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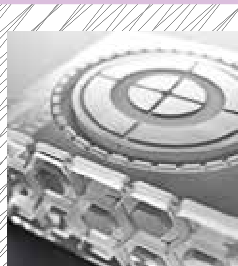
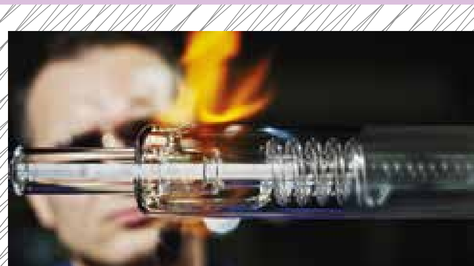
- PRECISION IN **GLASS AND CERAMICS**
- **MAGNETIC** VIBRATION ISOLATION
- DEMOWEEK 2017: **THAT'S HOW YOU MAKE IT**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The main cover photo (featuring the Smart Robotics founders, Mark Menting (left) and Heico Sandee) is courtesy of Bart van Overbeeke. Read the article on page 18 ff.

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FEATURES

DUTCH ROBOTICS

Robotics is hot... again. Over the past years, it has been hot, and then not. A lot has happened since a first series of Unimate robots were deployed at a General Motors factory in 1961. Even before, robots were described and created, and in 1941 Isaac Asimov published his three laws to ensure autonomous robots would not harm human beings. We have seen robots massively deployed in manufacturing, for increasingly more advanced tasks. Recently, the aspect of autonomy has been given more attention, leading to more advanced robots on the one hand, and to societal discussions on the aspect of robots taking over our jobs on the other. In addition to supplementing our human abilities in physical labour and dexterity, now also our cognitive and mental skills are at risk of becoming supplemented by autonomous robotic systems.

Most of the recent hot news on robotics does not come from the Netherlands; although we do have good examples of robotics technology, we're not a leader in the field at the moment. That being said, we do have a lot of ingredients and a historical basis to play a significant role in robotics.

One of these ingredients is the long standing tradition in advanced technology. A variety of Dutch companies like DAF, Philips, Stork and Océ in the past century have laid a foundation of advanced technologies for products and production; technologies that are still relevant and world leading. At the same time, a basis was created at the universities (of technology) to support the industrial activities with more advanced technologies.

Automation has been a vital part of Dutch industrial activities, and in the case of precision engineering it has been an inspiration for research as well. Professor Wim van der Hoek has based his expertise and research in precision engineering on industrial automation within Philips. Dutch precision engineering has not evolved out of watch making or optics, but rather out of relentless industrial automation: increasingly accurate and faster machines, to economically manufacture more and more advanced products – the pinnacle of this development being ASML.

Over the years, companies like ASML, together with the technology institutes and their suppliers, have developed a system approach to master the design of the very complex (automation) equipment. It is a rare combination of a collection of technical skill sets, a model-based engineering approach rooted in feedback control systems (also known as mechatronics) and a mental and interpersonal attitude to challenge and aim for understanding.

The combination of automation equipment design, precision engineering and a unique system approach gives us a strong position, even internationally. We understand the application of advanced robotics in the (further) automation of manufacturing processes, we have the precision engineering capabilities required for highly advanced robotic systems and, last but not least, we have our unique approach to system design, which suits well the field of advanced robotics. However, in order to also develop intelligent and autonomous robotics, we have to further integrate disciplines such as machine learning and artificial intelligence into our system design capabilities. This integration will only happen properly if it is driven by (local) OEMs which aim for intelligent robotic products.

So, it is time to seriously start working on our next pinnacle in autonomous robotic technologies.

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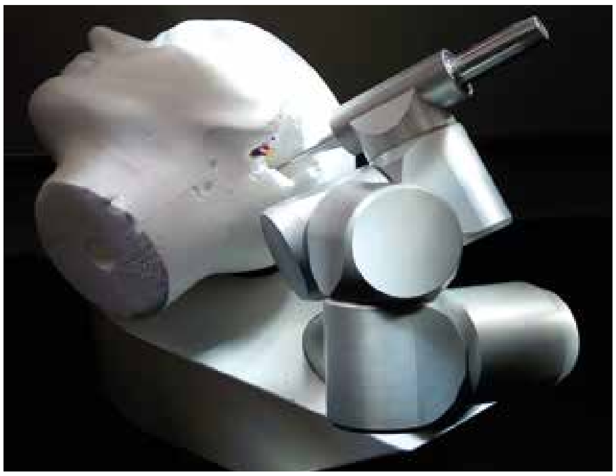
ADDING ROBOTICS SKILLS FOR REMOVING BONE

A new surgical robot, aptly named RoBoSculpt (Robotic Bone Sculpturer), which in fact is an advanced seven-axis milling robotic arm, can assist surgeons during complex bone removal procedures to potentially help more patients with better outcomes. The robot is being developed for compactness, precision and stability under load. It has a modular serial kinematic design and can use images to work autonomously. Currently, the first prototype is being built and first pre-clinical tests are scheduled in the Radboudumc in Nijmegen, the Netherlands, this year.

JORDAN BOS



We are all getting older and excessively loud sounds in daily life cause noise trauma in an increasing number of individuals. It is therefore not surprising to learn that the incidence of deafness is rising. The WHO estimates that 360 million men and women, including 32 million children, suffer from a disabling hearing loss [1]. The main reason is the loss of hearing functionality of the inner ear, the 'cochlea'.

The estimate is that only one in ten persons with severe to profound hearing loss can currently be helped with surgery [1]. One of the issues which might be solved using RoBoSculpt, is the limited number of surgical experts who can perform the complex hearing restoration procedures. RoBoSculpt can also aid in locating benign and malignant tumours in the ear and head region more effectively, as this usually involves extensive and time-consuming surgery.

The new RoBoSculpt surgical robot, which is patented and currently being developed at the Eindhoven University of Technology (TU/e), can aid surgeons to reduce risks, reduce invasiveness and reduce surgery time in the future. The aim is for RoBoSculpt to enable more surgeons to perform these crucial procedures and thus more patients can be helped with potentially better outcomes. The robot is in fact an advanced seven-axis computer numerical controlled (CNC) milling robot, which can use images to work autonomously.

This project was initiated when ENT (ear, nose and throat) surgeon Dirk Kunst from the Radboudumc Nijmegen, the Radboud university medical center, asked for help from the Control Systems Technology Group of Prof. Maarten Steinbuch at the TU/e. This group, already known for the development of the SOFIE [2], Preceyes [3] [4] [5] and MicroSure [6] [7] surgical robots, accepted the challenge via a Ph.D. project.

Medical problem

Procedures in the ear area for cancer removal, hearing restoration or infection removal often require bone to be physically removed with submillimeter accuracy within millimeters of critical structures. Currently, razor-sharp spherical drill bits, rotating with speeds up to 80,000 rpm, are used to remove this bone. The surgeon manually steers this drill bit while looking through a microscope. However, all structures are hidden in the bone and only become visible when structures are almost touched by the drill bit. Critical structures include the nerves responsible for facial expression and taste, a vein, an artery, the hearing and balance organs. If the surgeon hits the facial nerve, for

AUTHOR'S NOTE

Jordan Bos graduated cum laude in Mechanical Engineering at the Eindhoven University of Technology (TU/e), the Netherlands, and won multiple prizes for his graduation project. He started his Ph.D. project on RoBoSculpt in the Control Systems Technology group at the TU/e in 2013.

