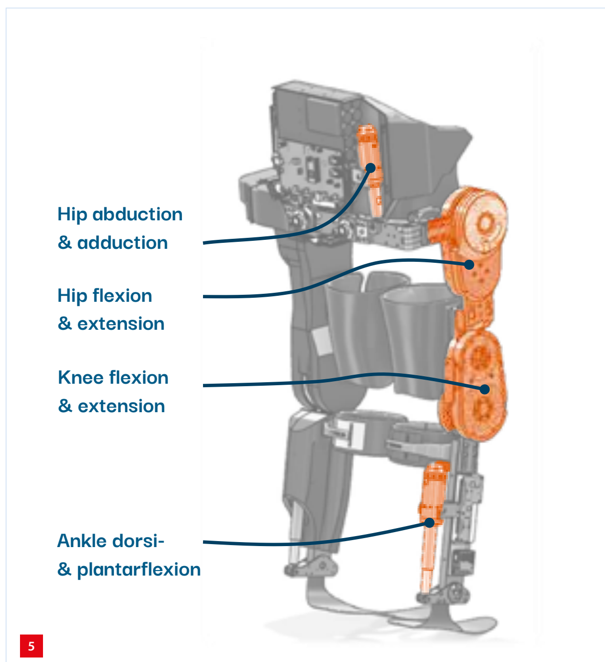
Another user-friendly improvement was changing the material for the force-bearing layer in the sole of the foot from titanium (strong but stiff) to carbon combined with kevlar (strong yet flexible).

Final quick-release hinge design.

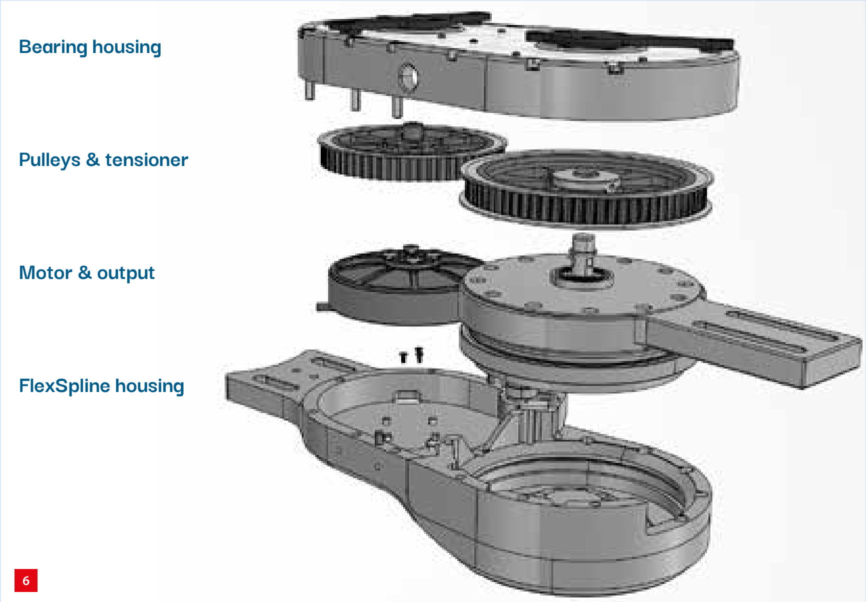
Joints

The exoskeleton comprises eight active joints (Figure 5): two in each hip (abduction & adduction, and flexion & extension, HFE), one in each knee (flexion & extension, KFE), and one in each ankle (dorsi- & plantarflexion). The rotational knee and hip joints (HFE and KFE) were redesigned to make them stronger (250 Nm of torque, i.e. a 67% increase) and thinner than in previous years.

A rotational joint consists of a bearing housing, two pulleys combined with a tensioner, a motor and output, and a flex-spline housing (Figure 6). The motor was used originally in a powerful drone (3,500 rpm, 3.6 Nm torque). The output, connected to either the lower leg or the hip, houses a harmonic drive with a gear ratio of 1:100; it is only 11 cm in diameter. The pulleys, used for transferring the motion from the motor to the harmonic drive, were new in the joint design, for two reasons. Firstly, the motor and the harmonic drive could now



Four different joints (two pieces each) in the exoskeleton.

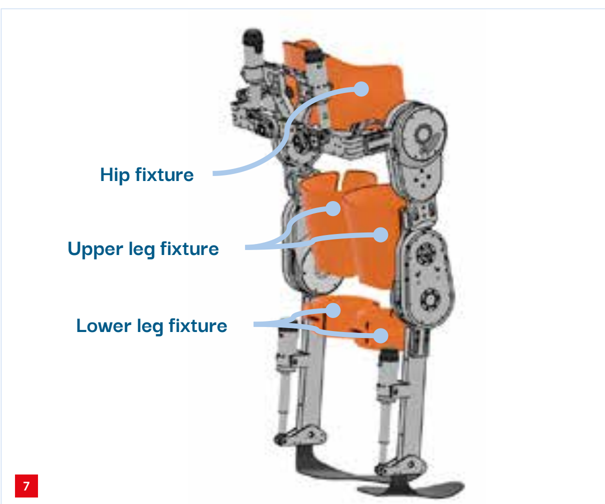


Exploded view of a rotational joint.

be placed next to each other rather than on top of one another. Therefore, the joint could be made thinner. Secondly, the pulleys provided an extra transmission (of 10:12), which made the joint even stronger, yielding a gear ratio of 1:120.

Fixtures

The pilot is connected to the exoskeleton by fixtures (Figure 7). Their design was aimed at providing a balance between comfort and support for the pilot. There are seven connection points. One hip fixture encloses the back of the pilot's hip and part of his torso; in the front, there is a corset that can be closed using snowboard buckles. Then there are two upper leg fixtures, two lower leg fixtures and two shoes, with footplates that are connected to the exoskeleton. Design requirements for the fixtures included safety, user-friendliness, appearance and performance (such as range of motion). Based upon a medical analysis of a paraplegic person (sensitivity to pressure marks, for example), positioning preferences for the fixtures were determined. Various concepts were evaluated and, for the final concept, a 3D scan of the pilot was made to ensure that the fixtures were shaped exactly to his body. Using a scan-based plaster model, the fixtures were made by vacuum forming heated plastic.



Overview of the various fixtures that connect the pilot to the exoskeleton; the footplates shown here are also fixtures.

Electronics

Power

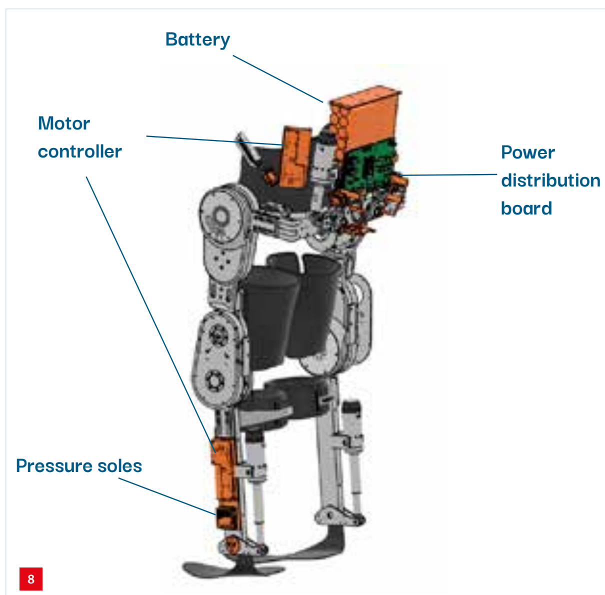
The electronics power various parts of the skeleton (Figure 8) through a power distribution board, which supplies the different voltage levels required. These parts include the motor controllers, the central computer in the backpack, and the sensors (position, temperature, pressure). The power distribution board was redesigned to be more compact, in order to compensate for the bigger battery pack, among other reasons. In fact, battery capacity was estimated to have doubled, to enable walking for a period in the order of one hour. For the first time, the complete battery pack was placed in a tray, to facilitate battery transfer and reduce the wiring between the pack and the skeleton.

Motor controller

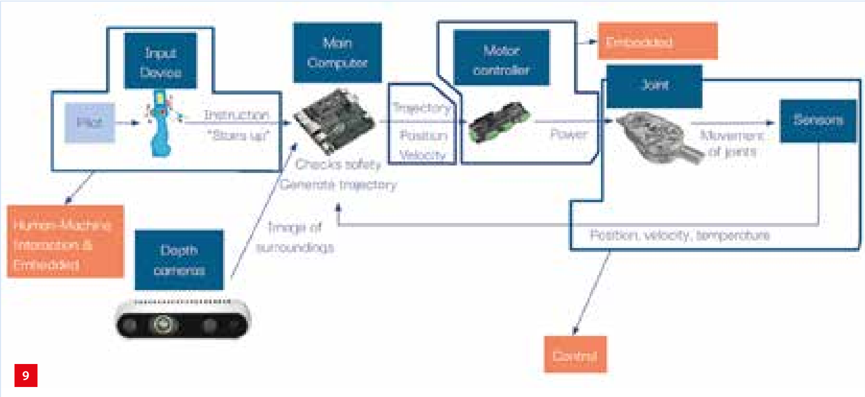
A new motor controller was needed for reliability reasons. A thorough analysis resulted in an overview of the requirements (ranging from 'must have' to 'could have'): reliability, battery voltage compatibility, right type of encoder connections, computer communication (EtherCAT) compatibility, reduced size, and open source. Finally, the ODrive motor controller from the ODrive community (*www.odriverobotics.com*) was selected.

Computer

Also, a new single-board computer was needed, because to realise the goal of dynamic walking more real-time data



Overview of the electronics of the exoskeleton.



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Software architecture of Project MARCH.

had to be processed, which called for larger processing power. An evaluation of key factors such as connectivity, performance, storage and memory, as well as size, resulted in a computer from motherboard specialist ASRock (*www.asrock.com*) being selected.

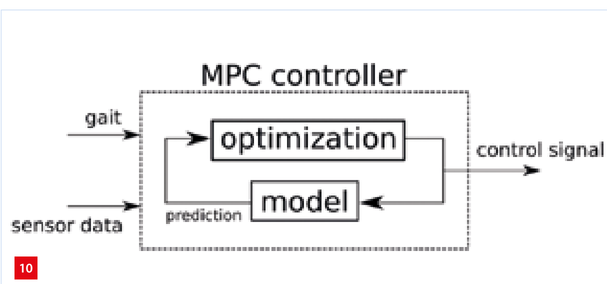
Software

Open source

The software architecture of Project MARCH (Figure 9) was based on the open-source ROS framework (Robot Operating System). For the R&D-oriented ROS 1, support was to end within a few years. Therefore, it was decided to upgrade to ROS 2, which is industrial grade and applicable in research, prototyping, deployment and production. As of this year, the Project MARCH software itself is also open source. An open-source licence was officially awarded, which allows the team to share their knowledge about powered exoskeleton technology.

Testing

Testing is crucial for software development. This starts in simulation and then the first physical test step, called airgaiting, naturally includes hardware testing. During airgaiting, the exoskeleton is in a stand and can literally walk in the air. Airgaiting is relatively easy to set up and not much can go wrong. If the airgaiting test is successful, the next step is groundgaiting, during which the exoskeleton walks by itself, with guidance but without a pilot inside. The final test step is when the pilot walks in the exoskeleton.



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Model-predictive control (MPC) for the gait of the skeleton.

Control

The main goal of control is to ensure that the exoskeleton follows a prescribed gait, i.e. the walking pattern. A motor controller uses two different encoders to determine the position and the rotational speed of the electric motor: an incremental encoder, directly attached to the motor, for determining the speed of the motor accurately; and an absolute encoder for the angle or position of the joint. With the information from these two encoders, using some kind of algorithm or model, the motor controller can be set to a current that is needed to reach the position or angular set point for the joint.

This year, model-predictive control (MPC) was introduced, to counter disturbances and model inaccuracies (Figure 10). MPC consists of two components. The first is a model of the system that describes how a joint moves when a certain current is put on the motor. The second one is an optimisation part that uses the model, gait and sensor data to calculate the optimal current that, if sent to the motor, should bring the joint as close to the gait as possible within a certain small time window. For future improvement, there are a lot of ways to enhance the model, such as adding friction dynamics or modelling the influence of the joints on each other, or even the influence that the pilot has on the joints.

Human-machine interaction

When the pilot is walking, still using crutches in this phase of Project MARCH evolution due to the challenge of balancing, he interacts with the exoskeleton. This human-machine interaction should feel comfortable for the pilot, especially as he has no direct influence on the movements the exoskeleton makes. It needs to feel like an extension of the pilot instead of like a robot. Currently, the pilot uses an input device on one of the handles of the crutches (Figure 11). With this input device, the pilot is able to select

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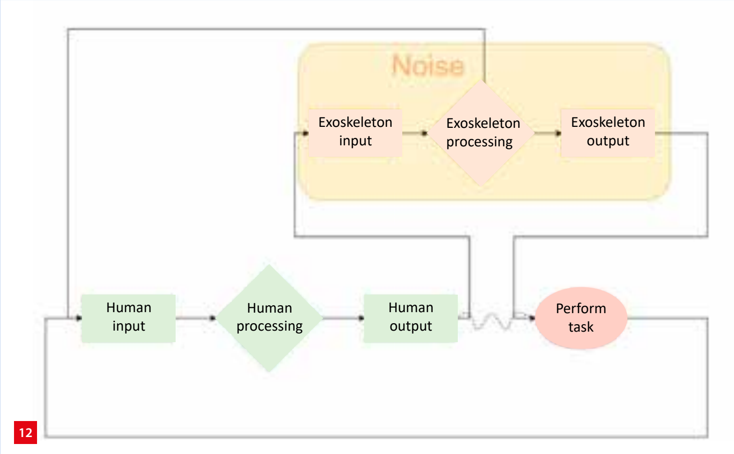
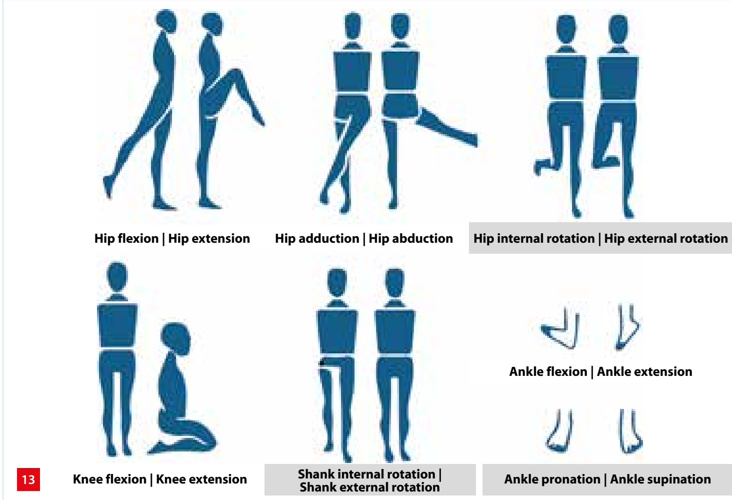
Input device.



Advanced model for human-machine (pilot-exoskeleton) interaction.



The DoFs of human walking. The DoFs with shaded caption are not included in exoskeleton movement. Note: shank = shinbone.

the right pre-programmed gait for the right situation (e.g. walking up stairs) and is notified by means of a vibration signal when the exoskeleton starts moving. Looking at the basics of human processing (input, processing, output, task performance), the interaction between the pilot and the exoskeleton adds an extra cycle that needs to be followed. The human output, in this case pressing the button on the input device, provides the input to the exoskeleton, which after processing generates an output, to actuate the required task performance. This means that there is always an extra loop present in this system, and if it is formatted in an advanced model (Figure 12), it can be classified as extra noise, which should be minimised.

This noise is found in most actions we take, but fortunately our brains are able to almost completely ignore this if the noise is small enough. For example, if you want to move your mouse cursor on a computer screen, you think actively about moving your arm across the table to navigate the cursor in a specific direction. That is because moving your arm to the left still results in the cursor moving to the left side. An ideal input device would allow for seamless navigation between types of movement without active thought. That is why Project MARCH is working on concepts that can bridge the gap between human and machine by exploring the application of EEG (electro-encephalogram) signals and smart glasses.

Human movement

To use his exoskeleton, the pilot has to select a walking pattern, the gait, and start moving (walking, sitting down, standing up, climbing or descending slopes/stairs) comfortably and smoothly. Gait design is based on the angles of the joints at a specific time. This year, the walking patterns were adjusted to a new pilot. Also, multiple movements have been added, such as ankle movement and hip abduction and adduction. These additional movements ensure that the walking patterns are more stable and thus the pilot has to lean on his crutches less. The ankle movements, for example, provide for the so-called toe-off that gives the legs a little extra push during walking.

Passive exoskeleton research

To optimise this year's gaits, research was conducted into the effect that movement limitations have on the exoskeleton's walking patterns. Until now, the gaits were based on the walking patterns of people who have no limitations when it comes to walking. However, a person who does not have any disabilities in this respect has seven degrees of freedom (DoFs) for movement, whereas the exoskeleton only has four DoFs (Figure 13). It is likely that the number of DoFs affects the way of walking. Together with OIM Orthopedie, a passive exoskeleton was designed that has the exact same limitations in walking as the real exoskeleton. A test person walked in a special lab to record the movements and thus the effects of the exoskeleton's limitations on human gaits, thereby providing a better basis for defining the exoskeleton gaits.

Dynamic movement

Dynamic gait

Once a functioning exoskeleton, a working input device and smooth walking patterns were available, it was time to start walking. A new project was begun to allow the exoskeleton

A schematic of dynamic gait control.

The depth camera in the exoskeleton.

to walk dynamically on a route where the pilot would encounter multiple random obstacles with unknown dimensions. This means that these obstacles could not be fully pre-programmed in the gait generator and the exoskeleton would need to react to its environment by using sensors, processing their data and actuating the exoskeleton according to the resulting dynamic gaits (Figure 14).

Foot location finder

For example, the height of a curb or a stair, or the angle of a slope or uneven terrain, would have to be registered. It was decided to implement a depth (3D) camera (Figure 15) in the hip base of the exoskeleton. When the pilot selects a gait, the depth camera will create a depth image, a so-called point cloud, of the environment. From this point cloud, the location where the exoskeleton can place its foot optimally should be determined.

This requires pre-processing of the point cloud, including transforming it from the viewpoint of the camera to that of a fixed-world frame. Then, a region-growing algorithm is used to find regions such as the steps of a staircase, which would be relatively easy because of their well-defined character, or a region such as a ramp, which could be challenging when it increases and decreases in slope continuously (Figure 16a).

Next, hulls (envelopes) are created from the regions. Each hull needs to describe a two-dimensional area, so that a foot location finder can check easily if a possible foot location has the support of some hull (Figure 16b). In case of a gait for stairs, for example, potential locations are tested to check whether they are reachable in height by the exoskeleton and provide support for the entire foot.

Pressure soles

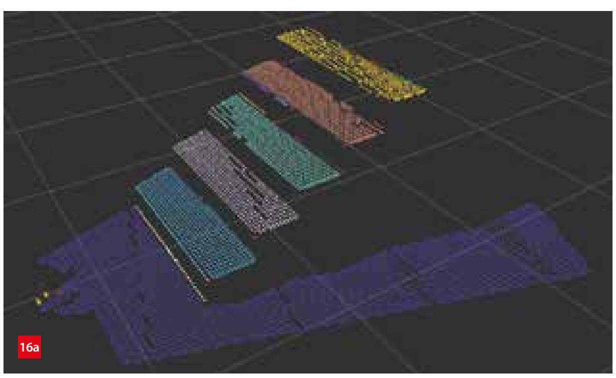
Other sensors the team continued to work on were the pressure soles. This year, the soles were used during the walking gait. In order to walk over flat or uneven surfaces, the exoskeleton should know that the swing of one leg has landed properly on the ground before the other leg can go to the swing phase.
In the future, the soles can also be used to provide the pilot with feedback, such as haptic feedback in the crutches, that he does not receive in his own legs, for example when to shift his weight when the swing leg has touched the ground.

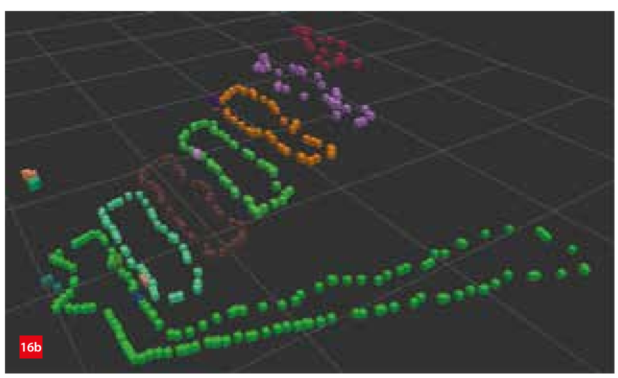
Impression of the final walk of the Project MARCH VI team's pilot.

Final walk

Following this extensive and thorough design process, leading to multiple improvements, it was time to hit the road. MARCH VI was assembled and last month the team's pilot performed a dynamic walk through the city of Delft successfully. In the meantime, MARCH VII has already started, to take yet another step towards the goal of helping people with paraplegia to walk again.

VIDEO
[V1] www.projectmarch.nl/nl/march-vi-exoskeleton





Point-cloud processing.
(a) Using a region-growing algorithm, regions have been found such as the steps of a staircase and a ramp below.
(b) These regions have been translated into (concave) hulls.

COLLIMATOR DESIGN FOR 35 G

The design principles of the late Wim van der Hoek, former Philips engineer and Eindhoven professor, are still current in high-tech systems engineering, including in the field of medical technology development. They are especially useful when high precision is required and conditions are challenging. This article presents a brief overview of the design philosophy, illustrated by an elegant example, from Van der Hoek's 'own' Philips; the design of a collimator, for a CT scanner, of which all parts are subjected to accelerations of 35 g.

MICHEL LOOS, ERIK MANDERS AND HERMAN SOEMERS

Wim van der Hoek (1924-2019) established his name in the 'precision world' with his work at Eindhoven University of Technology on design principles for precision mechanisms. However, he was also a Philips man in heart and soul and one of the founders of the Philips Centre of Manufacturing Technologies (*Centrum voor Fabricage Technieken*, CFT). Founded in 1968, the CFT played a leading role within Philips in the field of manufacturing processes and production mechanisation.

In the early days, Van der Hoek was one of the central figures in setting up the CFT and led the Mechanics and Mechanisms department. At that time, he already held the position of part-time professor and, in the form of lecture notes, started collecting examples for the design and calculations of cam-driven machines. Like no other, he was able to bridge the gap between academic knowledge of mechanical design and the daily Philips practice in the production mechanisation departments and later also product development. Scientific analyses were stripped down to manageable equations and insights that designers could use when making their many design choices.

For Philips, this meant that the development process for mechanical and mechatronic products and systems required fewer iterations and their behaviour (often in terms of dynamic and static accuracy) became much more predictable. Therefore, the required development effort

Dutch doyen of design principles

After the passing away of Wim van der Hoek, in early 2019, DSPE decided to publish a book about the Dutch doyen of design principles. The presentation took place on 18 November 2020, during an online Precision Fair event. The book (in Dutch) covers Van der Hoek's formative years, his career at Philips and Eindhoven University of Technology, where he developed his breakthrough ideas on achieving positioning accuracy and controlling dynamic behaviour in mechanisms and machines, and the reception and diffusion of his design principles. It concludes with his busy retirement years in which he continued to tackle – technical as well as social – design challenges, believing that technology should support people. The book (Figure 1) can be ordered via the DSPE website.

WWW.DSPE.NL

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Lambert van Beukering & Hans van Eerden, "Wim van der Hoek, 1924-2019, A constructive life – Design principles and practical learnings between criticism and creation" (in Dutch), ISBN 978-90-829-6583-4, 272 pages, DSPE, € 49.50 (€ 39.50 for DSPE members) plus € 6.50 postage.

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Michel Loos (senior designer), Erik Manders (senior architect mechatronics) and Herman Soemers (technology manager) all are associated with Philips Engineering Solutions in Eindhoven (NL).

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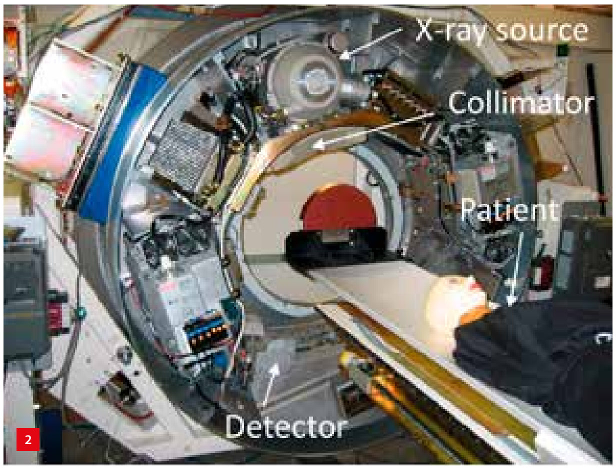
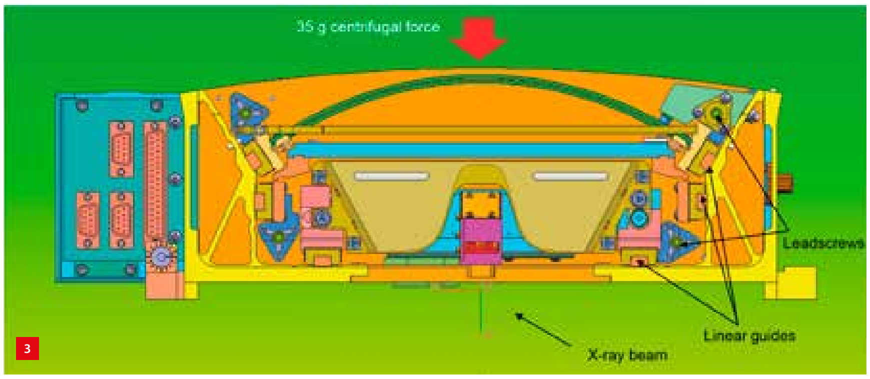


CT scanner equipped with a bore through which the patient can move. The X-ray source and collimator are located on one side of the rotor and the detector on the other side.



Design of the collimator, with the curved shutter blades in the X-ray beam and the linear guides and drives just outside the beam.

decreased. And because the application of his insights made it clearer which tolerances really mattered, in many cases less precise parts – at a lower cost price – were needed.

The core of the Philips design philosophy is still based on thinking in degrees of freedom. The continuity of the application of these insights is not self-evident within a company such as Philips, which is in a continuous process of change with a large (international) influx and outflow of designers. Despite this – or perhaps because of it – within Philips, both at home and abroad, designers are still regularly trained in using the design principles. The importance of this philosophy, which has meanwhile been laid down in the textbook "Design principles for precision mechanisms", by technology manager Herman Soemers, cannot be overestimated.

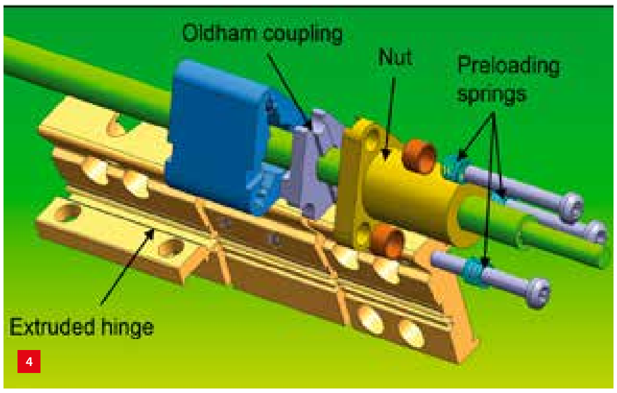
The Philips Centre of Manufacturing Technologies became Philips Applied Technologies in 2005 and evolved into Philips Innovation Services in 2011, recently renamed to Philips Engineering Solutions. Despite the changes, much was retained, such as working for a wide range of clients. Contributions to the design of mechanics and mechatronics range from consumer goods to large medical systems – and beyond Philips, especially the well-known high-tech for the semiconductor world. What all these applications have in common is that the design is very challenging and requires creative, new solutions, drawing upon the timeless design principles of Wim van der Hoek.

Collimator for a CT scanner

An elegant application of these design principles can be found in the design of a collimator for a CT scanner (Figure 2). This collimator (Figure 3) is intended to be able to adjust the shape and intensity of the X-ray beam. The unit includes moving shutter blades and filters, and sits directly behind the X-ray source; both modules are mounted on the rotor. This rotor has a bore through which the patient moves.
In modern systems, the rotor can rotate around the patient at a speed of up to 250 rpm. This results in centrifugal accelerations of approximately 35 g on all parts of the collimator.

Because the shutter blades have to block X-rays, they are made of a heavy material, such as lead or tungsten, which is very unfavourable for the forces on the linear guides and the construction. The linear guides are necessary to move the shutters and filters during operation. Since the beam must not be blocked by mechanics, these linear guides and also the components of the drive are located next to the beam. The need to drive well outside the centre of gravity, where very high g forces occur, while requiring a repeatability of the shutter blades in the micrometer range, made it necessary to remain rigorous in the application of the design principles. In addition, the cost price of the parts had to be kept low for this serial product. All-in all, this design assignment made considerable demands on the creativity of the designer.

In order to accurately introduce the forces on the collimator carriages, various parts are fitted with flexure hinges, leafsprings and sprits to correctly constrain the degrees of freedom. The production of hinges by means of wire-erosion was not an option here because of the desired cost price. Extensive use has been made of aluminium extrusion profiles; flexure hinges are immediately extruded and are therefore obtained – 'for free' – as a monolith. Simple milling operations are then sufficient to create decouplings in other directions.
Shutter blades and filters are driven via screw spindles with pre-tensioned plastic nuts. The spindles will bend as a result of g forces. To radially relieve each nut, it is secured via an axially preloaded Oldham coupling (Figure 4).
Here the shutter blades are not made of lead but of tungsten. This makes a separate 'supporting construction' (which would be necessary for the weak lead) superfluous. Because the blades have been given an arc shape, centrifugal forces are transmitted in the plane of the blade sheet and the



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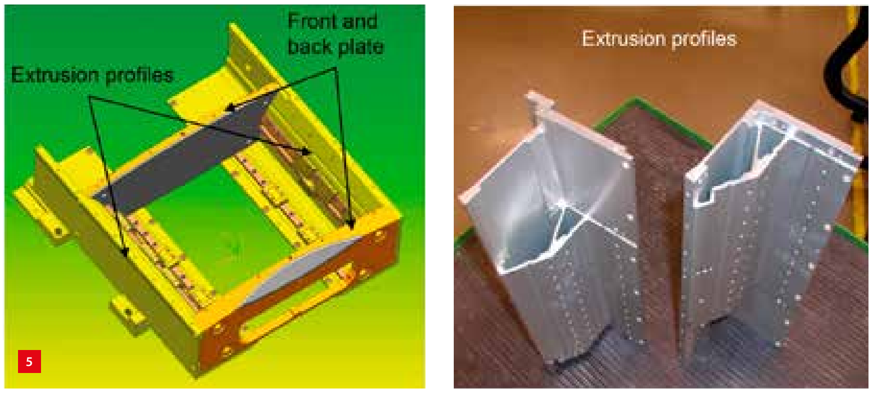
To radially relieve the nut, it is secured via an axially preloaded Oldham coupling.



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Design of the collimator frame according to the principle of the refrigerator vegetable drawer: tubular extrusion profiles with front and back plate make the frame a stiff assembly.

deformation of the blade is minimal. The curved blade construction makes parallel adjustment of both blades relatively easy. This is done by twisting the blade with the aid of a sprit, making use of the internal degree of freedom of the bent blade.
The open frame of the collimator is also largely made of extrusion profiles. In order to give this frame – in fact, an open box construction – the required high stiffness, the 'principle of the refrigerator vegetable drawer' has been applied (Figure 5). Box-shaped extrusion profiles with front and back plate make the frame a stiff assembly. Truly a 'VanderHoekean' solution.

The final realisation is shown in Figure 6.

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Senior designer Michel Loos showing the construction of the collimator with two curved shutter blades.

PROOF OF PRINCIPLE

In medicine, stents are used to open blood vessels. They are inserted into the vessel in a crimped state and then expanded. This typically involves small structures, large deformations, complex contact conditions and intricate material definitions. Can finite-element analysis support stent design?

CHRISTINE OBBINK-HUIZER

Introduction

Stents are used in medicine to allow blood to flow through a vessel or duct. In this article, the focus will be on coronary stents [1]. These are used when a blood vessel that supplies blood to the heart is occluded, for example by plaque. The stent, a thin metal structure, is first crimped so that it is small enough to pass through blood vessels on its way to the occluded region, then, once it is there, it is expanded so that the vessel opens (Figure 1), allowing blood to flow more easily and thus oxygen and nutrients to be delivered to the heart.

The process of first crimping and then expanding the stent was simulated using the Abaqus finite-element analysis (FEA) solver [2].

Geometry

Stents are often drawn flat, although their final geometry is tubular. Using a wrap mesh plug-in, flat geometry was wrapped into a tube (Figure 2). Stents normally consist of repeated segments. Multiple instances of the segment were created to form the complete tube (Figure 3). Here, a circular profile with a radius of 0.045 mm was assigned to the structure.

Materials

In this example, a balloon-expandable stainless-steel stent was simulated, comparable to Figure 1. Elastic-plastic stainless steel material properties were defined, with plasticity of special importance, to allow for the crimping and expansion of the stent.

A stent is designed to expand against a blood vessel. Like many human tissues, a blood vessel is a composite. Using the Holzapfel-Gasser-Ogden model [V2], the blood vessel wall was modelled as a hyperelastic matrix with families of fibres embedded in it. The families of fibres have a main direction and a degree of alignment with respect to this direction. It is possible to have completely aligned fibres, randomly oriented fibres or something in between, where there is a preference but not all fibres are oriented in the same direction. In the case discussed here, there was only a weak preference in fibre orientation. For the parameter concerned, κ (0 for perfect alignment, 1/3 for random orientations) values of 0.303 and 0.313 were used. The vessel wall consisted of three layers that had different properties and different main fibre orientations. These were taken from literature [3]. The main fibre orientations are visualised in Figure 4.

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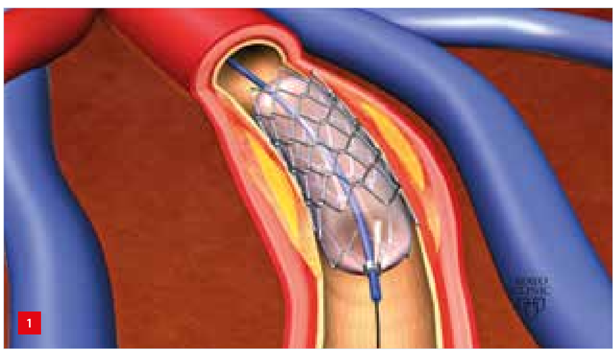
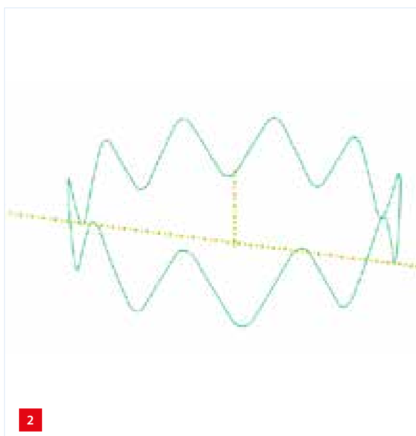
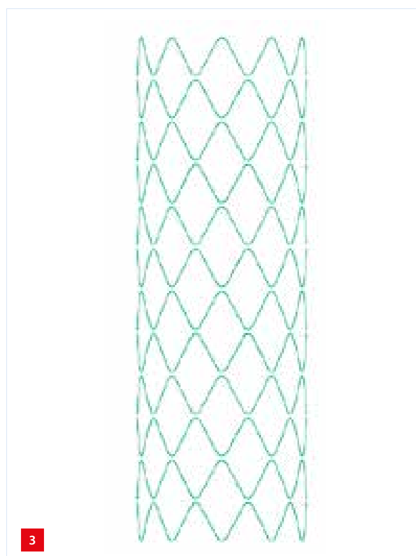


Coronary stent placement. Here, plaque has reduced the cross-section of the artery and hence the blood flow. The crimped stent was delivered using a catheter and then blown up using a balloon. This compressed the plaque and opened the artery so that blood could flow. The stent deformed permanently and thus keeps the artery open. See also the video [V1]. (Image: Mayo Clinic News Network)



Wrapped mesh.



Complete stent, with a length of approximately 10 mm and a diameter of 3.5 mm.

Main fibre orientations in the vessel wall. Each of the three layers has two main orientations, which have the same angle with the circumferential direction, but with a different sign. The fibre orientations in different layers are indicated in different colours. The outer layer is dark blue, the middle layer light blue and the inner layer red, while the thickness of the layers is 0.38, 0.35 and 0.27 mm, respectively. In comparison, the orientation of the fibres in the middle layer is more in the circumferential direction, while the fibres in the inner and outer layers are more longitudinally oriented. This is a transparent side view, hence the overlapping layers with their different fibre orientations.

Loading conditions

First, the stent was crimped (to fit the catheter used for inserting the stent into the vessel) and then it was expanded until it was pressed against the vessel wall. The analysis therefore includes the stent, a crimping tool, an expansion tool and the vessel (Figure 5).

The stent consisted of multiple instances of the beam structure shown earlier (Figure 2). These were locally connected via ties (Figure 6). Due to these local connections, cyclic symmetry conditions could not be used.

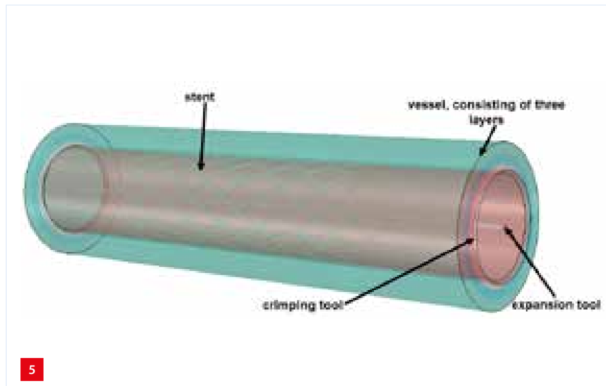
The vessel was modelled as a 3D solid. Both tools were modelled using surface elements. The crimping tool initially had a larger diameter than the stent, while the expansion tool had a smaller diameter than the stent after crimping. Four steps were simulated:

1. Crimping;
2. Removal of crimping tool;
3. Expansion;
4. Removal of expansion tool.

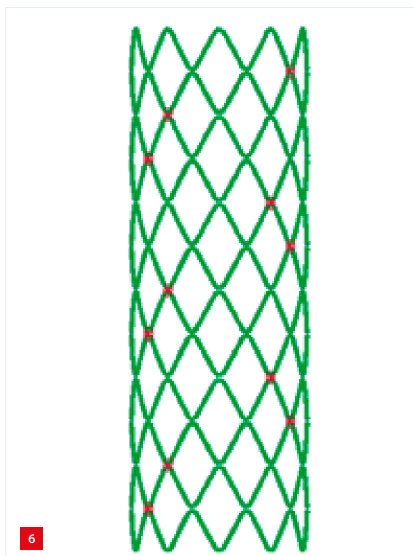
The displacement of the crimping tool was prescribed during the first two steps, while the displacement of the expansion tool was prescribed during the last two steps. No other boundary conditions were applied.