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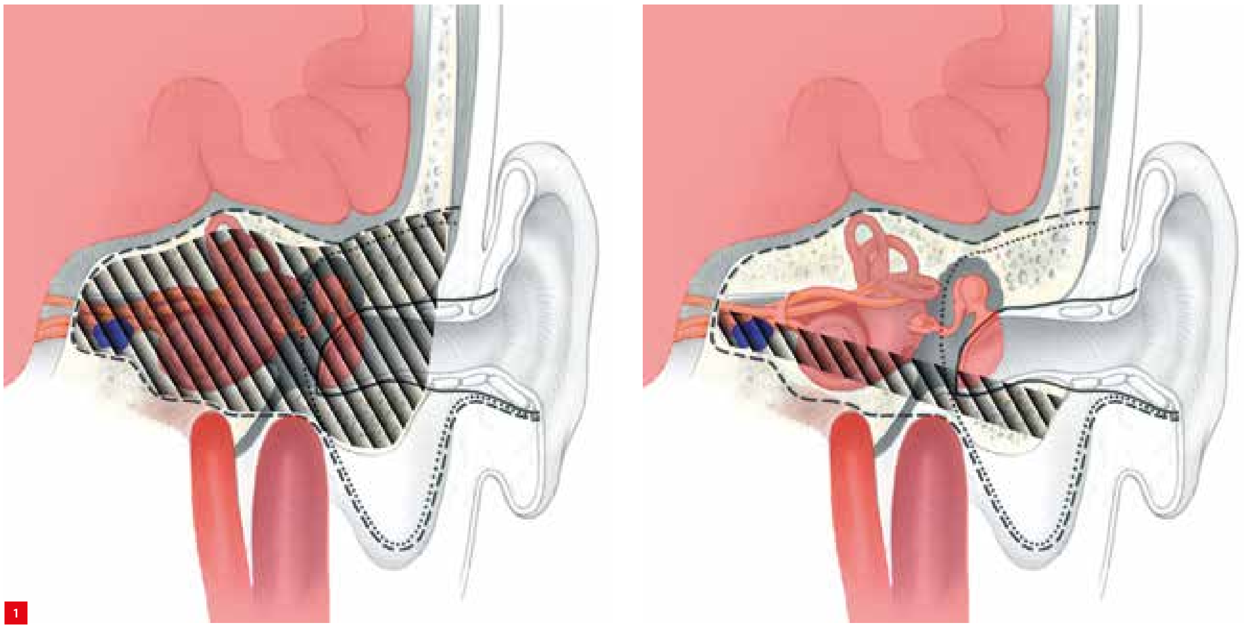


1 A cross-section of the human ear. All vital structures are visible in red and a tumour is shown in blue. The striped pattern shows a 2D surface of bone milled away in current surgery (left) and the bone removal which could suffice with the help of RoBoSculpt (right).

2 The RoBoSculpt surgical robot from the TU/e is the medical equivalent of an advanced and compact seven-axis CNC-milling machine

example, this can result in the permanent paralysis of half a face.

Surgeons currently do have access to CT and/or MRI data from a patient to plan the procedure. However, they cannot optimally map this information to the patient lying on the operating table. As a result, surgeons often have to remove an excessive amount of bone to explore the target, which can take up to six hours. An example is shown in Figure 1.

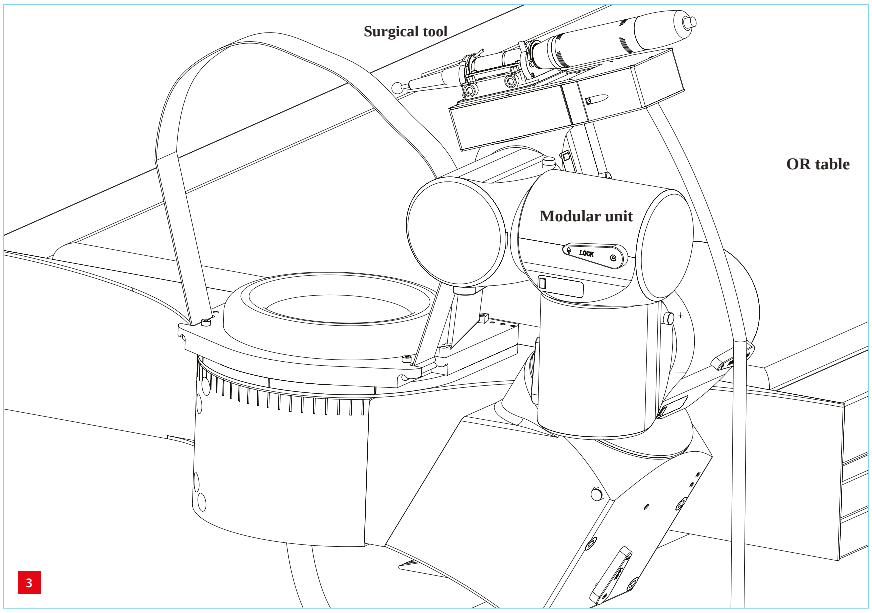
The solution seems simple: use a compact surgical robot, the medical equivalent of a CNC milling machine, which has high stability, guarantees accuracy, and can efficiently use existing Computed Tomography (CT) and/or Magnetic Resonance Imaging (MRI) data. An accurate 3D patient-specific map can be made from the location of all structures using image processing software. By connecting the patient to the robot with high stiffness and stability, it is possible to directly and accurately move towards the target with the potential of lower risks and shorter surgery time.

However, a robot which satisfies the demands cannot be found on the market yet. Furthermore, existing surgical robots such as MicroSure and Preceyes cannot be used, since they are not designed to withstand the relative high drilling and milling forces. Moreover, Preceyes and MicroSure are primarily focused on steering by the surgeon using a joystick; human motions are scaled and tremor is filtered. The biggest gains can, however, be achieved when a robot can remove bone autonomously with the surgeon still acting as supervisor. We aim to realise this with RoBoSculpt, from which the mock-up is visible in Figure 2.

Mechanical design

A schematic view of RoBoSculpt is shown in Figure 3. RoBoSculpt has seven degrees of freedom (DoFs) and fits inside a box measuring 160 x 180 x 200 mm^3. The mass is approx. 10 kg and the working volume of the robot is an ellipsoid with radii of 300 and 500 mm. The robot is designed to withstand forces up to 50 N. RoBoSculpt is designed for a repeatability of 50 μm. Besides precision, the robot is designed for human-robot interaction, safety and robustness.

In the remainder of this section, the design of RoBoSculpt will be discussed in a limited amount of detail. There are two reasons for this: 1) the patent portfolio is currently under expansion; 2) the Ph.D. thesis, which will be available at the end of this year, will be the first publication to present more detailed information.



3 *Design of RoBoSculpt.*

RoBoSculpt has a serial kinematic design, which results in a compact and robust solution with a relatively large range of motion. The disadvantages of serial robots in comparison with parallel and hybrid robots are often the relative low stiffness and large moving mass. Both disadvantages are reduced to a minimum by minimising the distance between the axes as much as possible, since bending stiffness reduces with length to the third power. The modular design makes it possible to reduce the cost and service price, by having more identical parts. The combination of the modular and the serial design makes it possible to change the number of DoFs of the robot.