Contact

Contact was an important aspect of this analysis. The crimping and expansion tools were in contact with the stent, the stent was in contact with the vessel, and different parts of the stent were in contact with each other. The tools themselves, however, should not be in contact with each other. Furthermore, all parts, including the vessel and the expansion tool, were already present at the start of the analysis. The vessel initially overlapped the uncrimped stent. Contact between the vessel and the stent, however, should not be considered at this stage; they should behave independently. Similarly, the expansion surface should not influence the analysis until the third analysis step. Additionally, the stent struts were modelled as beams, which do not have a thickness on the geometry (see the text box on the next page, “Solid versus beam models”). The beam radius should be accounted for in the contact evaluation.



Model set-up for crimp-expansion analysis.



Stent with strut thickness visualised and locations of ties indicated.

Solid versus beam models

Beam elements were used in the present model. These are 1D elements, which are suitable when one dimension of the structure is clearly larger than the other two. They are more computationally efficient than the alternative, i.e. using solid elements, because the behaviour through the cross-section of the beam is included inside the element, rather than needing multiple elements throughout the cross-section. Although the geometry of the beam is not explicitly simulated, it is possible to include contact on the beam's outer surface for a circular cross-section, as was done here. If the cross-section were rectangular, for example, then the actual outer surface of the beam could automatically be included for contact. It would then be necessary to add an additional surface that represents the outer surface of the beam and is coupled to the beam elements.

Alternatively, solid elements could be used. These are significantly more computationally expensive. Solid elements are also needed when the beam assumption is no longer valid, for example when taking a detailed look at the behaviour around local thickness changes, or the points where struts connect to each other.

All of these contact effects could easily be included in the simulation. The radius of the struts was accounted for automatically. By default, general contact included contact between all surfaces. At the start of the analysis, the vessel and the expansion tool were excluded from the contact. At the start of step 3, the vessel and the expansion tool were included, and the crimping tool was excluded. Friction was considered.

The analysis was performed using Abaqus/Explicit (see the text box, "Implicit versus explicit solver"). Compared with an implicit solver, the small time increments and no need for convergence of the non-linear solution algorithm of an explicit solver made it easier to find a solution to a complex contact problem such as this.

Results

The simulation was captured in an animation [4]. The stent was crimped to a small diameter. The contact conditions ensured that there was no overlap between different regions. Stresses were observed to be localised at the rounded parts of the struts, exceeding the tensile limit in this region. Potential damage to the struts was not included in this analysis. Since this analysis was

Implicit versus explicit solver

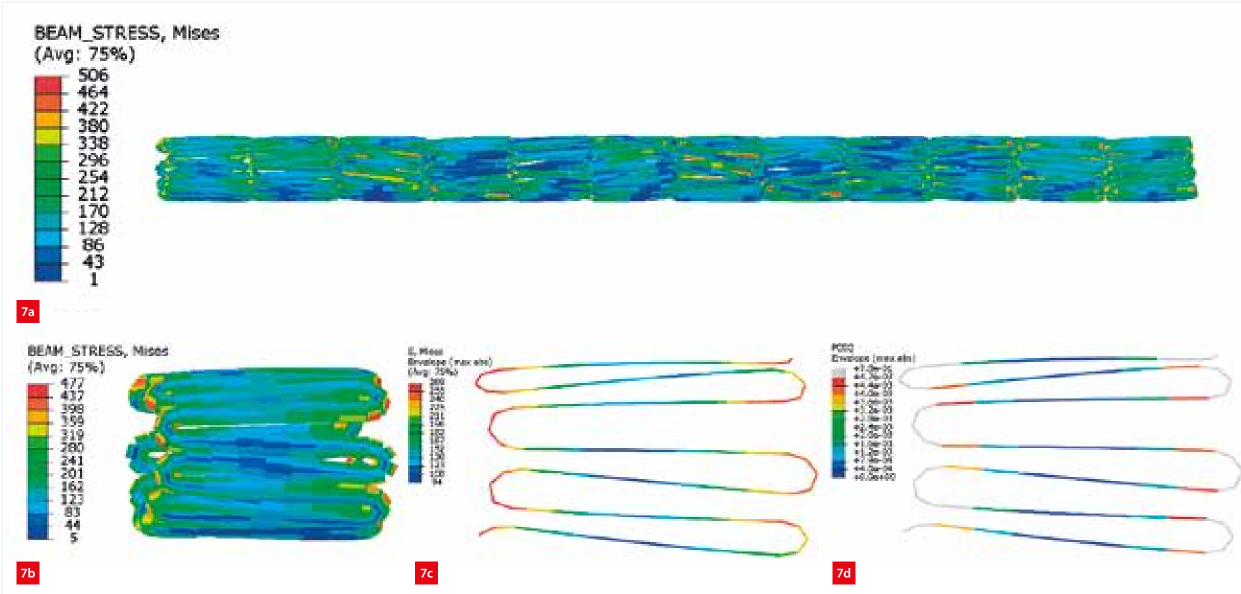
A fundamental question for each finite-element problem is the type of solver to use: implicit or explicit? This concerns the algorithm that is used for time incrementation. In both cases, the state of the model is calculated at multiple points in time and the new state is calculated based on the old state. With an explicit algorithm, the new state can be calculated directly from the data available in the current state. It is basically an extrapolation.

With an implicit algorithm, on the other hand, the new state cannot be calculated directly from the old state. Here, a coupled system of equations must be solved, which requires a nonlinear solution algorithm, typically the Newton-Raphson method. This process is iterative. As more iterations are performed, the calculated solution should get closer to the actual solution. If the error is small enough, the increment is considered converged. As problems become more nonlinear, obtaining a converged solution is more time consuming and challenging; in some cases, it is even impossible. Implicit solvers therefore work well for slow processes that are linear to mildly nonlinear, while explicit solvers work best for fast processes that are extremely nonlinear.

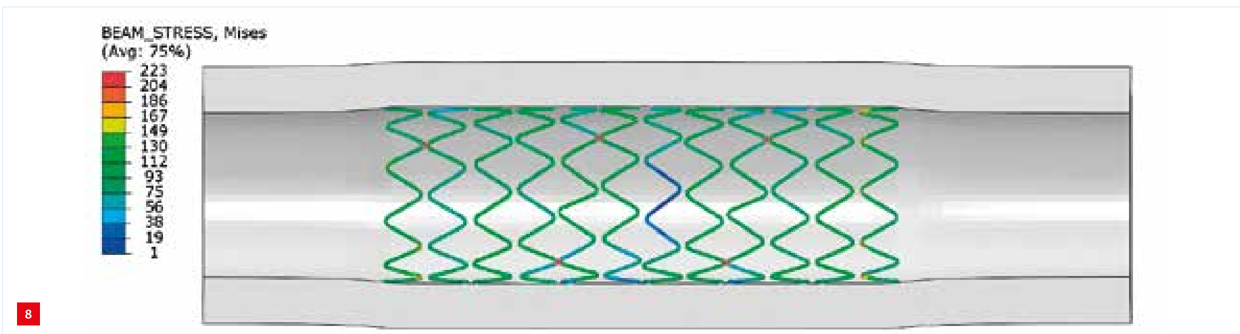
So, what about stent analysis? Crimping or expanding a stent is typically rather slow (order of magnitude seconds), but also extremely nonlinear due to the large deformations and complex conditions. These last points make it difficult, if not impossible, to find a solution with an implicit solver. For that reason, an explicit solver was used. A drawback of this is that dynamic effects can unintentionally play a role, and results can be more oscillatory. By applying the deformation more slowly, this effect can be reduced. Simulation time is then increased. An additional advantage of an explicit solver over an implicit solver is that it is not necessary to restrain all rigid-body motions (motions of the structure as a whole). For asymmetric stents, it is not possible to constrain the movement of nodes without possibly influencing the results.

on a 'quick and dirty' design, there is a lot of room for improvement on the geometry.

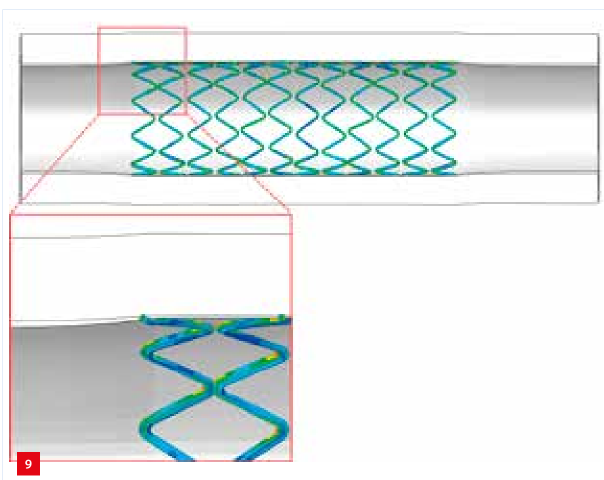
After the crimping phase, the crimping tool was removed, leading to elastic spring-back. The final diameter of the crimped stent was slightly larger than the minimal inner diameter of the crimping device.
Then the stent was expanded in the vessel. The vessel moved outwards, especially where the stent was located. When the expansion tool was retracted, the vessel moved



Results at the end of step 1 (crimping).
(a) Von Mises stress (MPa) for the entire structure, with beam profiles (thickness) rendered.
(b) Same as (a), now showing only the left segment. The beam stress output shown here allows stress through the cross-section to be plotted in the 1D line elements. The stress is highest in the bent corners.
(c) Von Mises stress in the front part of the segment of (b). Beam profiles have not been not rendered here.
(d) Equivalent plastic (inelastic) strain in the segment of (c). Grey regions have plastic strains larger than the maximum value specified for this material. This indicates that, for at least a part of the outer surface of the struts, the material may suffer damage.



Beam stresses in cross-section of the stent at the end of the analysis. The locations where the segments are connected to each other are indicated in red. The bent regions are not all aligned as they were at the start of the analysis. This is likely because of the limited amount of space during crimping, as some struts move sideways to create enough space for themselves.

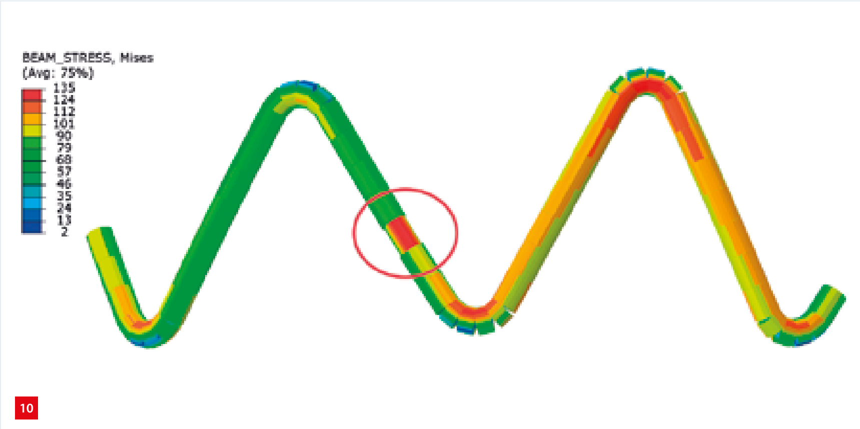


Beam stresses in an overlay of the model at the end of step 3 (expansion device at maximal expansion) and the end of step 4 (expansion device removed after expansion). In the zoom-in, half way down, the two (more or less horizontal) non-overlapping lines show the amount of elastic spring-back after stent delivery.

back partially, but was slightly more open than in the initial case. In this example, no plaque was included; the effect would be clearer if that had been the case. These analyses show the final shape of the stent, including the new internal diameter of the vessel, once it was opened. It also shows the stress levels in the stent. These can be used to assess whether this stent design can withstand the intended loading.

Influence of (geometrical) variations

In the analysis, the geometry was 'perfect': the thickness was the same everywhere, all radii were the same and as designed, etc. Also, the material properties were constant, the stent was perfectly aligned with the vessel and the displacements of the crimping and expansion surfaces were the same everywhere. The real world tends to be less perfect than the idealised version, and variations in the factors



Stress increase in the region with the smaller radius.

mentioned above can occur. These could be investigated numerically, by modifying the model and rerunning it.

For example, the radius of one element was reduced from 0.045 to 0.040 mm. When rerunning the analysis, the stress was higher locally in the region with the smaller radius (see Figure 7).

With this beam model, the change was rather abrupt. A more detailed analysis would require a (partially) solid model. Nonetheless, this analysis can provide an indication of the type of impact a local thickness reduction is expected to have, before going into more detailed analysis if needed. Also, local radius reduction can have a different impact in different regions. In this design, most of the deformation occurred in the corners. Reducing the radius in one of the corners could have an even larger impact in terms of stress increase and/or deformation, as compared to the case for the straight section presented here.

Boundary conditions and symmetry

One of the interesting topics for this type of analysis is the choice of boundary conditions: whether the movement of points on the geometry is restricted and, if so, where and how. In this case, boundary conditions were only applied to the tools, not to the stent or the vessel. The stent then has a lot of freedom to deform. This could have a positive result, because no unnecessary restrictions are imposed, but it could also have a negative one, because there could be non-physical movements, especially if the loading is applied rather quickly to reduce the simulation time. Ideally, motions of the entire structure are avoided, while allowing more local motions. However, this cannot be prescribed directly.

In some cases, symmetry conditions can be used: if there is symmetry in the model, then the symmetry-related parts should behave in the same way. Only a part of the structure needs to be simulated, which reduces the size of the model and the simulation time. The geometry cannot move off the symmetry plane, limiting the motion of the stent in a realistic way. The lack of symmetry in the current model, due to local connections between the stent segments, did not allow this approach.

More simulation work

The current example was quite simple and only intended to show the principle. In practice, different patients have a different vessel geometry, possibly including bends and bifurcations. Plaques can occur at different locations, and have different sizes. Simulations of patient-specific geometry can help to assess which stent is most suitable for which patient.

Positioning the stent is only the start of the process. When the stent is in service, it is loaded cyclically with the pulsatile blood flow. Given a normal heart rate of 60-80 beats per minute and a stent lifetime of 10 years, the stent should survive hundreds of millions of cycles. Fatigue behaviour during this period is important and it can take a very long time to measure it experimentally. Simulations can be used to predict fatigue behaviour.

For this kind of medical application, simulations are especially useful because of ethical limitations on experiments that can be performed on patients.

Conclusion

There is a lot of potential for stent analysis. General contact simulation functionality can account for even complex contact conditions, such as contact between the outer surface of beam elements, in a user-friendly way. The availability of an explicit and an implicit solver in a single package makes it possible to try out both options and/or do part of the analysis with one solver and another part of the analysis with the other. The inclusion of superelastic and Holzapfel-Gasser-Ogden material models in the material library allows most materials that are relevant for stents to be simulated with built-in materials. Though stent analysis is challenging, Abaqus offers the tools to make it possible.

Relevant Abaqus features

- The wrap mesh plug-in was used to wrap the flat geometry into a tube. It requires a mesh(ed geometry) in the assembly module and input of the circumferential direction, axial direction, name of the new part, origin and the wrapping radius. The plug-in creates an orphan mesh of the wrapped tubular structure. This works for shells, solids and beams. Here, beam elements were used.
- The built-in superelastic material model could be used typically for self-expanding nitinol stents.
- The Holzapfel-Gasser-Ogden model was implemented to model a blood vessel as a hyperelastic matrix with families of fibres embedded in it.
- The general contact option accounted automatically for the various contact situations between the various vessel and tool surfaces.

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VIDEO

[V1] *www.youtube.com/watch?v=I12PMiX5h3E*

[V2] *www.youtube.com/watch?v=D3BiR1bkE00*

STACKING ORTHOPAEDIC PRECISION PRODUCTS

Common additive manufacturing (AM) processes apply lasers for the sheetwise melting of metal powder. Such processes are called SLM (selective laser melting) or DMLM (direct metal laser melting). A quite recent development is the application of an electron beam instead of a laser beam. This technology is called EBM, electron beam melting. It does require a vacuum environment, but this disadvantage is compensated by the advantage of the easy stacking of printed products, such as titanium orthopaedic products.

FRANS ZUURVEEN

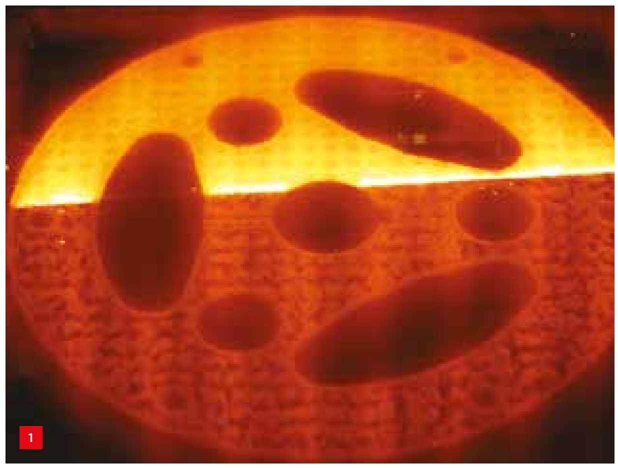
Figure 1 shows the melting of metal (e.g. nickel or titanium) powder. Figure 2 explains the electron-optical set-up designed by GE Additive for – among other AM applications – the production of titanium orthopaedic products. The column resembles the one applied in a scanning electron microscope, where emitted secondary electrons, for example, are captured by a sensor.

A filament in the EBM column acts as a cathode by emitting electrons, which are focused by means of electromagnetic lenses onto a spot at the thin anode powder layer on the building table. Deflection coils cause the electron beam to swivel according to a CAD-defined X,Y-pattern across the anode. After melting one layer the building table is lowered and a new powder layer is locally melted. The complete set-up is positioned in a vacuum chamber with a pressure of $5 \cdot 10^{-5}$ mbar, with an extra content of $4 \cdot 10^{-5}$ mbar helium to prevent contamination.

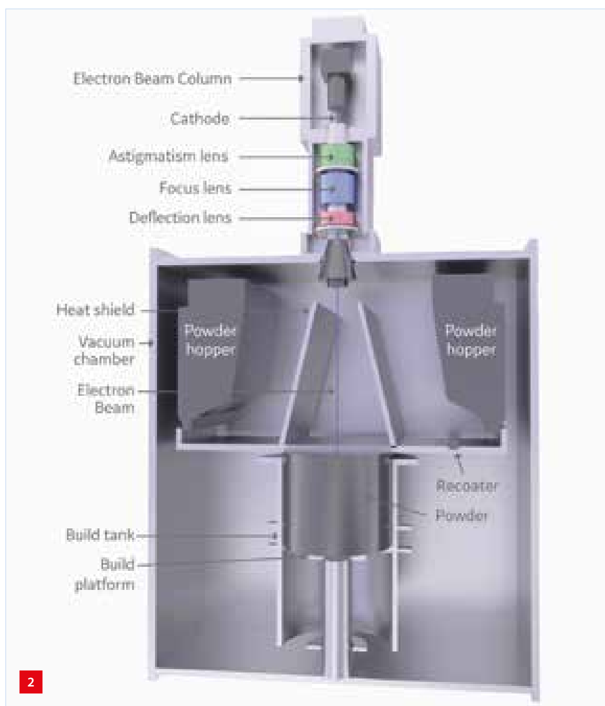
Figure 3 illustrates the deeper penetration of electrons into metal powder compared to the penetration of laser light. This difference helps to provide better, more homogeneous melting when producing products, orthopaedic ones, for example, but also complicated aerospace components. Another advantage of EBM, due to lower reflection, is the higher absorption rate of electrons by the printing powder, compared to laser-light absorption.

Orthopaedic products

A variety of orthopaedic products has been produced using GE Additive equipment. They can be manufactured from various kinds of exotic titanium alloys. At first sight, they look rather rough, but the application of a large powder grain size provides a relatively rough surface that actually facilitates the integration of the implanted part into the human body.



1 Melting metal powder, in this case nickel super alloy 718.



2 The complete EBM set-up housed in a vacuum chamber.

AUTHOR'S NOTE

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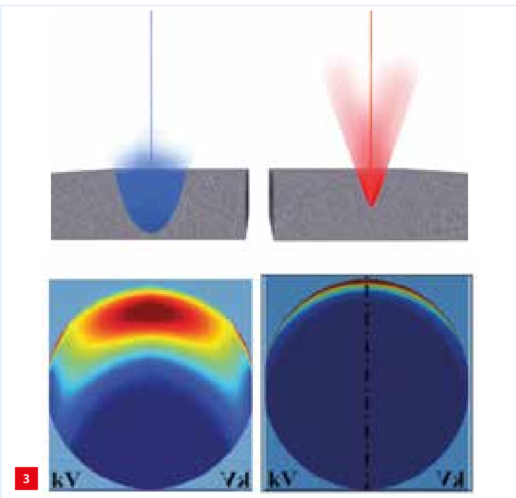
For the application of such 'difficult' materials that are sometimes inclined to be brittle or crack-sensitive, the EBM process can be executed at extremely high temperatures, even up to 1,000 °C. An advantage of these sophisticated process conditions is that the untreated powder particles, unaffected by the sweeping electron beam, are forced to sinter together. This means that powder particles stick together locally, which enables successively printed products to stay fixed in their positions with respect to one another. This eliminates the necessity to fix the printed parts on a base plate, as is common practice in conventional AM processes. Later in the process the sintered redundant powder can easily be blasted away.

Figure 4 shows such stacked printed products, temporarily mutually fixed by sintered powder. Here, this concerns rough hip-joint cups, which still have to be finished carefully at the inward surface, which accommodates the hip-joint sphere. The relatively rough exterior helps the integration in the human bone structure. Producing such stacked products in one single manufacturing cycle helps to produce low-cost human implants.



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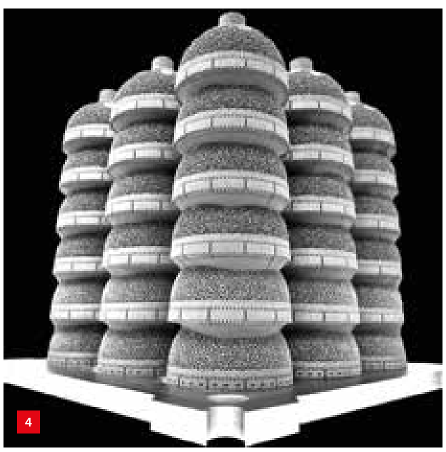
Schematic illustration of the respective penetration depth of electrons (left) and photons (laser light, on the right) in metal powder.



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Stacked rough hip-joint cups, mutually fixed by sintered powder. (Image: Amplify Additive)

GE Additive EBM machines

GE Additive is a division of the well-known global General Electric company. It has specialised in the development of AM machines using the EBM process. For that purpose, in 2016 GE Additive acquired the German firm Concept Laser and the Swedish firm Arcam. The Arcam machines are perfectly equipped to produce medium-sized series of orthopaedic products. In the Netherlands, the GE Additive machines are marketed and maintained by Landré Machines in Houten.

Figure 5 shows the interior of an Arcam machine, with the vacuum chamber. Not visible, above the chamber, is the EBM column. At the top, the printing powder hoppers can be seen at left and right, while lower down in the picture the build tank is visible. Inside the build tank is the mechanism for moving the partly printed products stepwise down in the layer-printing sequence.

WWW.GE.COM/ADDITIVE
WWW.LANDRE.NL

5

The vacuum chamber inside an Arcam printing machine.

To conclude

It is quite remarkable that the column of a scanning electron microscope can be used in a sophisticated version of additive manufacturing machines. Arcam therefore succeeded in the development of AM machines for the production of stacked orthopaedic products. There is a good chance that future owners of a new hip joint will be able to thank the creativity of GE engineers for their newly acquired walking mobility.

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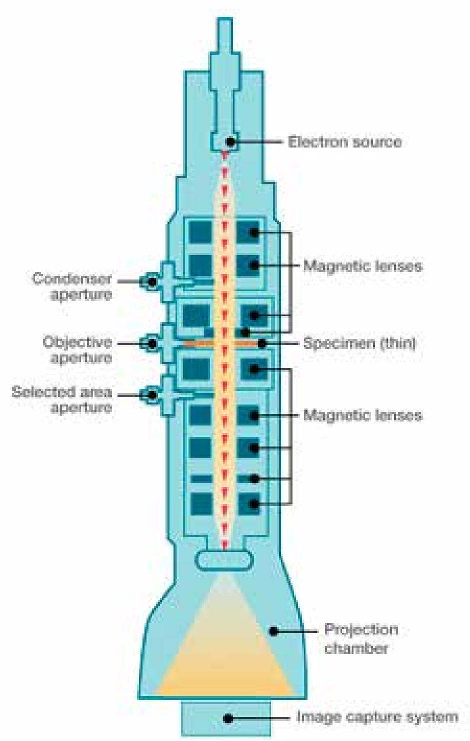
HIGH-PRECISION SAMPLE POSITIONING IN ELECTRON MICROSCOPES

Piezo stepper actuators are used in many nanopositioning systems because of their high resolution, high stiffness and fast response, and their ability to position a mover over an infinite stroke by means of a motion reminiscent of walking. A major drawback of employing piezoelectric actuators is their hysteretic behaviour. The history dependence of hysteresis prevents the application of a trivial compensating feedforward controller for existing hysteresis models. The method presented here exploits a new hysteresis modelling approach that allows for a straightforward feedforward controller that can be manually tuned, reminiscent of industry-standard tuning approaches for mechanical feedforward components.

NARD STRIJBOSCH, EDWIN VERSCHUEREN, KOEN TIELS AND TOM OOMEN

Introduction

High-tech electron microscopes, as designed and manufactured by Thermo Fisher Scientific, use beams of electrons to create images, magnifying micrometer and nanometer structures up to ten million times, thus providing a spectacular level of detail. These microscopes even allow researchers and scientists to view columns of atoms in crystal structures. The images acquired are a key enabler for advances in nanotechnology, life science, material science and semiconductor technology.



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General overview of an electron microscope.

The working principle of an electron microscope resembles that of an ordinary light microscope or slide projector, except that it uses an electron beam instead of a light beam; see Figure 1. The electron beam first passes through a set of lenses before it reaches the sample. Several phenomena occur that distort the electron beam when it passes through a sample, including energy losses and quantum-mechanical phase shifts. After the beam goes through the sample, another set of lenses guides the electron beam to a detector. The data from the distorted electron beam is translated, using image processing techniques, to an image of the sample.

An important aspect of obtaining high-resolution images is the positioning of the sample. Any disturbances acting on the sample have an impact on the image quality. One of the recent advances is cryogenic transmission electron microscopy (Cryo-EM), which can be used to make 3D reconstructions of macromolecules such as viruses; see Figure 2. These 3D reconstructions require a significant number of tilted 2D images. This leads to increasing positioning velocity requirements to decrease the time between consecutive images, thereby increasing the throughput.

AUTHORS' NOTE

Nard Strijbosch (Ph.D. candidate), Koen Tiels (assistant professor) and Tom Oomen (full professor) are all associated with the Control Systems Technology group within the department of Mechanical Engineering at Eindhoven University of Technology in Eindhoven (NL). Edwin Verschueren works as a mechatronic design engineer at Thermo Fisher in Eindhoven.
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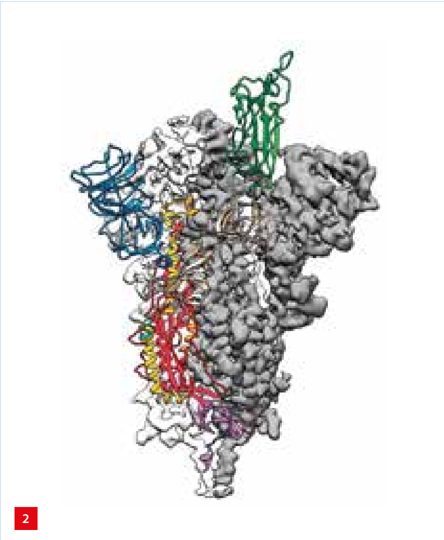
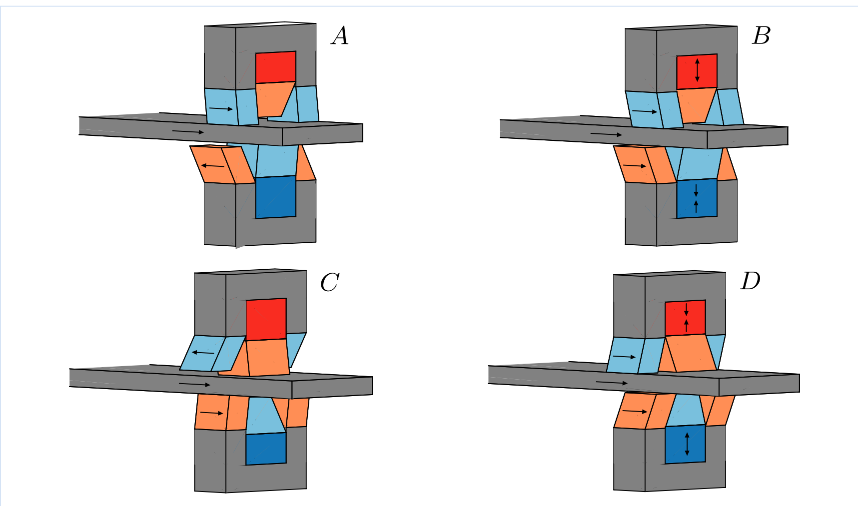


2 SARS-CoV-2 spike protein. Cryo-EM density data in white and grey [2].

Piezo stepper actuators enable the increasing accuracy and velocity requirements for sample positioning to be met. Individual piezoelectric elements provide high accuracy, high stiffness and fast responses times, albeit within a limited range. Combining several piezoelectric elements and exploiting them to propel a mover through walking leads to an actuator with a potentially infinite range, while maintaining the favourable properties of the individual piezoelectric elements.

The use of piezo stepper actuators for future high-accuracy and high-velocity electron microscopes creates two major challenges that require advanced control techniques. Firstly, it is well known that individual piezoelectric elements exhibit hysteretic effects. Hysteresis is a history-dependent nonlinear effect that is typically hard to model and compensate for. Secondly, the walking of a piezo stepper involves impact at contact, which must take place carefully to ensure smooth walking behaviour in order to avoid unwanted disturbances. Approaches to compensate for the disturbances introduced by the walking behaviour have been developed in e.g. [3] [4]. These approaches assume no history dependency, which is violated due to the hysteresis phenomena. The remainder of this article addresses the first challenge of compensating for the hysteretic behaviour. The main aim is to achieve this by extending well-known motion control techniques used in the high-tech industry, including semiconductor, printing systems and additive manufacturing.



Schematic representation of a piezo stepper actuator in each of its four phases, A to D, of a stepping motion. The different piezo elements are: longitudinal piezo of group 1 (blue); longitudinal piezo of group 2 (red); shear piezo of group 1 (light blue); and shear piezo of group 2 (orange).

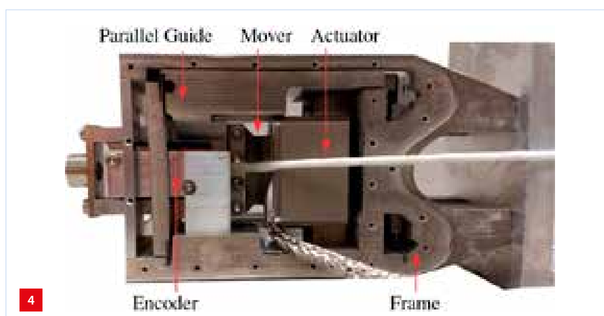
Piezo stepper actuators

Piezo stepper actuators consist of multiple piezoelectric elements in varying configurations that propel a mover; see e.g. [3] [4]. The piezo stepper actuator considered here is schematically depicted in Figure 3. This piezo stepper consists of two groups of piezo elements, each containing a longitudinal element that can extend perpendicularly to the mover, and three shear elements that can extend in the direction of the movement. When the longitudinal element of a group is extended, the corresponding shear elements are in contact with the mover, thereby dictating the position of the mover. Alternating between the two piezo groups results in a walking motion, which leads to an unlimited stroke of the mover. An experimental set-up that includes a piezo stepper actuator is shown in Figure 4.

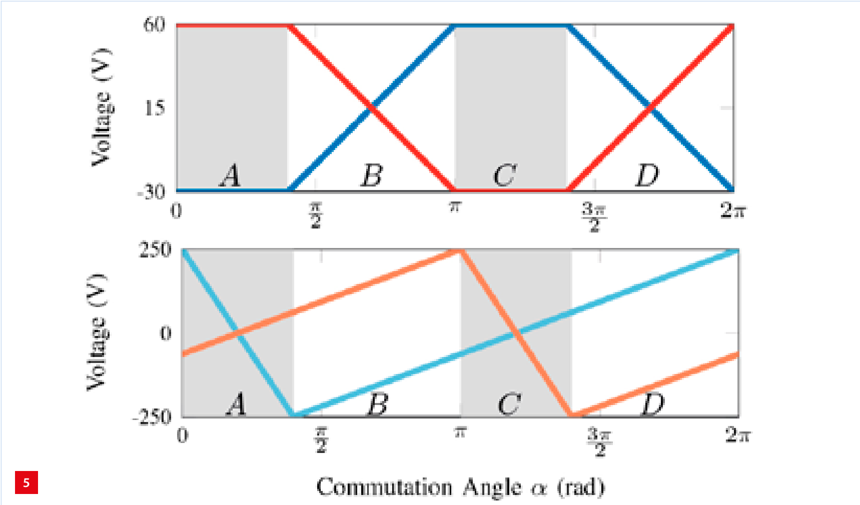
A set of waveforms is chosen judiciously to specify the relation between the inputs of the individual piezo elements, which in turn achieves the walking behaviour. The design of these waveforms is crucial in achieving high performance. The waveforms are mappings from the commutation angle α to the input voltages for the longitudinal piezo elements, c_1 and c_2, and shear piezo elements, s_1 and s_2. The waveforms are defined on the interval $\alpha \in [0,2\pi)$. A full cycle from $\alpha = 0$ to $\alpha = 2\pi$ includes a step from each piezo group.

The waveforms depicted in Figure 5 are designed to obtain four distinct phases, A to D, as shown in Figure 3:

A. Group 1 shear piezo elements in contact with the mover; group 2 shear piezo elements, not in contact with the mover, are retracting.
B. Transition phase. Shear piezo elements of both groups possibly in contact with the mover.
C. Group 2 shear piezo elements in contact with the mover; group 1 shear piezo elements, not in contact with the mover, are retracting.
D. Transition phase. Shear piezo elements of both groups possibly in contact with the mover.



4 *Piezo stepper actuator made by Heinmade [5].*



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Top: waveforms applied to longitudinal piezo elements.
Bottom: waveforms applied to shear piezo elements.
The colours of each line correspond to the colours of the piezoelectric elements in Figure 3.
The intervals A, B, C and D correspond to the four phases depicted in Figure 3.
Interval A: the longitudinal piezo element of group 2 is fully extended and the shears of group 1 are not in contact with the mover.
Interval C: the longitudinal piezo element of group 1 is fully extended and the shears of group 2 are not in contact with the mover.
B and D are the transition intervals.

Experiments reveal that the walking behaviour introduces disturbances that are highly reproducible in the commutation angle domain. These disturbances can be explained by physical sources, such as misalignment between the piezo elements or the contact dynamics between the shear piezoelectric elements and the mover. These disturbances can effectively be compensated for through learning-based techniques [3] [4], which exploit past error data to update the waveforms to compensate for the disturbances. These techniques are based on the assumption that the behaviour of the piezo stepper actuator is not history dependent. This assumption is not valid due to the hysteretic behaviour of the individual piezoelectric elements. Here, the aim is to compensate for this hysteretic effect using a feedforward controller that can be tuned during experiments.

Hysteresis

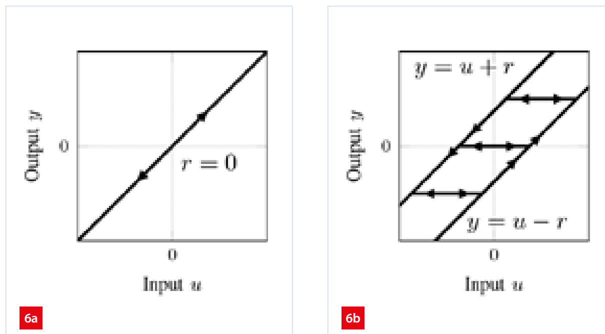
Piezoelectric actuators consist of a piezoelectric material that expands or contracts when placed inside an electric field. The internal energy losses in the piezoelectric material cause hysteretic phenomena [6]. This implies that the current position depends not only on the current input voltage, but also on its history, in particular the last instance in which the input direction changed. In other words, the hysteresis phenomenon is a memory-based nonlinearity. This behaviour can have a significant effect on the tracking performance of a piezoelectric actuator and should therefore be considered carefully.

Many models have been suggested to capture the hysteretic behaviour in piezoelectric actuators. The Prandtl-Ishlinskii model is a widely accepted one. It is a linear weighted superposition of a finite number of play operators, i.e.:

$$y(t) = \sum_{j}^{N} w_j H_{r_j}(u(t))$$

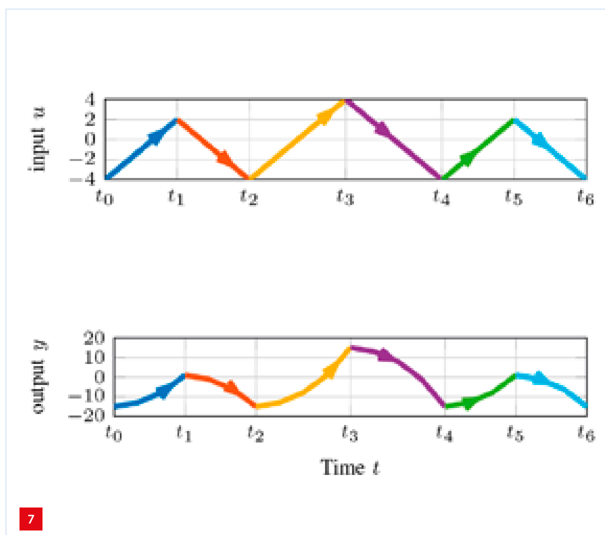
Here, N is the number of play operators and w_j the weight corresponding to the play operator H_{r_j}, as in Figure 6, with threshold r_j. In mechanical systems, a single play operator is often used to model the backlash or play between gears.

Results of a simulation study using the Prandtl-Ishlinskii model are given in Figures 7 and 8. A triangular input signal is applied to a Prandtl-Ishlinskii model that consists of four play operators. In the hysteresis loop in Figure 8, it can be observed that this leads to a piecewise linear approximation of the hysteresis loop. The inner and outer loop in Figure 8 indicate the history-dependent behaviour of hysteresis. Increasing the number of play operators allows the possibility of the model mismatch to decrease.



6a 6b

Schematic representation of a play operator.
(a) r = 0.
(b) r > 0.



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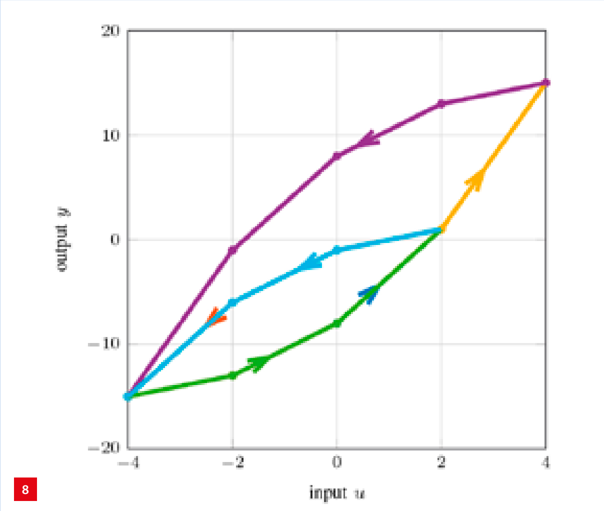
Input (top) and corresponding output (displacement) of the Prandtl-Ishlinskii hysteresis model.