The robot can clamp existing surgical tools. The surgical tool can make a linear motion over a stroke of 50 mm, with which coordinate drilling is made possible. This linear motion is guided using linear roller bearings which are preloaded. Rollers are chosen due to their increased stiffness compared to balls. The contact-lines of the rollers intersect with the axis of the tool, enabling a rigid fixation in two translations and three rotations.
The third translation, the moving axis, is driven by a pre-loaded leadscrew with anti-backlash nut. This enables a backlash-free position with high accuracy, stiffness and driving force, due to the large reduction ratio close to the output. An electric motor is connected to the leadscrew using an elastic coupling. The linear motion of the tool adapter is measured directly at the output using an absolute encoder, in order to enable precise measurements. Drilling and milling forces on the tool can be measured in all directions.

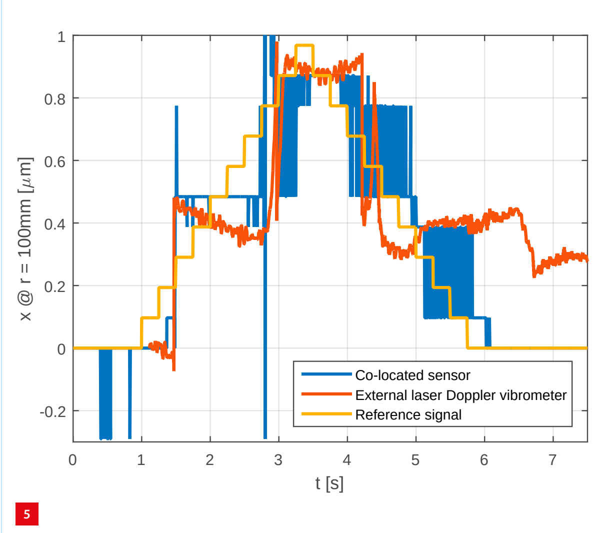
The frame of the linear drive connects to a six-DoF robotic arm, which is built using six almost identical modular units. Every module is responsible for one rotational DoF and fits inside a box measuring 70 x 70 x 90 mm^3. The bottom two modules are larger, in order to obtain higher stiffness and torque at a larger distance from the surgical tool. The axes are stacked perpendicularly on top of each other.

The mechanical structure is designed to achieve a relative high stiffness combined with a relative low mass so that high dynamic performance can be realised. Friction is kept to a minimum and all motions are designed to be backlash-free. Every module is filled to the bottom with mechanical and electrical components: it has multiple encoders integrated to ensure the integrity of the total driveline at all times and to achieve sufficient precision. An electromotor is used in combination with a reduction ratio for accurate positioning with high torques.
Multiple safety functions have been incorporated in the design for human-robot interaction and medical legislation. Each module contains dedicated electronics, which communicate with each other via an EtherCAT protocol. This enables the interchangeability of modules and reduces the wire harness to a minimum.

The modular robot with seven DoFs is fixed to the operating table headrest. The head of the patient is also fixed to this headrest. As a result, the required precision can be achieved, since the force and measurement loop between the patient and robot is kept small. The head of the patient is fixed by means of miniature bone screws placed in the skull. These screws can be used both as accurate reference points, and as a rigid and stable fixation of the patient with respect to the robot.

Due to the fixation of the skull with respect to the robot, RoBoSculpt can use pre-operational image data to calculate safe and minimally invasive trajectories towards the target. The trajectories will be translated in individual joint reference signals using the known inverse kinematics of the robot. Due to a redundant number of DoFs, these reference signals can be optimised for, for example, minimal joint velocities and accelerations, the avoidance of patient- and self-collisions and for trajectories with maximum stiffness, hence precision. The resulting joint-reference signals will be used to control the individual joints using encoders of the joints as feedback. Supervisory feedback can be provided using the vision of the surgeon and existing surgical navigation systems, which can act as independent metrology systems.

Besides autonomous milling using offline-trajectory calculations, real-time trajectory calculations will be possible. The surgeon can use a haptic device to steer the robot in real-time. Since the robot has a patient-specific map from medical image data, the movements of the surgeon can be corrected if required.



4 *Prototype of one module.*

5 *Micro-step measurements with one module.*

Preliminary measurements

To verify the design, one module – shown in Figure 4 – was realised and tested. These tests were successful, so the first prototype is currently being built. Figure 5 shows micro-step measurement results of one module using a non-optimised PID controller with low-pass filter and a voltage amplifier. Feedforward has not yet been implemented. Moreover, the prototype will use a current amplifier to enable improved performance.

In yellow, a reference signal with steps of 1 μrad, being 0.1 μm at an arm's length of 100 mm, is shown. Both a co-located sensor and an external measurement system, being a laser Doppler vibrometer placed at an arm's length of 100 mm, were used to measure the output movement of the module. The laser Doppler vibrometer was used to facilitate contactless measurements with high accuracy and to achieve minimum influence on the measuring error due to small angle and reflectivity deviations. However, a non-linear drift of approximately 0.5 μm over a timescale of 10 seconds in rest was measured with the laser Doppler vibrometer.
Figure 5 shows the results of a test with (unfiltered) measured steps of approximately 5 μrad. With an arm's length of 100 mm, which is typical for the robot, this results in manipulation possibilities of 0.5 μm using one module.

Perspectives

The Eindhoven research group intends to start with the first pre-clinical trials in the Radboudumc this year. While the focus for RoBoSculpt is on medical procedures in the ear region, the team also foresees opportunities in other procedures where precision bone removal and precision positioning with stability is required. Examples include spine, knee and hip surgery. Moreover, this compact and modular robotic arm can have added value outside the medical sector.

The Ph.D. project is expected to finish at the end of 2017. There is an opportunity to start a spin-off company with the help of Medical Robotic Technologies (MRT) [8]. MRT already helped Preceyes and MicroSure to start a spin-off company. RoBoSculpt is one of the winners of the recent 'ASML get in the ring' challenge, with which there is support from HighTechXL and ASML to start up a company.

If all goes well, RoBoSculpt might be able to enter the European and Asian market within a few years. To get there fast, they need support and investment from larger companies. If interest for RoBoSculpt can be raised outside the medical market, for example the manufacturing industry, this can speed up the process. ■

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IXI-PLAY, A SMART ROBOT COMPANION FOR KIDS

Robots are expected to change the world in the near future, but building a smart and agile robot appears to be a serious challenge. Due to the fast development of affordable electronics, the expectations are high, not only technology-wise, but also cost-wise. This article describes an attempt to develop and build a high-tech robot for consumer applications, showing the challenges and difficulties along the way.

BART DIRKX AND RUUD VAN DER AALST

AUTHORS' NOTE

Bart Dirkx and Ruud van der Aalst are the founders of WittyWorX, established in 2011. Their first product is IXI-Play, a robot companion for young kids. Currently, WittyWorX is operating as an engineering and project management service company.
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Introduction

There is no doubt that robots are getting more and more interest. This is fueled by rapid technological development of robots and applications. In industry, robots have been successfully applied for a long time. In consumer applications however, only few robots have made ground so far. The main reason for this is that expectations are high, predominantly caused by the rapid development of cheap electronics and applications. Also, the film industry has made people to believe that robots are smart, sometimes even smarter than humans. The current reality however is that robots are expensive, clumsy and all but smart, even the most advanced.