Hysteresis loop corresponding to the input and output (displacement) signals as depicted in Figure 7.

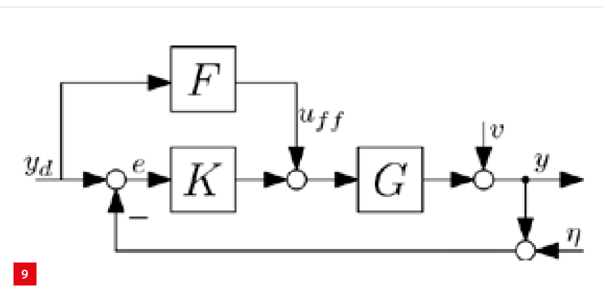
Motion control feedforward

Before moving to hysteresis feedforward, we will investigate traditional feedforward for general linear motion systems. A typical control architecture for motion systems is shown in Figure 9 (see e.g. [7]), where K and F are the feedback and feedforward controllers. When all systems are linear time invariant (LTI), then:

$$e = S\underbrace{(1-\mathrm{GF})}_{\text{feedforward}} y_d - \underbrace{S}_{\text{feedback}} v - \underbrace{S}_{\text{feedback}} \eta$$

Here, $S = (1 + GK)^{-1}$, v is a disturbance affecting the system and η is the measurement noise. The goal of feedforward is to obtain an input signal u_{ff} for the plant G, such that the desired trajectory y_d is followed. This is achieved if the feedforward controller is an exact inverse of G. The goal of the feedback controller is to attenuate the unknown disturbances v and η, and a possible residual $(1 - GF)y_d$ caused by incomplete knowledge of G in the design of F.

Industrial practice is to design the feedback controller in the frequency domain using loop-shaping techniques and subsequently manually tune the feedforward controller.



Typical control architecture for servo control.

This systematic manual tuning technique is used to determine the feedforward controller F during experiments without the need for accurate knowledge of the system. The case study (see text box) outlines the manual feedforward tuning procedure for an H-drive.

Case study: Manual feedforward tuning for mechanical systems

To illustrate a typical manual feedforward tuning approach, consider a general H-drive. The aim is to reduce the positioning error along a prescribed trajectory y_d. The model of the H-drive at low frequencies is simply given by its rigid body behaviour, i.e.:

$$y(s) = \frac{1}{ms^2}$$

Here, m corresponds to the mass of the system. Therefore, a candidate feedforward controller is $F = k_{fa}s^2$, which leads to the feedforward signal $u_{ff}(s) = k_{fa}s^2 y_d(s)$ and, by the inverse Laplace transform, to $u_{ff} = k_{fa}\cdot d^2y_d(t)/dt^2$. This feedforward is therefore also referred to as acceleration feedforward. Then, the error signal is given by:

$$e = S(1-GF)y_d = S\left(1-\frac{k_{fa}}{m}\right)y_d$$

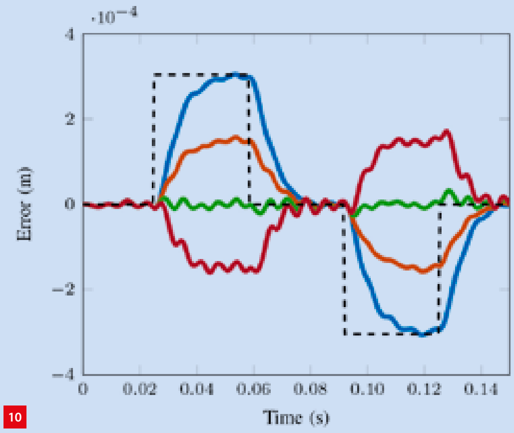
This feedforward structure clearly minimises the error if $k_{fa} = m$. However, accurate knowledge of m is not typically available. The main idea of a manual feedforward tuning approach is to tune the parameter k_{fa} during experiments, while evaluating the error for an appropriate reference signal y_d.

To this end, a stabilising feedback controller K, typically in the form of a lead filter, is implemented, without integral action. This implies that at low frequencies $|GK| >> 1$, for some constant c:

$$S = \frac{1}{1+GK} \approx \frac{1}{GK} \approx cs^2$$

Combining with the error signal, this leads to:

$$e(s) = cs^2\left(1-\frac{k_{fa}}{m}\right)y_d$$



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Tuning the feedforward parameter k_{fa} for an H-drive in an experiment where $d^2y_d(t)/dt^2$ is given by the dashed line (--). The error signals correspond to experiments with k_{fa} = 0 (blue), k_{fa} = 10 (orange), the optimal value k_{fa} = 21 (green), and k_{fa} = 31 (red).

Applying the inverse Laplace transform, this becomes:

$$e = c\left(1 - \frac{k_{fa}}{m}\right)\frac{d^2 y_d(t)}{dt^2}$$

This directly reveals how to determine the feedforward controller: choose k_{fa} such that the error is not correlated with the acceleration signal. This can be done by performing experiments under normal operating conditions. Tuning of the value of k_{fa} can be done in a straightforward manner, since the error depends affinely on k_{fa}; see Figure 10.

This idea is adopted widely in industry and applied in a very similar way to manually tune many feedforward components, including viscous friction or snap feedforward, or possibly nonlinear components such as Coulomb friction [7]. A key point is that all of these feedforward elements are memoryless. However hysteresis depends on the history of the system, thereby preventing the use of these memoryless feedforward elements. In the next section, we outline how manual feedforward can be achieved for hysteresis. The key idea is the use of a new memory model.

Feedforward for hysteresis

The history dependency of the hysteretic behaviour in piezoelectric actuators prevents a straightforward inverse that can be used for feedforward. A fundamentally new way to model these hysteresis phenomena is through memory (MEM) elements; see [8] for a recent overview. The key idea is described below; for more details, see [9].

A variable p is introduced, which can be interpreted as a variable that keeps track of the history.

Exploiting this variable, the Prandtl-Ishlinskii model is rewritten as:

$$\dot{y}(t) = M\big(p(t)\big)\dot{u}(t)$$

An example of a typical function $M(p)$ is given in Figure 11. This $M(p)$ is rather straightforward, where the number of levels corresponds to the number of play operators, and is constant for each level.

This new notation of the hysteresis model allows for a straightforward inverse, leading to the following feedforward controller:

$$\dot{u}_{ff}(t) = \frac{1}{M\big(p(t)\big)}\dot{y}_d(t)$$

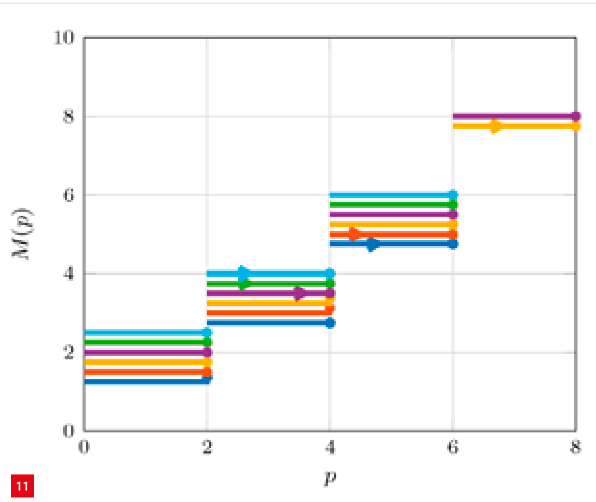
Tuning the feedforward controller now boils down to finding the constants in the mapping $M(p)$. In each of the ranges of p where the mapping $M(p)$ is constant, the hysteresis model behaves as a linear spring, i.e.:

$$y(t) = c_p u(t)$$

With c_p a constant, the corresponding feedforward controller is given by:

$$u_{ff}(t) = \frac{1}{k_s} y_d(t)$$

Hence, in each of these ranges the constant value of the mapping $M(p)$ can be tuned as if it were a linear system; this is similar to the tuning approach in Figure 10.



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Function $M(p)$ for a Prandtl-Ishlinskii model that consists of four play operators. Each colour corresponds to a branch generated by the input signal from Figure 7. To visualise the start and end point of each line, all lines have a slight offset with respect to each other; in reality, all lines perfectly overlap.

Tuning the feedforward parameter k_s is done typically by applying a constant reference, i.e. $y_d = c$, leading to the error signal:

$$e = c\left(1 - \frac{c_p}{k_s}\right)$$

This error signal is affine in the unknown parameter k_s.

Changing the amplitude of the reference y_d will change the history and consequently change the variable p. Hence, a suitable reference signal to tune all of the constants that constitute the hysteresis feedforward is a piecewise constant signal with varying amplitudes, as depicted in Figure 12. Each change of the amplitude leads to a different history and thereby another level of the mapping $M(p)$ can be tuned.

This leads to the following procedure:
1. Select N play operators and their corresponding thresholds.
2. Choose a piecewise constant reference with low amplitude to tune the first weight, i.e. the first level in $M(p)$.
3. Increase the amplitude to tune the next level of $M(p)$.
4. Repeat step 3 until all levels are tuned perfectly. If the desired performance is not achieved, return to step 1 and increase the number of play operators.

This procedure is applied to the shear piezo elements in the piezo stepper actuator. The error data of this experiment is given in Figure 12.

Results

Applying this feedforward controller in a normal servo task to the piezo set-up given in Figure 4, shows a significant performance improvement compared to only feedback; see Figure 13. A factor of ten improvement is achieved in terms of the maximum error value.

The remaining error after applying the compensating feedforward is caused mainly by an error in modelling the hysteric behaviour in the Prandtl-Ishlinkskii model, with only four weights. Higher performance levels can be achieved by exploiting this approach with an increasing number of weights or with a different hysteresis model, see e.g. [10], although tuning a feedforward controller with a different model can be significantly more complex.

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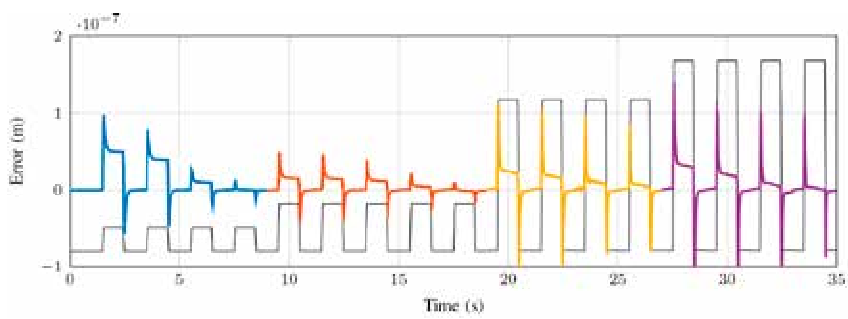
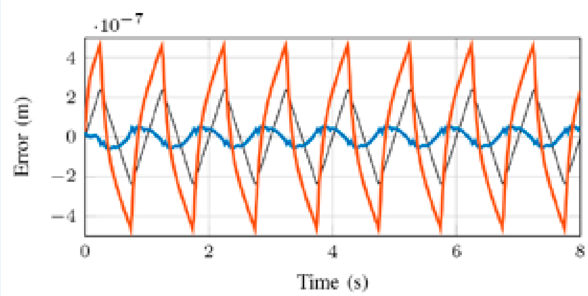


12

Manual tuning procedure for hysteresis feedforward applied to a piezoelectric actuator. The desired trajectory (scaled and shifted in black) is piecewise constant with four different amplitudes; each amplitude ensures a different range of p is active. The four tuning steps:
- *blue: decreasing c_{p1};*
- *orange: decreasing c_{p2};*
- *yellow: decreasing c_{p3};*
- *purple: decreasing c_{p4}.*



13

Closed-loop experiment with a piezoelectric actuator following a triangular desired trajectory (scaled and in black). Two different cases are studied:
- *in red: only feedback;*
- *in blue: with feedforward compensation determined using the manual feedforward tuning procedure of Figure 12.*

ANALYSIS, DESIGN, ENGINEERING AND CALIBRATION

In mid-June, the online DSPE "Precision Engineering in Vacuum" Knowledge Day attracted over 40 participants. Following an introduction about the leading association in the Dutch vacuum community, they were treated to various angles on the vacuum challenges in high-tech system design, ranging from analysis and design to engineering and calibration. The meeting ended with a vacuum application for the greatest 'vacuum' of all, space.

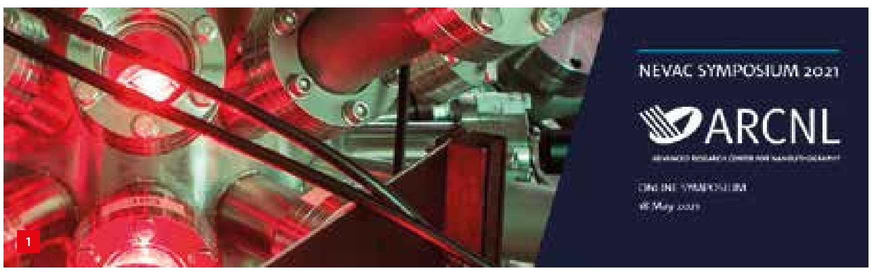
EDITORIAL NOTE

This report was based on the presentations at the online DSPE Knowledge Day, 15 June 2021.

Vacuum community

Sense Jan van der Molen, chairman of NEVAC and professor of physics at Leiden University (NL), started off with an introduction of the Dutch Vacuum Association (*Nederlandse Vacuümvereniging,* NEVAC). Next year, NEVAC will celebrate its 60th anniversary. From the outset, the association has been dedicated to knowledge exchange in the fields of vacuum technology and vacuum-related disciplines. NEVAC organises symposia, excursions, award ceremonies and the annual NEVAC day, and publishes a magazine and textbooks. It also provides education on vacuum technology, training in the design and operation of vacuum systems, and application courses on deposition techniques, leak testing and residual gas analysis.

NEVAC's biggest challenge, according to Van der Molen, is to strengthen the vacuum community by connecting academics, engineers and companies – and to restore its pre-corona liveliness.



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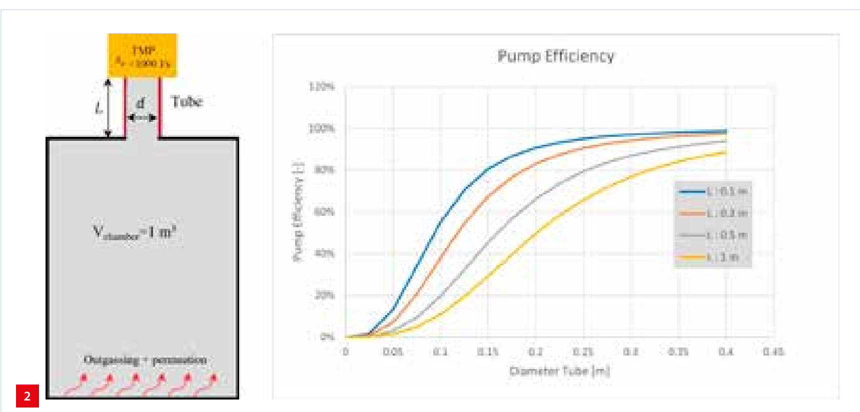
NEVAC organises, a.o., symposia, such as the online NEVAC Symposium 2021, hosted by the Amsterdam-based ARCNL (Advanced Research Center for Nanolithography). (Photo: Ivar Pel)



2

Simple case for calculating the pump efficiency (TMP is a turbomolecular pump with nominal pump speed of 1,000 ℓ/s).

Flow and thermal analysis

The technical presentation programme started with the analytical perspective. Johan Jacobs, owner of Simex-Technology, discussed several cases of vacuum-related flow and thermal analysis. These included outgassing and permeation budgeting, virtual leak and effective pump-speed calculations, PCVD (plasma-activated chemical vapour deposition) reaction gas distribution analysis, and heat transfer in vacuum.

For outgassing and permeation budgeting, Jacobs discussed the complete procedure, starting with the specification of pressure and timing requirements and the subsequent selection of a vacuum pump. After derivation of the outgassing and permeation specifications and collection of the data for the relevant materials as used in vacuum, the total outgassing can be calculated. Finally, if specifications are not met, pump speed and material selection can be adjusted.

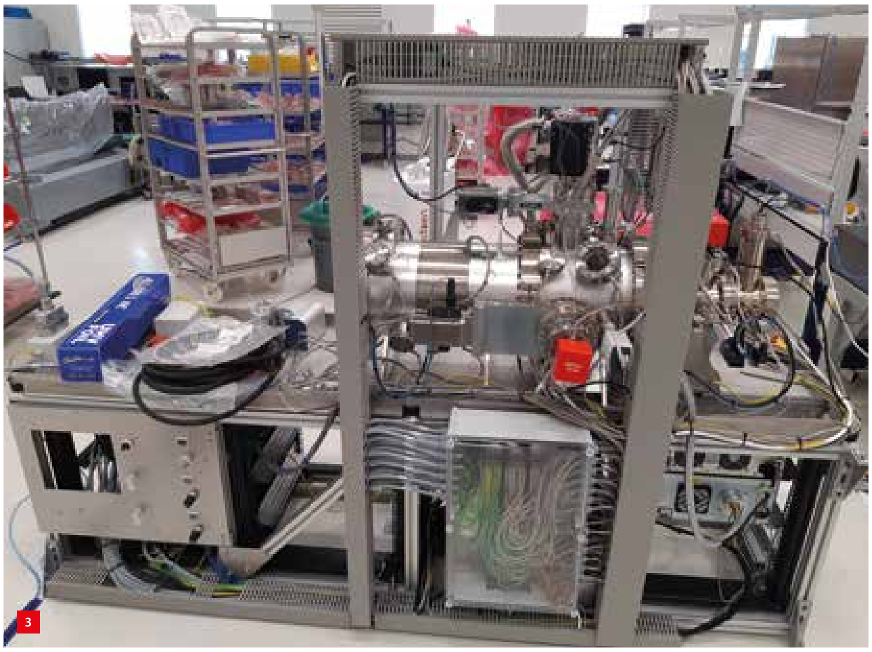
To conclude, Jacobs discussed one of the big challenges in high-precision vacuum applications, i.e. heat transfer. He showed an example in which below (vacuum) pressures of approx. 10^{-2} mbar radiation, as compared to conduction, was the dominant transfer mechanism. Consequently, in high vacuum, radiation is the only heat transfer mechanism, which makes it hard to remove all the heat from the system. Therefore, thermal design – to minimise heat generation and/or thermal effects – is crucial in vacuum system development.

UHV system design

Peter van der Heijden, expert in special processes at VDL ETG in Eindhoven (NL), then presented the short-time realisation of an ultrahigh-vacuum (UHV) system for e-beam system development. He focused on defining the main requirements and starting the design process. The requirements for the UHV system were based on the concept of a two-chamber system with vacuum pressure levels of $1 \cdot 10^{-8}$ mbar for the main chamber and ultimately $1 \cdot 10^{-10}$ mbar for the e-beam source chamber.

Basic calculations taking account of contamination processes such as outgassing, diffusion, permeation and leakage were used to determine the best pumping strategy using sorption pumps and a turbomolecular pump fitted with a pre-pump. To prevent outgassing due to extra components and to maintain cost-effectiveness, no turbomolecular pump was used on the source chamber; an additional advantage is that the sorption pump, in contrast with the turbomolecular pump, does not induce any vibrations. Components such as pumps and valves and their required treatments, including polishing and bake outs, were subsequently selected.