Developing a useful robot is hard. Robots have to deal with real-world, physical applications. They have to sense the environment around them, classify and do something with that. This is much more complicated than virtual or screen applications where all of the environment is known beforehand and anything is possible. Even when a robot is correct most of the time, this is not enough to be convincing. Besides that, because robots have actuators, they tend to be expensive, especially when industrial-grade motors are used. IXI-Play is an attempt to develop a consumer robot that is both advanced and affordable.

Motors and gears

DC motors have many advantages. Therefore, it is no surprise that they are the most commonly used actuators around. DC motors are low-cost, powerful, and easy to control, but for robotic applications they have a few drawbacks. DC motors have maximum torque and efficiency at low rpm. However, to be able to deliver full power, they need to run at high rpm, typically half of their maximum speed. Robotic applications, however, typically require maximum power at low rpm.

To be able to also deliver high power at low speeds, often a gear box needs to be installed. This comes at a cost. Not only is a gear box expensive, in many cases as expensive as the motor itself, it also ruins dynamic performance. Gear boxes add backlash, noise and poor backdriveability. Preferably a low gear ratio is chosen, but this results in a large motor-gear combination. Many consumer robots are built using RC servo motors. These motors are a good example of high noise and poor dynamics, yet low cost.

Stepper motors have relatively high torque, but a more limited range than DC motors because their torque reduces quickly at higher speeds. They are also much heavier, bulkier and more expensive. A big advantage of stepper motors is that they can be used in open loop without losing position as long as the load is not too high. These motors are often seen in 3D printing applications.

Elliptec piezo motors

Piezo motors are known for their high accuracy and strength, but also high cost. One exception are the piezo motors from Elliptec. Because they use only one piezo, they can be produced at relatively low cost.

Advantages:

- Silent (operating frequency > human hearing frequency)
- High dynamics: < 100 µs response time
- Fast: 300 mm/s
- Compact and lightweight: 25 x 8 x 3 mm^3, 1.2 g
- Friction coupling (1 N)
- Suitable for both linear and rotary applications

Disadvantages:

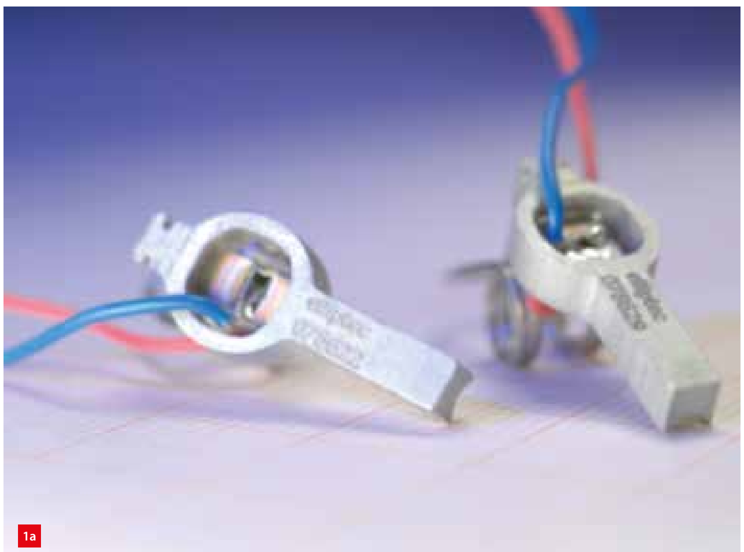
- Limited force (0.2 N)
- Hard to control
- More expensive than DC motors

Because of their properties, Elliptec motors (Figure 1) were chosen for IXI-Play.

Mechanism

To be able to provide a full set of motions, a 6-DoF parallel manipulator (DoF = degree of freedom), better known as Gough-Stewart platform (en.wikipedia.org/wiki/Stewart_platform) or hexapod, was chosen (Figure 2). This platform is statically determined, meaning that all motors can work in parallel without crosstalk. The challenge was to make this platform as compact as possible to keep the base of the robot small.

The first step was to transfer the linear motion of the Elliptec motor into a rotary motion and at the same time add a small transmission ratio to increase the applied force. For this a crankshaft mechanism was chosen. By putting the pushrod closer to the centre of the wheel the piezo motor force geared up to 0.3 N in zero position. When the wheel is rotated, the crankshaft mechanism increases the gear ratio up until the Top Dead Centre (TDC). At this point the gear ratio is infinite and vertical movement zero. This is also the case for the Bottom Dead Centre (BDC). Figure 3 shows the force diagram for an alternating constant wheel rotation giving a simple 0.5 Hz Z-movement.



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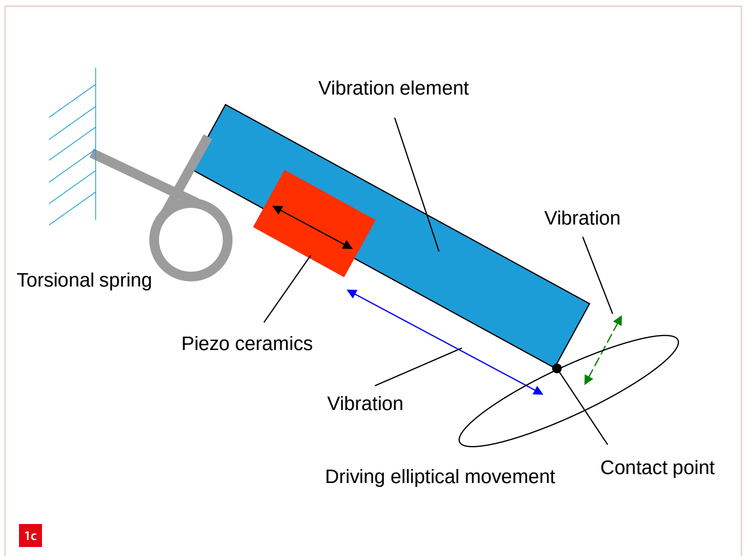

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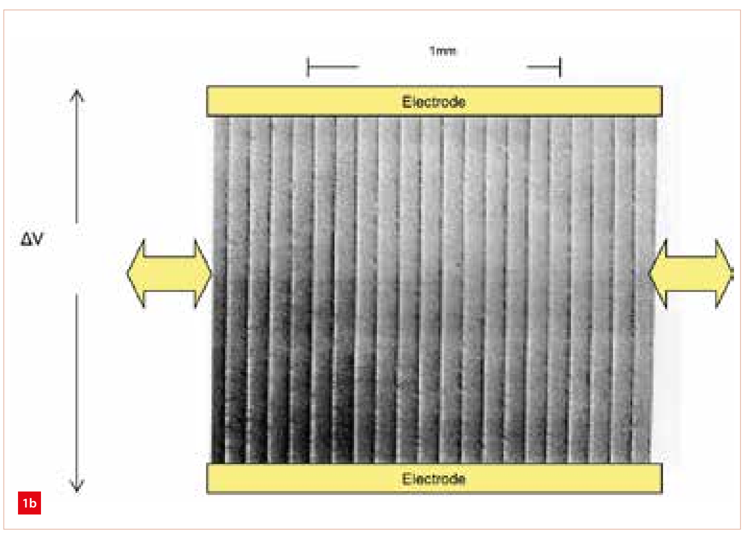

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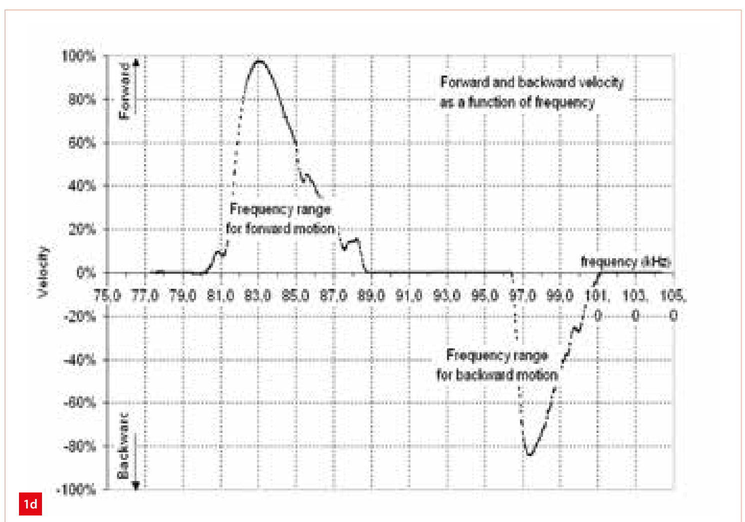
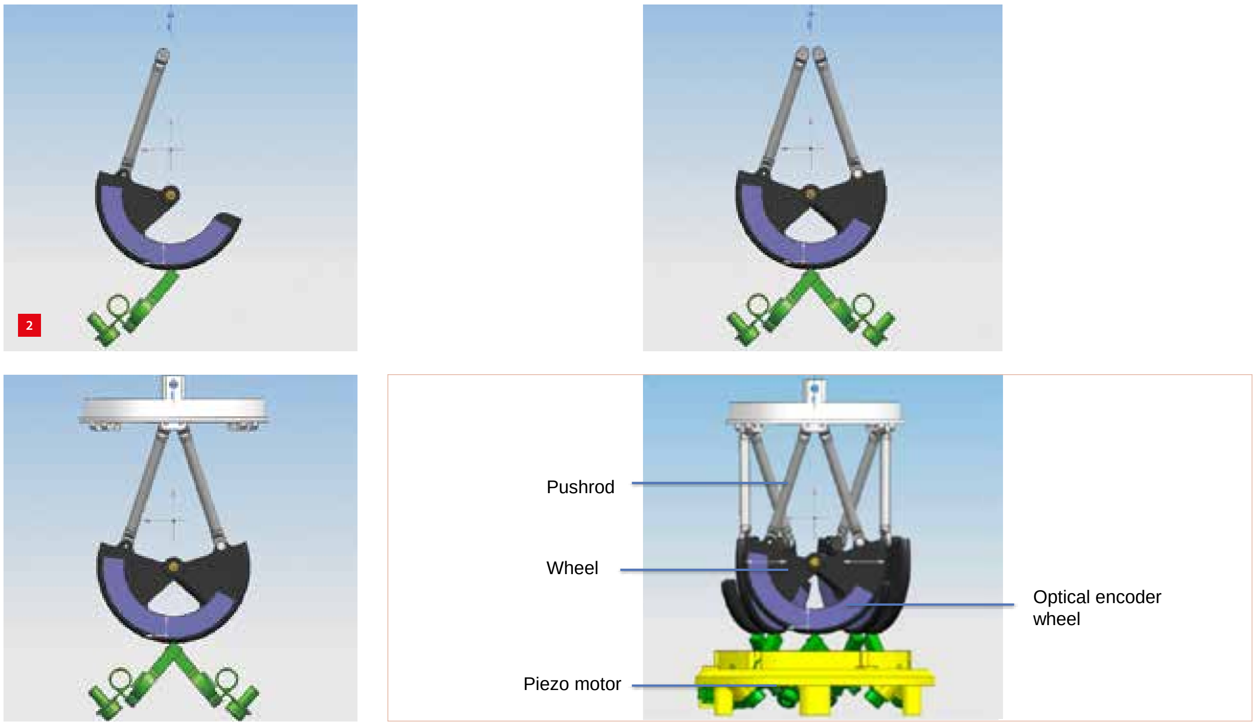


1d

1 The Elliptec piezo motor (Source: Elliptec)
(a) Physical appearance.
(b) The stacked piezo element, needed for driving the motor at 5 V.
(c) Motor principle: the piezo brings the motor in its eigenfrequency causing the tip to make an elliptic movement, which pushes the counterpart forward in the lower part and moves it back in the upper part of the ellipse.
(d) Forward motion is generated by triggering the first eigenfrequency (83 kHz), backward motion is triggered at 97 kHz. Speed is controlled by amplitude control.



2 *Construction principle (in four stages) of a compact hexapod mechanism for IXI-Play.*

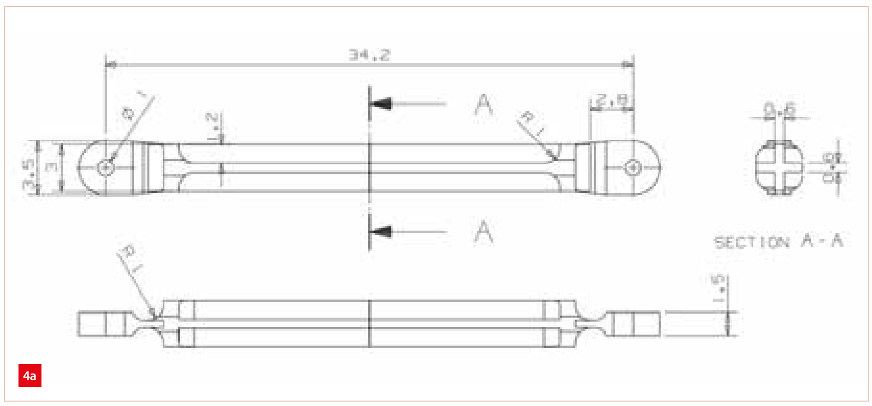
3 *Force diagram for an alternating constant wheel rotation giving a simple 0.5 Hz Z-movement. The motor force is the sum of the six motors.*

4 *First pushrod design.*
(a) Drawing.
(b) FEM analysis.

Although possible, the TDC and BDC are not chosen as end position because at these points backdriveability is also zero. To enable outside forces to move the mechanism back, preventing breakdown, the vertical stroke is limited by 140° wheel rotation. The maximum force is limited by the transmission ratio at this point and the holding force of the piezo motor, ca. 4.3 N per segment.

Each wheel segment drives a pushrod. Two segments are combined to form a kite-shape mechanism for controlling the outer end in two DoFs; vertical and horizontal. By combining three of these elements a compact hexapod mechanism is formed with a top platform which can be controlled in all six DoFs (Figure 2). A precondition for this is that the pushrods can only have one DoF; axial.