Based on this selection, the basic calculations were redone, yielding effective pumping speeds of 50-100 ℓ/s for the various pumps and a final vacuum level of $0.6 \cdot 10^{-10}$ mbar in the source chamber, well below the required value. The system design includes a by-pass between the two chambers to increase the pumping speed. Within 36 hours after venting to ambient pressure, the end pressure is reached, which again surpasses the requirement (48 hours).



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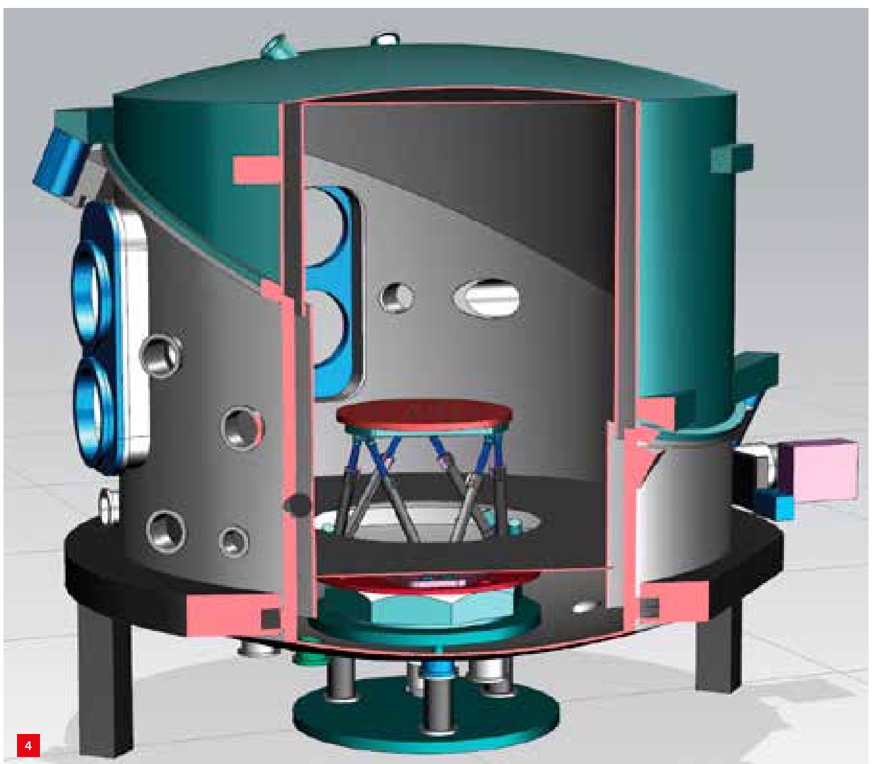
The design and construction of the UHV system was realised by VDL ETG within eight months of the project assignment.

Calibrating space instruments

Freek Molkenboer (TNO), senior systems engineer at TNO in the department of Nano-instrumentation, described vacuum as the 'big enabler' for big science, for example in nuclear fusion, elementary particle, gravitational wave and space research. The realisation of the CSI facility was commissioned for calibration of space instruments. CSI is a medium-sized thermal vacuum vessel fitted with an optical stimulation system and a high-accuracy in-vacuum motion system for manipulating the instrument to be calibrated so that its complete field of view can be covered.

The thermal vacuum chamber was designed as a vertical cylinder with a slanted door to facilitate instrument (un)loading. To achieve state-of-the-art cleanliness, semiconductor vacuum design principles were applied. Two separate thermal shrouds fed by two separate closed-loop gas-mixers were included to cover a temperature regime of –80 °C to +80 °C, with an additional bake-out system (> 100 °C) for the vessel itself.

The manipulation system for rotating the instrument around two axes was constructed – using low-expansion materials – as a hexapod on top of a rotation system, for increased mechanical stability over a large temperature range and an instrument pointing accuracy < 0.001°.



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Design of the CSI facility.

By the end of this year, the CSI facility at TNO should be ready for the calibration of space instruments.

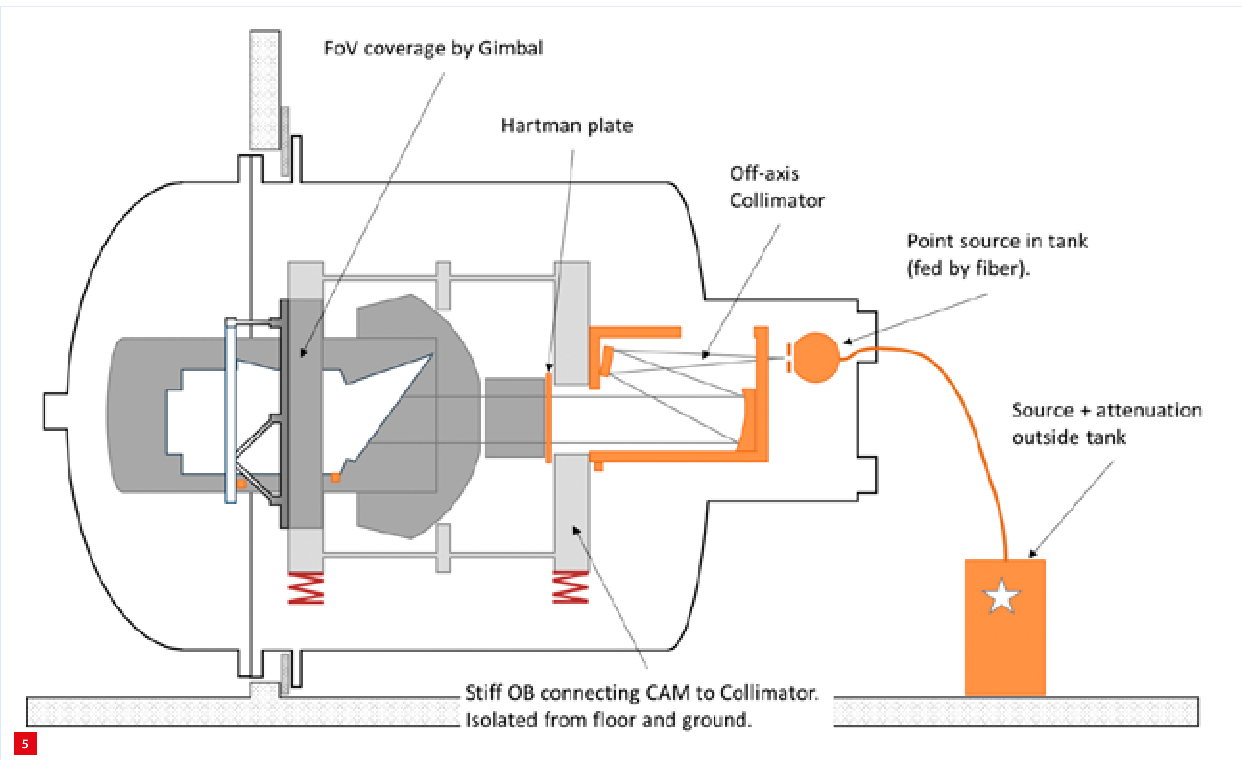
Star simulator

As the final contribution, Gabby Aitink-Kroes, senior opto-mechanical system engineer at SRON (Netherlands Institute for Space Research), discussed the engineering of space instruments for multi-wavelength astronomy. She referred to space as 'vacuum for free' at 10^{-18} mbar pressure. In particular, the thermal conditions are challenging, with extreme cold and large temperature variations due to changing (solar) irradiation conditions. Instruments have to be kept at a constant, extremely low temperature for noise suppression. This requires UHV design as well as cryogenic engineering of cryostats, based on the building of temperature layers to reduce radiative effects and the application of different cooling principles for different temperatures.

Aitink-Kroes then focused her presentation on the design of the PLATO star simulator. PLATO (PLAnetary Transits and Oscillations of stars) is one of the projects in which SRON participates. This ESA (European Space Agency) space mission aims to discover Earth-like exoplanets and determine their main properties (such as diameter, density and irradiance of the parent star). With cameras, exoplanets can be detected by looking for minute variations in the luminosity of a star as a result of a planet moving in front of the star and obscuring part of the star light. SRON will test the cameras that European partners are building for this mission and is developing test systems such as the PLATO star simulator to verify and guarantee the quality of the cameras.

In addition, Aitink-Kroes showed a few examples of kinematic guiding mechanisms (indent (set & forget) and slider designs) and flexure mechanisms (tip-tilt actuator, chopper, shutter) that are frequently applied in space instrumentation. She concluded with the transport requirements for space instruments, with the vibrations and shocks induced by the launch posing the ultimate test. This marked the landing of a successful DSPE Knowledge Day.

INFORMATION
WWW.NEVAC.NL
WWW.SIMEX-TECHNOLOGY.NL
WWW.SRON.NL
WWW.TNO.NL
WWW.VDLETG.COM



Design of SRON's PLATO Star simulator.

THE NEW NORMAL

Once again, in light of the global COVID-19 pandemic, the euspen International Conference & Exhibition, the annual high-profile event for the precision engineering community, was held virtually, on 7-10 June. Today's "new normal" was not only reflected by the virtual character of the event, but also by the topic of one of the keynotes: complex data as the new normal in precision engineering.

DISHI PHILLIPS

1

The original plan to hold this year's euspen conference in Copenhagen, DK, at the Technical University of Denmark (DTU), was a natural choice, because DTU is recognised internationally as a leading university in the technical and natural sciences. The photo shows the new home of the DTU Biosustain – Novo Nordisk Foundation Center for Biosustainability at the DTU Lyngby Campus. (Image: DTU)

Tutorials and workshops

The event, the 21st edition of the euspen Conference, started with two full-day interactive tutorials taking place on Monday: "Optical Metrology for Precision Engineers" delivered by Dr Peter de Groot from Zygo Corporation, US, and "Passive Damping in Mechatronics Systems by Means of Polymers" delivered by Dr Ir. Ing. Theo Ruijl and Ir. Ing. Pieter Wullms, from MI-Partners, NL.

In addition, the afternoon was filled with three workshops. The euspen-led workshop, "Machine Learning in Precision Engineering", was chaired by Prof. Richard Leach, University of Nottingham, UK. The industrially focused workshop covered the current state of the art in machine learning for precision engineering.

European research programmes

The other two workshops were related to European research programmes. "Metrology for Advanced Manufacturing" was chaired by Dr Harald Bosse, *Physikalisch-technische Bundesanstalt* PTB, DE, and Alexander Evans, *Bundesanstalt für Materialforschung und -prüfung* BAM, DE, who informed and engaged with the euspen community about the ongoing work on the AdvManuNet joint network project, which aims to establish a European Metrology Network for Advanced Manufacturing.

"High Precision Process Chains for the Mass Production of Functional Structured Surfaces – ProSurf" was chaired by Dr.-Ing. Oltmann Riemer and Dr.-Ing. Lars Schönemann, both from Leibniz-Institute for Materials Engineering IWT, DE. The project, funded under the European Union's Horizon 2020 research and innovation programme, aimed to transfer a selection of advanced methods for surface modification into industrial mass production lines that use replicative processes. The workshop was also used to showcase the performance of ProSurf's solutions and demonstration studies improving actual products of the industrial consortium members.

AUTHOR'S NOTE

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

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Keynotes

Prof. Anja Boisen, Danmarks Tekniske Universitet (DTU), DK

Microdevices for oral drug delivery

DTU's research centre of excellence IDUN (Intelligent Drug delivery and sensing Using microcontainers and Nanomechanics) combines research in nanosensors/centrifugal microfluidics and microfabricated devices for oral drug delivery. This allows the exploration of the synergy between sensor development and the search for new pharmaceutical delivery tools and materials. Examples of recent findings and results within microdevices for drug delivery were shown. The hypothesis is that oral drug delivery can be improved significantly by utilising micrometer-sized devices loaded with drugs and sealed by lids that open at specific locations in the body. The containers protect drugs during passage through the stomach and facilitate adhesion to the intestinal wall for controlled and unidirectional release. Recent findings and results within polymer fabrication and in-vitro/in-vivo characterisation were presented.

Peter Fuglsang, Siemens Gamesa, DK

Offshore blade development research needs

The wind energy industry has undergone a dramatic development during the latest two decades and is now a mainstream energy source and seen as one of the handles the world has to reduce carbon footprint while the need for energy capacity is rising. The cost pressure in the wind market has increased significantly due to the fierce competition among OEMs combined with auction-based tenders leading to fewer subsidies. This leads to a need for innovation in the entire value chain in order to reduce cost; at the same time, it also leads to OEM cash constraints and short-term and incremental thinking. With a focus on large blades for wind turbines, this presentation provided an understanding of the wind energy sector and market together with the major industry trends. The presentation demonstrated the value of setting a long-term agenda for innovation and development of new technologies. Also, it was discussed how this long-term agenda defines research topics, such as new composite materials, and industry-academia collaboration.

Prof. Bianca Maria Colosimo, Politecnico di Milano, IT

Complex data as the new normal in precision engineering: opportunities and challenges

Precision engineering is facing a new renaissance, due to the widespread adoption of emerging process technologies (e.g. additive manufacturing, micromanufacturing) combined with paradigm shifts in metrology (e.g. X-ray CT), sensing and computing (e.g. Industry 4.0 and big-data mining) A new generation of massive, highly unstructured, multi-sensor, spatially and temporally correlated data represent the "new normal", i.e. the basic ground to develop novel solutions for quality inspection, monitoring and control. Two main dimensions of data complexity were specifically discussed: i) data describing product quality, where freeform, topologically optimised shapes and lattice structures have to be modelled, monitored and inspected; ii) process data, available as multiple streams of signals, images and video images, that have to be modelled and monitored to prevent and possibly correct flaws. Starting from real industrial scenarios, opportunities and challenges of complex data mining were discussed to highlight directions for future research.

Dr Jonathan Pearce, National Physics Laboratory (NPL), UK

New perspectives on applied thermometry

Traceability of temperature measurements to the International Temperature Scale of 1990 (ITS-90) is a critical factor in establishing low measurement uncertainty and reproducible measurements. Unfortunately, in a large number of temperature measurement settings traceability is lost due to factors relating to the measurement situation, e.g. unknown sensor calibration drift, surface emissivity, reflected thermal radiation, and heat flow effects. Some developments at NPL to facilitate in-situ traceability were discussed, including novel low-drift and self-validating temperature sensors, traceable surface temperature measurement methodologies using thermographic phosphor coatings, an in-situ combustion reference standard (portable standard flame) of known temperature, traceable fibre-optic thermometry, a 3D thermal imaging capability, and a practical driftless 'primary' Johnson noise thermometer which measures temperature directly without recourse to any temperature scale. In addition, implementation of the developments in process environments was outlined. The unifying factor is that the measurements are aimed at being traceable to the ITS-90 with the linkage maintained through understanding and quantifying the uncertainty of measurement.

Prof. Dr.-Ing. Gisela Lanza, Karlsruhe Institute of Technology (KIT), DE

Sustainable production enabled by remanufacturing: Production under uncertain product specifications

The current social, economic and global political situation is characterised by great uncertainty. The periods of time in which humanity is undergoing profound changes are becoming increasingly short-cyclical. In view of the growing population worldwide and the increasing scarcity of essential raw materials, the course must be set today in order to look into a sustainable future. This is especially true for manufacturing companies, as there is no doubt that the traditional linear economic approach, "take – make – use – dispose", is no longer a recipe for success in the long run. Closed-loop models such as remanufacturing offer the opportunity to continue to operate economically but also ecologically. In remanufacturing, used products are recovered and dismantled, and selected components are returned to the production process. In particular, the decision as to whether a used product is suitable for a next lifecycle is nowadays mainly made by skilled personnel following an inspection, since the use of the products results in a high variance in the states of the declining old products. In addition to possibly missing product components, signs of aging and wear and tear such as corrosion or cracks must be detected and evaluated at the same time. This poses unprecedented challenges for automated quality assurance concepts, as they have to adapt to constantly changing conditions. At the same time, new methods, such as artificial intelligence, offer the opportunity to master these challenges.

More 'virtual' interaction

The conference format was modified this year to incorporate more 'virtual' interaction. All presentations were delivered live and the programme was designed to have keynote presentations throughout the week. The seven technical sessions were sprinkled with industry presentations and each time an interactive debate took place after the final oral presentation, thus allowing all presenters from that session an opportunity to answer the delegates directly.

Keynotes and sessions

The five renowned conference keynote presenters offered a broad perspective of precision engineering with their anticipatory titles answering the thirst of questions that kept coming from delegates; see the text box on the left.

The conference programme featured a total of seven sessions, each comprising four to six presentations:

1. Replication and Additive Manufacturing;
2. Advances in Precision Engineering and Nanotechnologies;
3. Non-Mechanical Manufacturing Processes;
4. Mechatronics, Control and Handling;
5. Metrology;
6. Mechanical Manufacturing Processes;
7. Measuring Instruments.

Commercial presentations

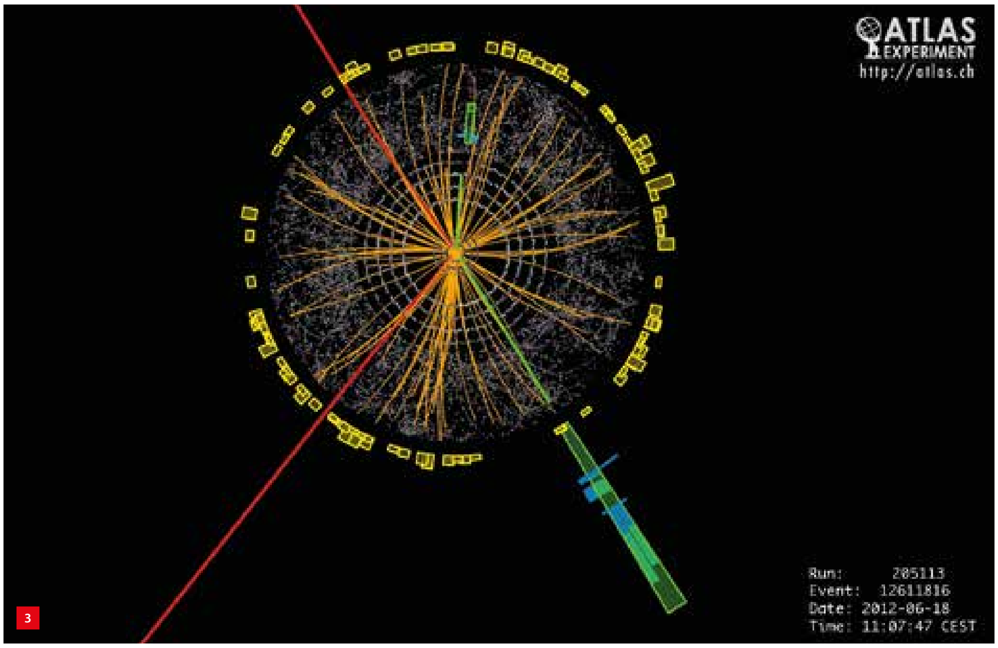
To support the exhibitors, they were offered a social platform for delivering pre-recorded soundbites as well as live, commercial presentations. Contributions were made by AMETEK Precitech, attocube, Fanuc, Hexagon, Huber, IBS Precision Engineering, Heidenhain, JPE, KERN Microtechnik, Mitaka Kohki, Moore Nanotech, Olympus, PI (Physik Instrumente), Professional Instruments, Queensgate, SmarAct, and Wittenstein.

Poster presentations

Taking on-board feedback from last year, break-out rooms were implemented for the extensive poster presentations. Each poster presenter was given time to present their posters live to the delegates inside the break-out rooms. The three poster parallel sessions enabled delegates to switch rooms and listen to their session of interest. The themes of the sessions matched those of the oral presentation sessions.

Talent programme

It was announced that euspen will continue its support for students from around the world and even in these extraordinary times, there was a challenge for the euspen Talent Programme. The challenge for 2021 was set by LEGO System to design methodologies for process performance characterisation while complying with product quality for



The ATLAS experiment at CERN, the intended host of euspen's 22th International Conference & Exhibition, from 30 May to 3 June 2022. (Image: CERN)

validation and verification of polymer powder bed fusion manufacturing. This virtual challenge addressed LEGO System's needs for innovation in its operations.

Students were placed into teams, aptly named Train, Duplo, Technich, Minifigure, Creator, Studios and Ninjago. Despite time-zone differences, language barriers and differing skill sets, they managed to produce a pre-recording of their final solution in a short video which was delivered at the virtual conference. The three winning teams were announced during the conference and will be potentially invited to attend LEGO System in Denmark to further develop their prototype into reality.

Scholarships

Finally, each year euspen hosts the Heidenhain Scholarships. The Heidenhain group of companies has been associated with the euspen annual event for over ten years, and has provided over 100 scholarships to date; it was brought into a philanthropic foundation over 40 years ago with a philosophy to invest in research, development, social and scientific projects.

Scholarships are available for students or researchers registered for Masters/Ph.D. or equivalent courses at a recognised international higher education institution. Whilst the scholars could not receive their recognition in person, they have still been awarded this prestigious accolade. In consideration of this, euspen will be inviting the winners of its 20th and 21st virtual conferences to the next real-life international conference.

The 2021 scholarship winners were Ángela Rodríguez Sánchez, University of Nottingham (UK); Maria Hübner, TU Ilmenau (DE) / Aalto University (FI); Weihai Huang, Keio University (JP); Laurent Spitaels, UMONS (BE); Zongchao Geng, University of Huddersfield (UK); Pengfei Fan, University of Strathclyde (UK); Bo Pan, Dalian University of Technology (CN); Martin Wittke, Technische Universität Ilmenau (DE); Monica Katherine Gonzalez, KTH Royal Institute of Technology (SE); and Joe Eastwood, University of Nottingham (UK).

2022

The past two years have forced us all to change, adapt, accommodate and accept. We have all found new skills and resolve to keep networking alive as much as we can. Looking forward, euspen is planning to do a full circle and return back to CERN in Geneva, CH, (Figure 3), where last year the 20th international conference had been planned, in the confidence that the 22nd edition, from 30 May to 3 June 2022, will be the start of new beginnings and stronger relationships, with real-life social activities and discussions.

IT ALL DEPENDS ON THE SURFACE

In almost all branches of industry, part-specific surface finishes have a major impact on product quality. Accordingly, rising demands are being placed on cleanliness and the absence of burrs, as well as on design and surface finish. Thanks to innovative and optimised solutions, these requirements can be met reliably, reproducibly and cost-effectively.

DORIS SCHULZ

Recurring themes can be seen in almost all sectors of industry: transformation processes, changes in manufacturing technologies, new and improved materials, the trend towards automated and digitised production processes, as well as stricter climate protection targets and regulatory requirements. All of these pose new and different challenges for companies. On the one hand, they necessitate the further development or adaptation of key expertise and processes, and on the other hand, technology-based diversification, for example into segments beyond the existing market. As varied as the requirements may be, production steps such as deburring, cleaning and surface finishing play a decisive role when it comes to quality.

Mobility

Electromobility is catching on fast, and car manufacturers and suppliers are expanding their capacities accordingly. This presents challenges both in the production of components for electric motors and for battery modules. For example, drive shafts, housing parts and gears are designed with complex geometries. In some cases, these components also have drilled holes with intersections.

1

Thanks to innovative developments in the world of deburring and surface finishing, for example in the field of vibratory finishing, new and changed requirements concerning precision and surface properties can be met reliably and cost-effectively. (Image: Rösler Oberflächentechnik)

At the same time, parts are often designed with the lowest possible material thicknesses in order to save mass and thus extend range.

This calls for optimally-adapted solutions for deburring and surface finishing in order to meet the high requirements for burr-free and precision surfaces as well as for throughput and cost-effectiveness. Depending on the component and task, manufacturers of deburring and high-precision surface finishing equipment offer both new and improved systems and processes. These include, for example, developments in the field of vibratory finishing (Figure 1) as well as laser and ECM technologies (Figure 2). Laser technology opens up new perspectives and fields of application in both deburring and surface finishing, e.g. microstructuring. Both laser and electrochemical metal machining (ECM) or precision electrochemical machining (PECM) also enable shapes such as bores to be created without burrs.

In combustion technology, although new developments for passenger cars are no longer on the list of priorities for vehicle manufacturers, work is still continuing to further improve existing units and engines. The aim is to reduce consumption and emissions and optimise performance at the same time. To achieve this, some of the tasks set include increasing fatigue strength by means of smooth edges, radii and transitions as well as by improving the surface finish of components of the same or smaller size and with more complex geometries. Likewise, components such as connecting rods must be lubricated more effectively

2

PECM is used, among other things, for manufacturing medical devices, in this case a stapler for closing wounds with staples. Workpieces are microstructured in a multiple tool with an imaging accuracy of < 20 μm and a surface quality of R_a < 0.1 μm. (Image: EMAG ECM)

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.

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by adding holes, the structure of injection valves must be optimised, and fuel combustion must be improved by modifying the design of the nozzle holes. Corresponding results can be achieved using solutions from deburring technology, precision and burr-free machining.

Medical engineering

In the medical market, surfaces move more into focus. One reason for this is the European Medical Device Regulation (MDR), which came into force this spring and is causing manufacturers to take a closer look at the surface quality of their medical products. Another reason is that medical devices are becoming ever-smarter and more complex.

In addition to cytotoxicity and bioburden, for the first time the new MDR for sterile products now also addresses residues from manufacturing processes, such as particles which can be released by the product. This also applies to the process of deburring. The aim is to prevent, for example, a grinding burr from a cannula or other instrument, or a manufacturing residue on a pedicle screw or implant from entering a patient's body and causing damage. For these tasks, new and optimised solutions such as ultrasonic deburring (Figure 3) make it possible to carry out deburring and cleaning operations efficiently, reliably and in a manner that can be validated in accordance with regulatory requirements.

Specifically engineered material and surface properties can help to improve the function of a product. These include functionalised surfaces that, for example, improve and accelerate the osseointegration of implants or prevent germ growth. One way of achieving this, e.g., is to use structures in the micro- and nanometer range, which are applied to the surface by laser structuring or ultra-precision machining.

Industrial sectors

However, it is not only in the automotive & supplier industry and medical device sector that applications

Ultrasonic deburring can also be used to reliably remove internal and hidden burrs. Parts are cleaned and deburred at the same time. (Image: Doris Schulz)

Automating deburring and surface finishing processes unlocks great potential in terms of improving quality, precision, reproducibility and cost-effectiveness – provided the automation concept is optimally designed and sustainable. (Image: Supfina)

and processes need to be reviewed and adapted. Demands on surface quality have also changed and increased in the machinery and equipment industry, in measurement, precision and sensor technology, in the tool and mould-making industry, in energy and environmental technology as well as regards manufacturing equipment for the semiconductor industry. Irrespective of whether the quality of subsequent processes such as coating, bonding, laser welding and assembly or flawless product function is to be ensured, today strict specifications governing the technical cleanliness of components are a matter of course in virtually all branches of industry.

To meet the strict specifications, reliable deburring is a must. Depending on the required cleanliness, even ultra-fine burrs in the submicrometer range must be removed. For this purpose, the industry offers, among other things, innovative system concepts that enable reliable deburring and cleaning in a single process. Another aspect that is gaining in importance in an increasing number of industries is functionalised surfaces. Whether it is a specific degree of roughness or a defined structure that is called for, an appropriate machining process using the most suitable technology is indispensable.

Automation

Automating deburring and surface-finishing processes is key in order to meet the high demands for precision, reproducibility, throughput and efficiency (Figure 4). Among the main aspects to be considered are the simplicity and sustainability of the automation concept. This includes, for example, the number of products for which it can be used, the capability to quickly integrate new products, and the degree of effort involved for in-house maintenance staff. Consequently, the automation concept is ideally based on specifications that take into account the company-specific workflow as well as the lifecycles of manufactured products.

DeburringEXPO 2021

Which processes can be implemented to meet the higher quality requirements for deburring and creating precision surfaces in a reliable and cost-effective way? Which new technologies are available for the production steps of deburring, cleaning and surface finishing? What needs to be considered when selecting the most suitable process? How can deburring and surface finishing processes be automated and connected? Answers will be provided at this year's leading trade fair for deburring technologies and precision surfaces, DeburringEXPO 2021, at the Trade Fair Center Karlsruhe in Germany, which will be running from 12 to 14 October.

The exhibition portfolio, which includes all deburring technologies such as processes for creating precision surfaces, is rounded off by three theme parks: "Automated Deburring with Industrial Robots", "AM Parts Finishing" and "Cleaning after Deburring". The integrated expert forum at DeburringEXPO ensures a valuable knowledge transfer.

WWW.DEBURRING-EXPO.DE

Exakt Fijnmechanika – where even precise is not accurate enough

Exakt Fijnmechanika is a specialised supplier of high-precision mechanical parts for medical, defence, aerospace and industrial purposes. Exakt manufactures precision-mechanical parts to demanding specifications. The 100% Dutch company, situated in the North of the Netherlands, produces medium-large to very large series with extremely high precision in a very precise and consistent manner. Products have dimensions ranging from 0.1 mm to 50 mm, with accuracies starting at 1 µm.

Exakt has Swiss-type CNC precision lathes in-house for turning extremely small parts with highest accuracy.

The Exakt machine park mainly consists of Swiss-type CNC precision lathes, which enable turning of extremely small parts with highest accuracy. All machines are multi-axis, up to eight axes, and equipped with driven tools for complex operations and complicated shapes. A precision wire-EDM machine is available for producing parts with a roughness R_a below 0.2 µm, using a wire diameter of 0.07 mm. Exakt has a separate finishing department in place, comprising drum machines for dry and wet polishing for very precise finishing, as well as set-ups for cleaning and packaging.

NIST-traceable measurement

In Exakt's ultramodern measuring room with a NIST-traceable measuring set-up from Hexagon, and multiple stereo microscopes, all products can be measured and checked optically, tactile and visually in such a way that errors can be excluded. By means of the ISO 9001:2015 certified quality management system and supported by statistical measurement data, dimensions as agreed with the customer are guaranteed.

Quality control

Exakt guarantees highest quality standards. With experienced staff coming from medical and defence industries, Exakt clearly understands the need for traceability and consistency. To meet product requirements, the quality department is adequately staffed and equipped for up to 100% inspection of produced parts. Customers' quality regulations are adopted in Exakt's daily process. To support industry's needs even more adequately, Exakt is in the process of certification according to AS9100D.

Transparent partnership

Exakt contributes all of its knowledge to improve production cost-effectiveness and pricing. Whether medical instruments, custom (threaded) fasteners or complex night-vision components made of standard stainless steel or titanium alloys are required, Exakt Fijnmechanika is the partner of choice when even precise is not accurate enough.

Exakt's quality department is adequately staffed and equipped for up to 100% inspection of produced parts.

INFORMATION
WWW.EXAKT.NL

UPCOMING **EVENTS**

Please check for any rescheduling, online reformatting or cancellation of events due to the coronavirus crisis.

Face-to-face & online meeting

14-15 September 2021, Gilze Rijen (NL)
DSPE Conference on Precision Mechatronics 2021
The fifth DSPE conference on precision mechatronics, organised by DSPE, will be a special edition, in view of the uncertain pandemic situation.
It will combine two elements:
(1) inspirational presentations by multiple invited international speakers from adjacent application areas like bio-inspired mechatronics, robot-assisted surgery, virtual reality, artificial intelligence and more;
(2) the opportunity of the community to meet/network and exchange ideas in a pleasant atmosphere including a BBQ.

WWW.DSPE-CONFERENCE.NL

15-16 September 2021, Den Bosch (NL)
Materials+Eurofinish+Surface
At this event, a combination of three trade fairs, product developers, product designers, engineers, R&D professionals, production staff, materials specialists and researchers can meet the entire materials value chain.
WWW.MATERIALS-EUROFINISH-SURFACE.COM

Virtual event

21-23 September 2021
SIG Meeting Advancing Precision in Additive Manufacturing
Special Interest Group (SIG) Meeting hosted by euspen and ASPE, focusing on, a.o., dimensional accuracy and surface finish from AM, design for precision, standardisation, metrology, and integration of AM into an overall holistic manufacturing process.
WWW.EUSPEN.EU

22-23 September 2021, Aachen (DE)
30th Aachen Machine Tool Colloquium
The general topic of AWK'21 (Aachener Werkzeugmaschinen-Kolloquium) is "Turning Data into Sustainability". The focus is on how sustainable development in production can be initiated in order to successfully deal with drastic crises and to sharpen the entrepreneurial view for the future.

WWW.AWK-AACHEN.COM

27-29 September 2021, Eindhoven (NL)
Opto-Mechanical System Design course
The course focuses on the mechanical and mechatronic design of optical systems, and is intended for mechanical, mechatronic and optical engineers involved in opto-mechanical system design. It will also be a very valuable course for any engineer interested in opto-mechanical design approaches and solutions.
WWW.DSPE.NL/EDUCATION

30 September 2021, Enschede (NL)
TValley Tech Conference
Event of the TValley robotics and mechatronics innovation cluster, featuring knowledge sessions on advanced perception & AI, systems engineering, human machine interaction, autonomous systems, and automation & big data.
WWW.TVALLEY.NL

12-14 October 2021, Karlsruhe (DE)
DeburringEXPO
Fourth edition of trade fair for deburring technology and precision surface finishing. Three theme parks will cover "Cleaning After Deburring", "Automated Deburring with Industrial Robots" and "AM Parts Finishing", respectively. See the preview on page 39 ff.
WWW.DEBURRING-EXPO.COM

10-11 November 2021, Den Bosch (NL)
Precision Fair 2021
The Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum. The theme of this 20th anniversary edition will be: Precision technology, the next 20 years. This year, Belgium will be the partner country.
See the fair update on page 48.
WWW.PRECISIEBEURS.NL

15 November 2021, Düsseldorf (DE)
Gas Bearing Workshop 2021
Fourth edition of the initiative of VDE/VDI GMM and DSPE, focused on gas-bearing components and technology for advanced precision instruments and machines.
See the preview on page 47.
WWW.GAS-BEARING-WORKSHOP.COM

Virtual event

17-18 November 2021, Raaba (AT)
SIG Meeting Micro/Nano Manufacturing
SIG Meeting hosted by euspen, focusing on, a.o., micro- & nanomanufacturing technologies and applications, machining technologies for moulds and microparts, metrology & quality control for microparts, microreplication and additive techniques, and assembly & handling.
WWW.EUSPEN.EU

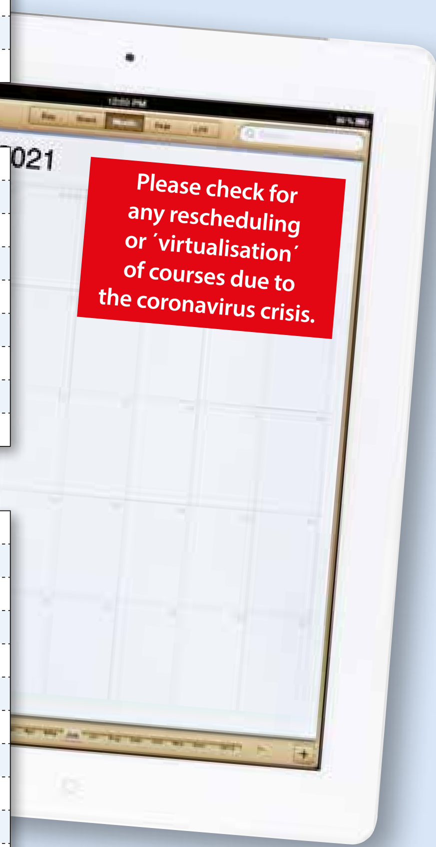
24 November 2021, Utrecht (NL)
Dutch Industrial Suppliers & Customer Awards 2021
Event organised by Link Magazine, with awards for best knowledge supplier and best parts & process supplier, and the Best Customer Award.
WWW.LINKMAGAZINE.NL

1-2 December 2021, Den Bosch (NL)
Food Technology 2021
Knowledge and network event about high-tech innovations in the food industry.
WWW.FOOD-TECHNOLOGY.NL

2-3 December 2021, Utrecht (NL)
International MicroNanoConference 2021
Conference themes include nanotechnology for Health & Life Sciences and Agri & Food, and miniturization, manufacturing and scale-up in nanotechnology.
WWW.MICRONANOCONFERENCE.ORG

8-9 december 2021, Eindhoven (NL)
RapidPro 2021
The annual event that showcases solutions for prototyping, product development, customisation and rapid, low-volume & on-demand production.
WWW.RAPIDPRO.NL

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	11 October 2021
Mechatronics System Design - part 2 (MA)	5	HTI	8 November 2021
Fundamentals of Metrology	4	NPL	to be planned
Design Principles	3	MC	22 September 2021
System Architecting (S&SA)	5	HTI	11 October 2021
Design Principles for Precision Engineering (MA)	5	HTI	15 November 2021
Motion Control Tuning (MA)	5	HTI	13 September 2021
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	2 November 2021
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned
Actuation and Power Electronics (MA)	3	HTI	to be planned
Thermal Effects in Mechatronic Systems (MA)	3	HTI	14 December 2021
Dynamics and Modelling (MA)	3	HTI	30 November 2021
Manufacturability	5	LiS	31 January 2022
Green Belt Design for Six Sigma	4	HI	20 September 2021
RF1 Life Data Analysis and Reliability Testing	3	HI	20 September 2021
Ultra-Precision Manufacturing and Metrology	5	CRANF	to be planned
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	1 November 2021
Advanced Optics	6.5	MC	24 February 2022
Machine Vision for Mechatronic Systems (MA)	2	HTI	upon request
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned
Modern Optics for Optical Designers (T2Prof) - part 1	7.5	HTI	to be planned (Q1 2022)
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	to be planned (Q1 2022)
Tribology	4	MC	26 October 2021
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	6 December 2021
Experimental Techniques in Mechatronics (MA)	3	HTI	4 October 2021
Advanced Motion Control (MA)	5	HTI	11 October 2021
Advanced Feedforward & Learning Control (MA)	3	HTI	to be planned (Q1/Q2 2022)
Advanced Mechatronic System Design (MA)	6	HTI	to be planned
Passive Damping for High Tech Systems (MA)	3	HTI	23 November 2021
Finite Element Method	2	MC	4 November 2021
Design for Manufacturing (Schout DfM)	3	HTI	30 September 2021



ECP² program powered by euspen

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

WWW.ECP2.EU

Course providers

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

Content partners

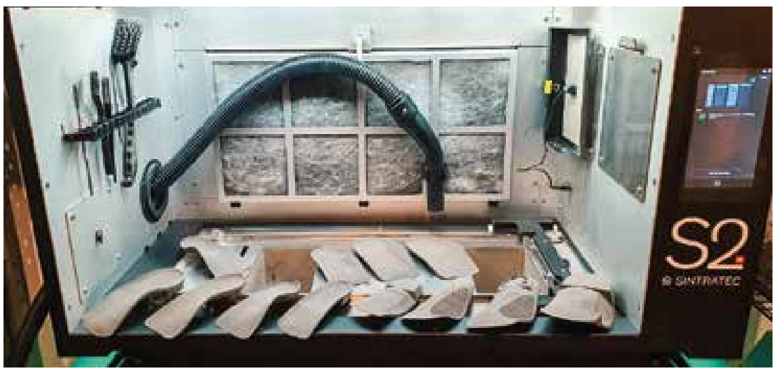
- DSPE
  WWW.DSPE.NL
- Mechatronics Academy (MA)
  WWW.MECHATRONICS-ACADEMY.NL
- Technical Training for Prof. (T2Prof)
  WWW.T2PROF.NL
- Schout DfM
  WWW.SCHOUT.EU
- Systems & Software Academy (S&SA)

Faster treatment with 3D-printed orthoses

Australian company Advanced Family & Sports Podiatry (AFSP) has explored the potential of 3D-printing for manufacturing customised foot orthoses. To respond more quickly to their patients' needs, in-house 3D printing seemed like the obvious choice. Thus, in 2020 the team at AFSP started to experiment with fused deposition modelling (FDM) and stereolithography, but soon reached the limitations of these technologies.