In the first design, the pushrods were made out of a single piece of plastic, but from the tests it became clear that the six of these were too stiff, especially for *Rz*-movement (Figure 4). Therefore, a redesign was made consisting out of bushings, held together with a nylon string in the centre (Figure 5). The outer ends are still plastic flexures with holes for the rotation points. These are the only points in the design with slack or play. The piezo motor is pretensioned with a spring, which eliminates the play in the wheel rotation point.



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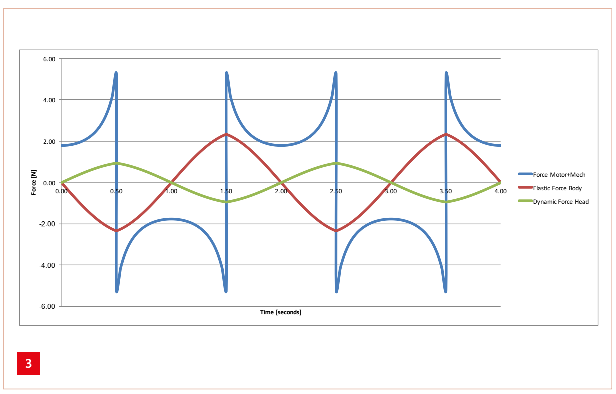

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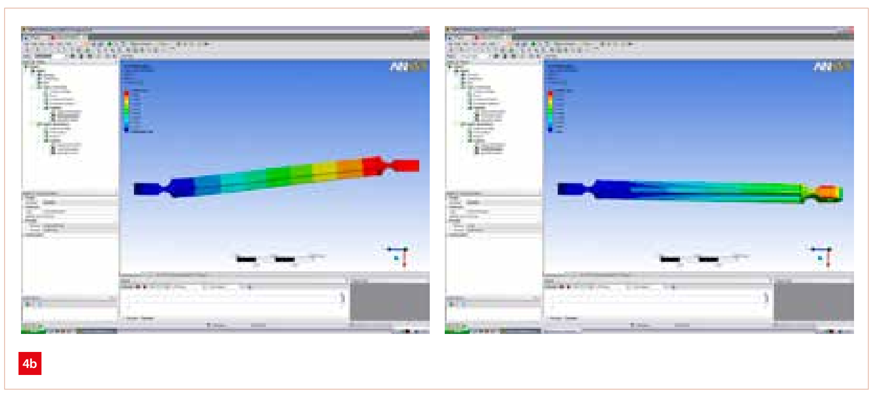

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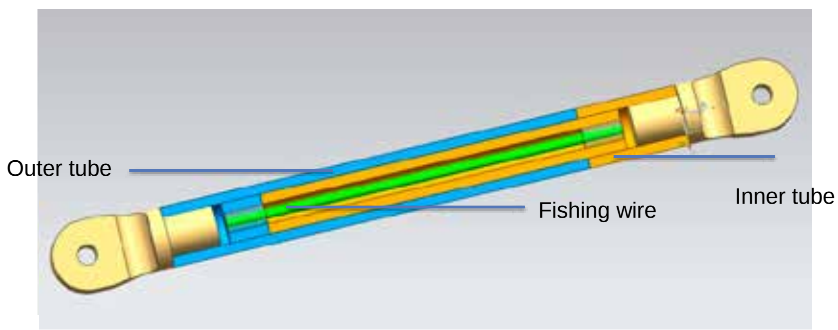


5 *Pushrod design fixating only one DoF.*

This results in a compact 6-DoF hexapod that is almost silent during operation. Because of the dynamics of the piezo motors, the direction of motion can be reversed almost instantly, enabling high dynamics. This platform can make full-stroke movements of 2 Hz and small stroke movements of > 15 Hz.

A drawback of parallel mechanisms is that for the platform to operate well, all motors need to have the same performance, i.e. speed and force. If one motor does not perform as well as the others, this has direct impact on the movement. This effect was observed while developing the IXI-platform. It appeared that individual Elliptec motors differ in performance. This became especially clear during motion tuning, where a clearly audible resonance was observed in the range of 2 to 5 kHz. Investigation showed this to be the result of differences in eigenfrequencies of the individual motors.

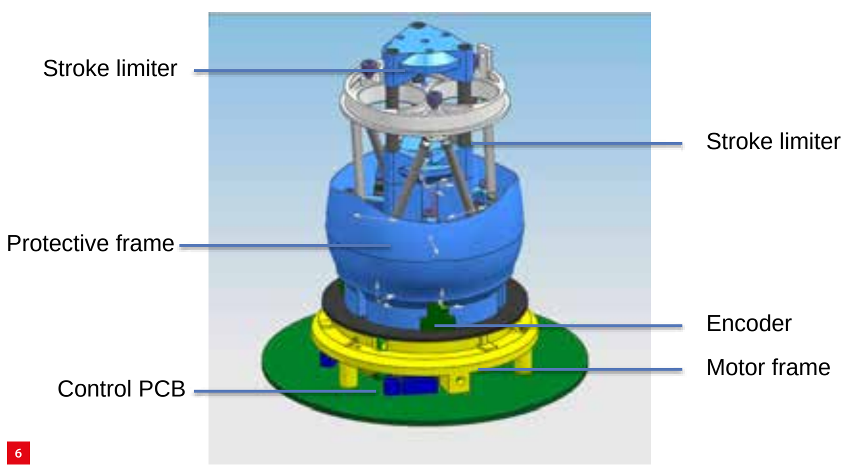
Because of manufacturing tolerances and wear, every motor has its own specific set of eigenfrequencies for forward and backward motion, respectively. At start-up, a sweep over a specific frequency range can be performed to find the exact eigenfrequencies for forward and backward movement. If more motors work in parallel, the differences in eigenfrequencies result in low-frequency resonances in the human audible range. This was the case with the IXI-platform.

To avoid the problem, all motors have to be controlled with the same frequencies. Because every motor has its own optimal frequencies, this results in suboptimal performance if the differences between the motors are large. This was resolved by testing each motor and then selecting a set of six motors with nearly equal eigenfrequencies.

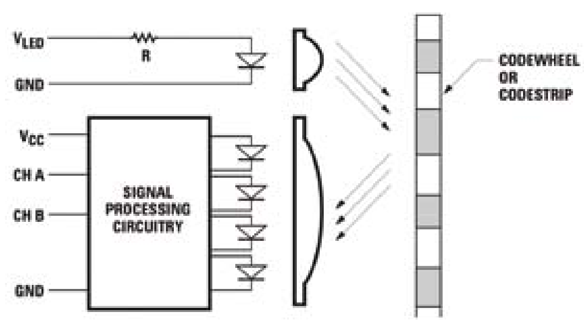
Because of its size, the hexapod mechanism is fragile by itself. To protect this mechanism against outside forces, stroke limiters were added to the structure (Figure 6). *Z*-movement is limited by end stops. Three vertical rods were designed in for limiting *X*, *Y*, *Rx*, *Ry* and *Rz*. These rods were also used for cable feedthrough for the electronics in the head.