Especially in a medical field like podiatry, 3D-printed objects have to fulfil special requirements. They need to have a high degree of dimensional accuracy and can involve complex shapes to contour and help the foot and ankle function. They also need to have resistance to deformation and heat, and some flexibility without shattering, and have a high heat deflection temperature to preserve the orthotics shape under stress. Furthermore, a low moisture absorption is also key due to the environment such orthoses are commonly used in. The selective laser sintering (SLS) process was selected as one of the few additive technologies that could meet these demands.

This spring, AFSP acquired a Sintratec S2 system and started producing customised and semi-custom orthoses from durable Sintratec PA12 nylon material. Soon after, the full potential of the SLS technology became evident, in terms of the speed of production, accuracy of the build, unrestricted design freedom to test and push new shapes for the benefit of clients.



The Sintratec S2 system is ideally suited for AFSP's short-run productions.

With SLS, the AFSP podiatrists can manufacture individualised orthoses within 24 hours.

Accelerating medical device R&D with micro 3D printing

AntiShock, Haifa, Israel, is an innovative medical device start-up company that develops a disposable, non-invasive, continuous monitoring system that measures patients' systemic fluid responsiveness (preventing intravenous fluid overload). Fluid overload is a common condition among intensive care unit patients that not only has negative financial and clinical implications, but more importantly can cause organ failure, and – in severe cases – death.

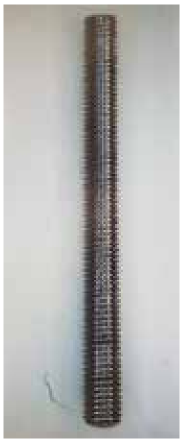
To solve this challenge, AntiShock is developing a breakthrough electro-optical sensing medical device based on a tiny electro-optical sensor. This sensing device is built out of several small mechanical moving components that have to be strong and accurate. Therefore, to validate its product and produce a working prototype device, AntiShock had to locate and use advanced and accurate manufacturing technologies.

The two leading manufacturing technologies that were chosen were CNC and the stereolithography (SLA) 3D-printing process that gave AntiShock the ability to create the first product mock-up. However, when moving to a more advanced stage in their R&D, the company confronted a very challenging task – it needed to produce a small-dimension highly detailed component (about 1 mm in diameter). SLA 3D printing could not provide the required levels of detail and accuracy, and while CNC could, it was extremely expensive.
While searching for a solution to their problem, AntiShock came across Nanofabrica, the developer and manufacturer of an innovative and disruptive micro 3D-printing system. Nanofabrica's process uses an ultrahigh-resolution digital light processor (DLP) engine, achieving repeatable micron-levels of resolution by combining the DLP engine with adaptive optics that electronically controls various critical optical working point parameters such as focus, tilt and astigmatism.

The challenge went beyond printing the component, there was also a need to print a small-size thread (with a non-standard pitch) and fit a small screw on top of it. The components had to fit each other perfectly, and the 3D-printed component had to be strong enough to sustain mechanical loads. After reviewing the part's size, geometry, thickness, and estimating the mechanical loads it had to withstand, Nanofabrica accepted the challenge and decided to print the part. Within a few days, the part was delivered and it passed AntiShock's first qualification step. After carefully assembling the parts, it was found to be a perfect fit.

Note 1: This report was provided by 3D Evaluate, the online platform that connects buyers of industrial 3D-printing systems and OEMs/resellers of professional solutions.

Note 2: Last month, Nano Dimension, a US-based, industry-leading additively manufactured electronics and printed electronics manufacturing system provider announced that its acquisition Nanofabrica has been renamed to Nano Dimension's Fabrica Group.




On the left, the 3D-printed threaded screw inside AntiShock's medical device. On the right, a perfect fit between the parts. (Images: AntiShock)

WWW.ANTISHOCK.CO
WWW.NANO-FABRICA.COM
WWW.3DEVALUATE.COM
WWW.NANO-DI.COM

ITEC becomes independent semiconductor equipment manufacturer

This summer, semiconductor equipment manufacturer ITEC announced its launch as a separate independent entity. This move allows ITEC, while remaining part of the Nexperia group, to address the third-party market in time to serve the current semiconductor boom. ITEC has always been at the forefront of semiconductor production, according to general manager Marcel Vugts. "With an installed base of more than 2,500 of the industry's most advanced tools, ITEC is committed to embed the latest technologies and process expertise into tailored solutions that redefine manufacturing. We enable our customers to excel in quality, productivity, and sustainability with the lowest total cost of ownership."

ITEC was formed in 1991 as a division of Philips (subsequently NXP and Nexperia) to provide semiconductor, RFID and miniLED manufacturing equipment and systems. In 2021, ITEC became an independent company within the Nexperia group of companies. ITEC provides high-productivity assembly, test, inspection and smart manufacturing platforms, targeting mass volume manufacturing from small signal to power MOS devices. ITEC is headquartered in Nijmegen (NL) and has a large supply chain and customer support office in Hongkong.

WWW.NEXPERIA.COM

Motion control for digital pathology

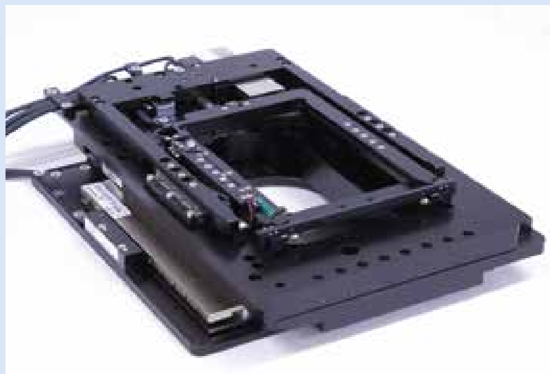
Digital pathology – the acquisition, management, sharing and interpretation of pathology information, including slides and data, in a digital environment – is increasingly used by biopharmaceutical companies and clinical research organisations to help to streamline drug development processes in discovery, pre-clinical, and clinical trials. It is also used for quantitative analysis of emerging companion diagnostics and novel theranostics (a combination of therapeutics and diagnostics).

This opportunity has become especially relevant with the use of assays that are difficult to discern with the human eye, such as markers that exhibit diffuse staining characteristics across multiple cellular compartments of which, for example, only one may be clinically relevant.

The increasing complexity of such assays is driving the development of digital pathology solutions with advanced high-throughput image capture (brightfield, fluorescent or multispectral) coupled with pattern recognition to morphologically identify relevant tissue types and individual cellular compartments followed by the ability to quantify intensity of staining. Digital pathology requires top-end nanometer-level precise motion control solutions to facilitate high-speed and high-quality scanning/imaging while maintaining a small footprint so as not to take up too much space in a lab/clinical environment.

In the area of digital pathology, the xyz motion control stage moves the slides that are to be scanned underneath a fixed microscope or camera that captures images of the slides. The key is image capture at a high rate of speed with absolute focus on precision, which requires that the chosen motion control solution must combine smoothness (meaning highest possible image resolution), flatness (controlling the z-axis, meaning maintenance of focus), and straightness (reducing overlap between scanning 'passes' and increasing throughput).

US-based ALIO Industries claims to be the only company that is in a position to fulfil all criteria, specialising in motion control solutions that provide repeatable nanometer-level accuracy stages perfect for digital pathology applications, where the requirement for image stitching of the scanned data is vital (as is the case in top-end metrology systems).



A custom-built stage from ALIO Industries used in a digital pathology application. The stage moves in X-, Y- and Z-direction. The top open plate can move out and pick up samples, then move in and line up for processing.

WWW.ALIOINDUSTRIES.COM

4th Gas Bearing Workshop welcomes Switzerland

The Gas Bearing Workshop is aimed at creating a (European) platform for the gas-bearing community, comprising experts, scientists, research engineers, users and manufacturers/vendors in this field. The fourth edition will be held on 15 November 2021 in Düsseldorf, Germany. It is organised by the VDE/VDI-Society Microelectronics Microsystems and Precision Engineering (GMM) from Germany and DSPE from the Netherlands. Partner in support of the workshop is the *Bond van Materialenkennis* (a Dutch network of experts in the area of material technology).

Experts in gas bearings will present new applications and leading-edge R&D. As usual, the programme reflects the wide application field of gas bearings, including precision air-bearing spindles for applications in ultra-precision manufacturing, and small, high-speed spindles that are used in turbomachinery. All bearing technologies will be present, ranging from aerostatic to aerodynamic, and from rigid geometries via tilting pads to foil-bearing designs.

For the first time, there will be contributions from Switzerland, adding one more country to the GBW community, which already includes the Netherlands, Belgium, Germany, Italy, France and the UK. One such contribution is the keynote, by Jürg Schiffmann of EPFL, Lausanne, on recent advances in gas-bearing-supported small-scale turbomachinery. Another Swiss contribution will be delivered by Christof Zwyssig of Celeroton, Volketswil, who will discuss design challenges in high-speed turbo compressors with herringbone gas bearings. The programme includes a table-top exhibition and poster presentations. Once again, the venue is Hotel Courtyard in Düsseldorf Seestern.

WWW.GAS-BEARING-WORKSHOP.COM

Alive and kicking – Precision Fair is celebrating its 20th anniversary

The Precision Fair, the Benelux premier trade fair and conference on precision engineering, is back on the physical track. After the 2020 edition had to be cancelled because of the Covid-19 pandemic and was replaced by a virtual event, this year the fair will in all probability be held as a physical event, at the Brabanthallen in 's-Hertogenbosch (NL).

At least, that is the status as of August, when fair organiser Mikrocentrum stated: "The Precision Fair has been the most important annual meeting point for precision technology professionals for the last 20 years. There is considerable need to bring the network back together by the end of 2021 and to share the latest developments in precision technology with one another. With the place of trade fairs on the Dutch government's roadmap and the advent of vaccines, the perspective for the end of 2021 is optimistic. The organisation has started and over 240 exhibitors have already registered. Naturally, the safety of all persons involved in the Precision Fair always comes first."

The theme of the Precision Fair 20th anniversary edition will be: "Precision technology, the next 20 years". After the successful introduction of an annually changing partner country (then Switzerland) in 2019, the Precision Fair focuses on Belgium as partner country in the upcoming edition. The programme features over 50 conference lectures, including the Big Science track, an international meet & match, a Young Talent programme with pitches and poster presentations, and ceremonies for the Wim van der Hoek Award and the Ir. A. Davidson Award, under the auspices of DSPE.

Read also the Editorial on page 4 by the advisor and former managing director of Mikrocentrum, Geert Hellings, on the evolution towards the International Precision Fair 2.0.

20th EDITION

Precision fair 2021

WWW.PRECISIEBEURS.NL

Precision wire-EDM machine for large workpieces

Precision components are getting bigger. Engineers also want higher accuracies and ultralow surface roughnesses in large workpieces. Although the accuracies of other machining technologies have improved, wire-EDM remains the best solution for the highest accuracy or razor-sharp contours. That is why Mitsubishi Electric has launched the MV4800R-CONNECT wire-EDM machine with a large cutting area for workpieces up to 1,250 mm. Compared to the MV2400R, the new machine has a greater range in the X- and Y-axis.

The self-developed Tubular direct drive has remained for the purpose of high accuracy. Regular linear drives exhibit an effect of reversing the magnetic poles, which can lead to a vibration that is reflected in the workpiece surface and accuracy. Mitsubishi Electric therefore applies the Tubular direct-drive concept, which works completely frictionless. To realise this, the machine builder uses non-ferrous disc magnets with a tube around them, over which the motor moves. Similar drives are found in the medical industry; they are used, for example, in MRI scanners. Mitsubishi Electric is the only manufacturer in the world to use this drive technology in wire-EDM machines; it guarantees a positioning accuracy of 2 µm over the entire length for twelve years. Surface roughness can be as low as 0.12 µm.
All Mitsubishi wire-EDM machines have the crash protection system as standard. If the machine detects the slightest resistance during a movement, the MV4800R-CONNECT stops with a retraction motion in the opposite direction to prevent damage. In the unlikely event of wire breakage, the machine can automatically feed it back into the spark gap on site without first having to return to the starting position. This saves a considerable amount of time. The wire-EDM machine has the ability to stretch the wire before it is fed in. The thinnest wire that is used to cut has a diameter of 0.15 mm.

In the Netherlands, Mitsubishi Electric is represented by Dymato.

Mitsubishi Electric's new MV4800R-CONNECT wire-EDM machine with extended X- and Y-range. The inset shows a processing example.

WWW.MITSUBISHIELECTRIC.COM
WWW.DYMATO.NL

Intelligent measuring system for accurate laser machining

For industrial production processes with extremely high accuracy requirements, labour costs for quality control are generally high too. If it is possible to reduce measuring procedures, defect parts and machine operating times for readjustment, significant cost savings can be made. This was the objective of a collaboration between Scanlab and stoba Customized Machinery: to ensure a stable laser machining process for microdrilling, along with an automated final product inspection, which also automatically initiates adjustment of the process parameters if necessary.

Scanlab is supplying the core component for a new machine concept of stoba Customized Machinery for laser drilling in the micrometer range. The processing machine integrates the five-axis precSYS microprocessing system with a femtosecond laser and optical measurement for automatic correction of drilling results. As such, significant increases in productivity are attainable with 24/7 industrial use of the machine.

In stoba's new FocusONE laser machine, Scanlab's micro-drilling head is connected to an optical measuring system via EtherCAT. The stoba measuring system can inspect drill holes starting from 25 µm in diameter. The integrated software for machine control analyses the measuring results and automatically adapts the process parameters as required. If, for example, the drilling result shows a trend which indicates a reduction in the diameter of a few µm, the system automatically corrects the drilling diameter based on an individually set threshold. For reliable batch tracing, the entire production process is, of course, comprehensively monitored and recorded.

Precision microdrilling of an injection nozzle (with femtosecond laser and 5-axis scan system). (Image: stoba)

WWW.SCANLAB.DE
WWW.STOBA.ONE

Two rotary encoders in one device

The new KCI 120 Dplus dual encoder from Heidenhain delivers motor feedback and position measurement in just one rotary encoder, with a positioning accuracy of down to ±40". By measuring the position downstream from the transmission gear system, the KCI 120 Dplus compensates for inaccuracies inherent in highly mobile and dynamic robots. This is necessary because, in order to achieve the desired mobility, articulated robots, for example, operate with serial kinematics and up to six axes. Each axis influences the accuracy, because it is driven by a servomotor via a gear system that exhibits zero-position error, reversal error, and joint elasticity. In addition, forces and dynamic effects of the machining process impair the positioning accuracy.

In order to perform its dual functions, the KCI 120 Dplus encoder has one central scanning unit and two separate circular scales. It is thus very compact and easy to integrate. The purely serial EnDat 2.2 interface with functional safety permits its use in safety-related applications such as human-robot collaboration.

WWW.HEIDENHAIN.COM

Parallel vs. stacked serial kinematics

When faced with a multi-axis motion application, many users stack motion stages, and in fact that is a fine approach for assemblies of just a few axes. But as applications become more complex, so do the equivalent stacks-of-stages, and very real and practical considerations begin to come into play. PI presents an overview.

Stiffness

Some stage manufacturers publish stiffness specifications in terms of axial deviation per unit force, but this is of little utility in estimating the dynamic performance of a stage... or a stack. A more pertinent metric is the resonant frequency, as it integrates both the effective coefficient of stiffness of a mechanism and the summed mass of its construction. In PI's experience, most high-quality conventional linear stages will exhibit resonant frequencies in the order of 75-120 Hz, unloaded. Upon stacking the resulting structure can have significantly limited responsiveness and long settling times.

Inconsistent dynamics

The bottom stage in a stack carries the mass of the entire stack, and so on up to the top stage, which carries only the application load. So tuning is a laborious, axis-by-axis process, with different settings for each axis... and consequently different responsiveness.

Inflexible rotation-centrepoint placement

Stacked stages place the centre of their tip/tilt and rotation motions at the geometric centres of each rotation-stage and goniometer bearing. These can sometimes be arranged to coincide at a desired point in space (for example, at the focal point of a lens) via custom adaptor plates and fixtures, but this takes time and effort, and is inflexible should application needs change. And significant changes can alter the dynamics of the stack, necessitating a re-tuning of each axis.

Cabling

Managing cables deserves more attention than it often gets. To begin, cables can be a conduit for vibration that can impact an entire application set-up in unobvious ways. As a stage moves, any cable being dragged along can contribute to parasitic motions and other errors. Generally, cabling problems scale with the number of axes in a user-stacked system (manufactured stacks sometimes benefit from integrated cable management).

Central aperture

Many applications, especially in optics, benefit from transmissive construction of the motion stack. This is difficult or impossible to achieve with a stacked structure of many axes.

Size, weight and fragility

Stacks can be substantial in height and mass. And since the bottom stages bear the burden of the entire tall stack, their bearings are vulnerable to brinelling and other damage from inadvertent forces. This often necessitates disassembly for shipping, adding cost and hassle and introducing variability when reassembled.

Orthogonality and parasitic errors

Stacked axes interact in complicated ways; for example, run-out in the X-axis is seen as unwanted motion in the Y- and Z-axes; angular deviation of an axis similarly imparts motion in the travel directions of the other axes, with magnitude proportional to the distance to the moving axis. In addition, in stacks this multiplicative lever arm can be large.

Attack the stack

All these issues can be avoided by utilising principles of parallel kinematics, according to PI: "Attack the stack." Instead of a tall stack of all the necessary axes with the workpiece perched on top, such systems support a single workpiece in parallel by a tripod or hexapod structure, forming a much stiffer yet lighter-weight structure than is possible by stacking. The best examples of the breed utilise non- or minimally-moving internal cables with conveniently integrated cabling to the controller. User tuning requirements can be eliminated while providing precision and accuracy that can surpass the performance of some of the best available single-axis stages.

In prior years, the main obstacle to choosing this class of mechanism was the challenge of controlling the workpiece in a user-friendly way, using familiar Cartesian coordinates (X, Y, Z, θX, θY, θZ). This changed with the introduction of PI's first hexapod two decades ago. That instrument utilised a fully-integrated industrial PC-based digital controller running firmware that transparently managed the coordinate transformation process, providing flexible control in all six degrees of freedom (DoFs) with a programmable rotational centrepoint, settable by a single software command.

PI offers two basic architectures for six-DoF mechanisms: six-legged hexapods, and three-legged planar parallel manipulators. The hexapods utilise a variety of motion technologies for the actuator legs, ranging from brushed or brushless DC servo-motors to piezo actuators. Both fixed- and extendable-strut designs are utilised depending on application needs. The planar parallel manipulators utilise three fixed-length legs in a tripod configuration, driven by three XY-actuation modules, which provide extended transverse travels for the assembly. Motion technologies can include piezomotors, rotary and linear DC servomotors, and stepper motors. In conclusion, there is nothing wrong with serial kinematics. They work well for many applications and PI offers a large variety of standard and custom designs with stepper motors, piezo motors, and linear motors / air bearings. However, when 4+ DoFs are required, the superior performance of a hexapod or hybrid tripod warrants a close comparison.

Parallel (left and middle) vs. stacked serial kinematics.

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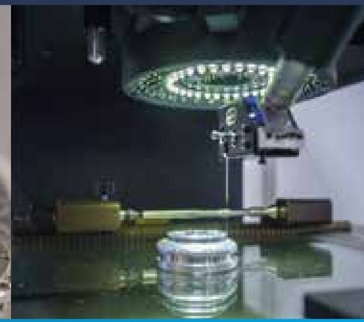

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