Metrology

To be able to control the hexapod in closed loop, position sensing is needed. The best location for this appeared to be the wheels. Because each motor needs to be controlled, on each wheel a reflective optical encoder was added. This encoder (Agilent AEDR 8300) consists of a LED and an opto-sensor in a single package (Figure 7). The signal of the LED is reflected by the code wheel and detected by the sensor. For IXI-Play this code wheel was etched out of 0.2 mm metal sheet, cut to size and then glued onto each wheel. The resolution was 0.3°, which was more than enough for the application. The reflective encoder has two signals (A and B) to determine direction. Unfortunately, this encoder is incremental, so every time the robot is reset the zero position has to be found. This was done by putting the robot in its lowest position during start-up.



6 *Stroke limiters to protect the mechanism against outside forces.*



7 *Schematic of the Agilent AEDR 8300 encoder with code wheel. (Source: Agilent)*

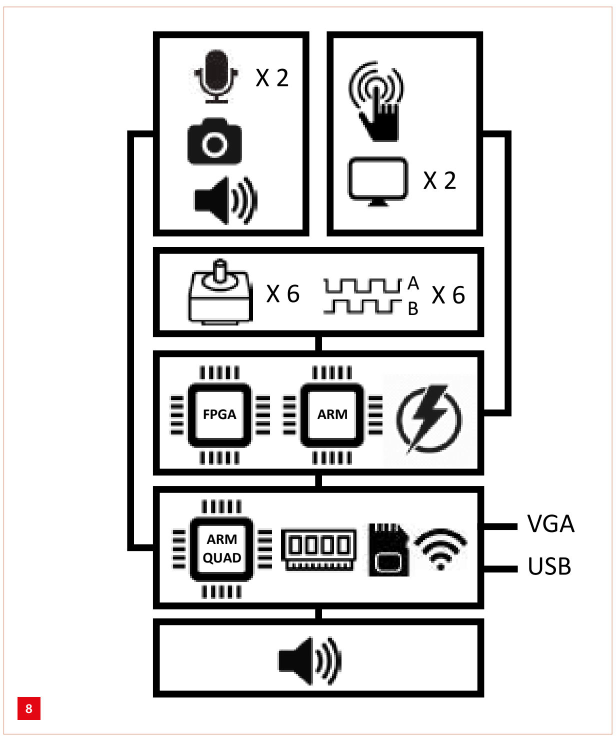
Electronics

For controlling the robot and running applications no suitable electronics board was available at the time. A Raspberry Pi was too big to fit in the base and carried only a 700 MHz single-core ARM processor. Instead, an Android TV Stick was used. Although developed for video streaming and decoding, this device appeared to be the best available for IXI-Play. It holds a 1.8 GHz quad-core ARM processor, 2 GB RAM, 8 GB storage, WiFi and Bluetooth. A webcam can be connected to one of the available USB ports for image recognition.

Using an Android OS (operating system), the TV Stick was highly suited for running unique IXI-Play apps, e.g. games or Q&A interaction. However, a disadvantage of Android is that it is a non-real time OS, which makes it unsuitable for motion control. This problem was resolved by developing a separate real-time control board.
This board holds:

- Power electronics for the Elliptec motors.
- ARM processor for initialising and controlling the motors, 6-DoF kinematics and processing external I/O, e.g. eyes and touch sensor.
- FPGA for processing the encoder signals and other tasks in a later stage, e.g. video and audio (pre)processing.
- USB connection for communication with the Android TV-Stick.

Figure 8 shows the hardware architecture. The first prototype of this board was developed in the Netherlands, but then redesigned, produced in Vietnam with the help of Hurli, and debugged by SensoRon; see Figure 9.



8 *Hardware architecture. The Android board (non-real time) is used for running applications as well as microphones, camera and speakers. The control board delivers power to all systems and holds an FPGA and ARM processor for real-time processing, e.g. reading encoders and controlling the motors. This board also reads the touch sensor and controls the OLED screens (eyes).*

9 *Robot control board for controlling motors, processing encoder signals and calculating inverse kinematics. Bottom side and top side.*

The robot has no screen, which would require off-line programming. To enable online programming, the video output and a USB port of the Android device are brought to the outside of the base for connecting an external monitor and USB data cable or mouse.

Software

The software is split up into two parts:

1. Android OS for easy app development and communication to the outside world via WiFi, Bluetooth and USB (e.g. ADB).
2. Dedicated Real-Time OS for motion control, calculating inverse kinematics (IK) and processing pre-programmed motion sequences.

The Android part can be programmed and tested on the robot using monitor and mouse. For Android a full software development kit as well as many toolboxes are available, e.g. OpenCV for image recognition. For recognising markers IXI-Play uses an open-source toolbox called ReacTIVision. This toolbox was transferred to Android with the help of Sioux Vietnam. The IXI-app was developed by students from KU Leuven and later improved by Sioux.

On the real-time controller board encoder signals are taken in by the FPGA. These signals are pre-processed and then sent to the ARM processor to be used for motion control (PID) and velocity control of the piezo motors. This is done by the ARM processor together with on-the-fly calculation of 6-DoF IK. Full algorithmic calculation appeared to be too much for the ARM processor. A first order approximation did the job. This IK work including analysis and programming was done by a graduate student from Eindhoven University of Technology (TU/e).

With IK in place, motion sequences can be programmed in Cartesian coordinates, which makes it easy to program complex kinematic movements, e.g. in-plane X-Y-movement or combinations of movement like bobbing while rotating around the Z-axis.

Internal and external body

Most internal frame parts and the motor mounting plate were made by 3D printing. Selective Laser Sintering (SLS) gave the best results. Also the head was 3D printed and finished by applying primer, putty and paint. A tedious job. For enabling organic movement, the body was made out of silicone rubber. The outside shape was defined by design, but the required thickness for uniform deformation was unknown. Simulation appeared to be only possible with a solid material model, which was not available. Therefore, a trial & error approach was used. The first model collapsed, but by locally increasing wall thickness, deformation was brought to an acceptable level. This shape was copied into a mould for silicone rubber casting. An injection-moulded bearing element (a student assignment at Fontys University of Applied Sciences) was in-moulded to allow the head to turn or shake 'no' while the body remains in place.

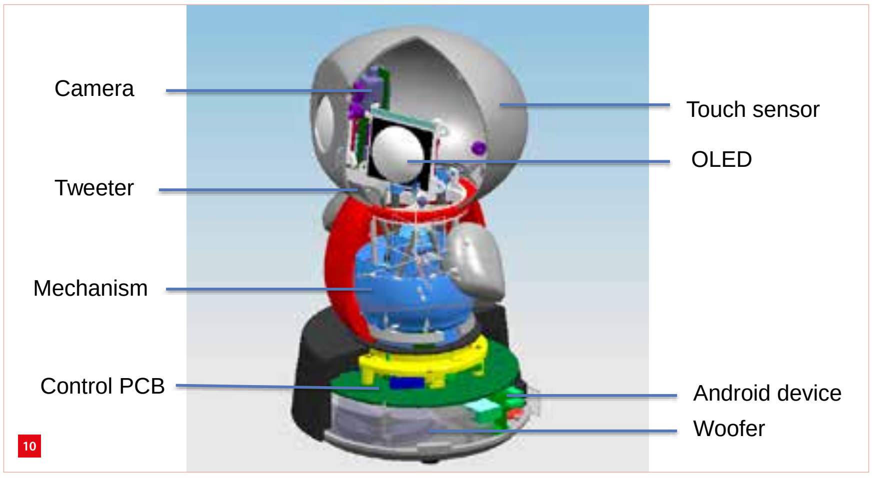
Eyes

Many robots have mechanical eyes, but experience in previous projects showed that these eyes are complicated, fragile, expensive and limited in expressions (even with eyelids). Displays are simple, robust and cheap, and provide unlimited expression possibilities including colours.
For IXI-Play, OLEDs were chosen because they provide a clear image with saturated colours (the only disadvantage is flickering when making videos). IXI-Play was developed before round smart watches became popular, so displays are square. Therefore, they cannot be brought too close to the surface without the corners sticking out. To overcome this, a lens was placed on top of the OLED to optically bring the image to the surface. The result was convincing and a hollow lens appeared to work best. This lens was produced in small numbers using injection moulding with the help of Gebrema.

Eye animations are stored on the control electronics of the OLED display. The ARM processor on the real-time control board triggers each animation. First eye animations as well as sound samples and movements were developed by a graduate student from Delft University of Technology (TU Delft). They have been used in many user tests and videos.

Assembly

Figure 10 shows the assembly of the IXI-Play platform including all elements and modules. The total platform is approx. 21 cm high, including base. A video showing the motion of the platform can be found online (*www.youtube.com/watch?v=EpFYtI-QyC8*); see Figure 11.



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Conclusion and considerations

Developing an advanced consumer robot is all but simple. Let alone the human interaction design, not touched upon in this article. There is a limited number of standard parts and building blocks that can be easily integrated. For IXI-Play, many modules needed to be custom built to fit into a small space. Fortunately, 3D printing in combination with CAD and regular manufacturing techniques enables fast product development. On the other hand, the complexity and large number of disciplines involved make building an advanced robot a challenge.

This article covered mainly mechatronics development. For a robot companion to perform useful functions, also speech recognition, image recognition and artificial intelligence (AI) need to be in place. Speech recognition is getting there, but image recognition and AI, although developing rapidly, are still in their infancy. Because of this, it seems that it will still take some time before consumer robots will meet consumer's expectations regarding functionality and affordability. But as long as the interest is there, the technology will follow. ■

10 *Assembly of the IXI-Play robot showing the different elements.*

11 *Screen capture of video showing motion; on the right the interior of the robot.*

11

THE POWER OF DESIGN PRINCIPLES

AUTHOR'S NOTE

Niels van Giessen is the recipient of the 2016 Wim van der Hoek Award. He studied Mechanical Engineering at Avans University of Applied Sciences in Den Bosch, the Netherlands, and received the award for his graduation project. He now is a pre-Master student of Mechanical Engineering at Eindhoven University of Technology, the Netherlands.
For confidentiality reasons only a global overview of his award-winning project can be presented here.
The author acknowledges the support of Hans Steijaert of VDL ETG.

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Parts in robot arms commonly demand an optimal combination of stiffness, weight, dynamic behaviour and tolerances in order to achieve high speed and precision. The redesign of the robot arm discussed here will improve production yield, product cost and precision, demonstrating the power of design principles.

NIELS VAN GIESSEN

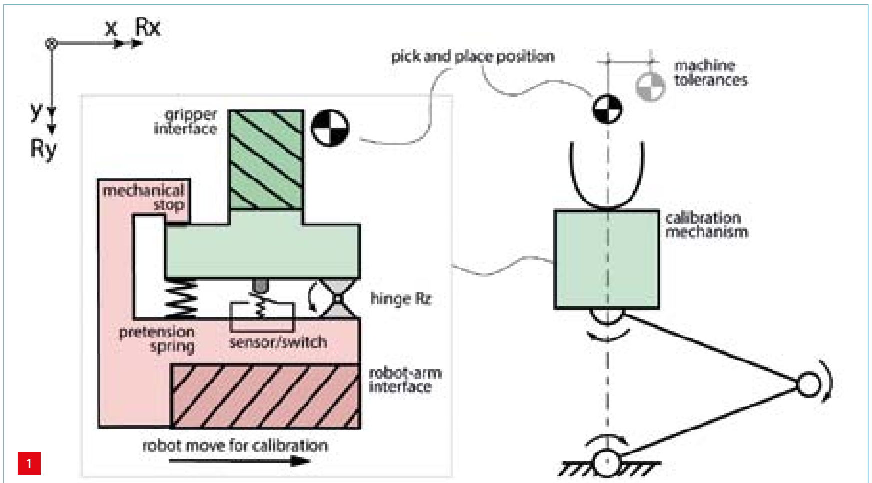
Issue

The present robot-arm mechanism includes a sensing device for calibrating the robot position in order to compensate for manufacturing tolerances, as illustrated in Figure 1. With respect to the mechanism, the tolerance chain of the robot allows for ±0.45 mrad out-of-plane tilt between the interfaces indicated in Figure 1 (both *Rx* and *Ry*). In many cases, the current design does not allow the manufactured mechanism to pass its tilt qualification test. Furthermore, costs needed to be reduced and anticipated robot speed increases demanded for mass reduction in order to retain precision. Ultimately, a redesign was called for.

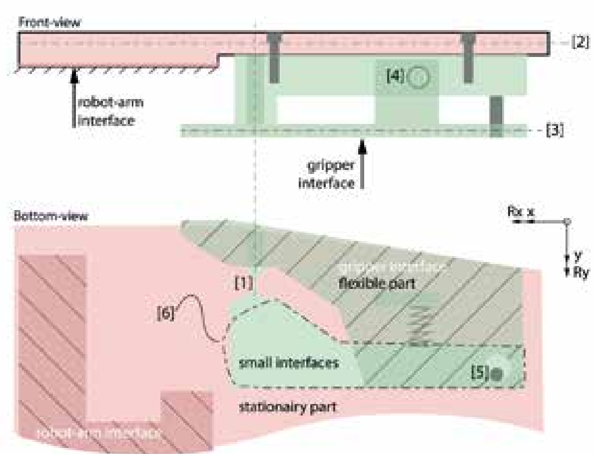
The current design

The current design is indicated in Figure 2. The hinge (*Rz*) is realised with an elastic hinge [1]. Although an elastic hinge originates from the design principles 'toolbox', this doesn't instantaneously make it a good design. Closer examination of the design revealed that the focus should be on tilt stiffness and manufacturing tolerances, as eventually confirmed by the analysis. The construction features two thick plates [2] and [3], of which the stiffness in the critical tilt direction is relatively low. This is illustrated in Figure 3, by comparing them to leaf springs.

As a result of this compliancy, systematic tilt of 0.4 mrad (*Rx*) and 0.42 mrad (*Ry*) is caused by gravity (systematic, part 1), as derived from model calculations and measurements. Torque induced by the pretension spring [4] adds another 0.31 mrad (*Rx*) and 0.24 mrad (*Ry*) of tilt (systematic, part 2). Friction at the stop-pin [5] and lack of stiffness introduce significant hysteresis (position uncertainty). Therefore, the tilt will vary within a range of 0.5 mrad (*Rx* and *Ry*) by robot dynamic forces. The interfaces of the assembled parts [6] are small. In the worst case, the parallelism fabrication tolerances of the parts can

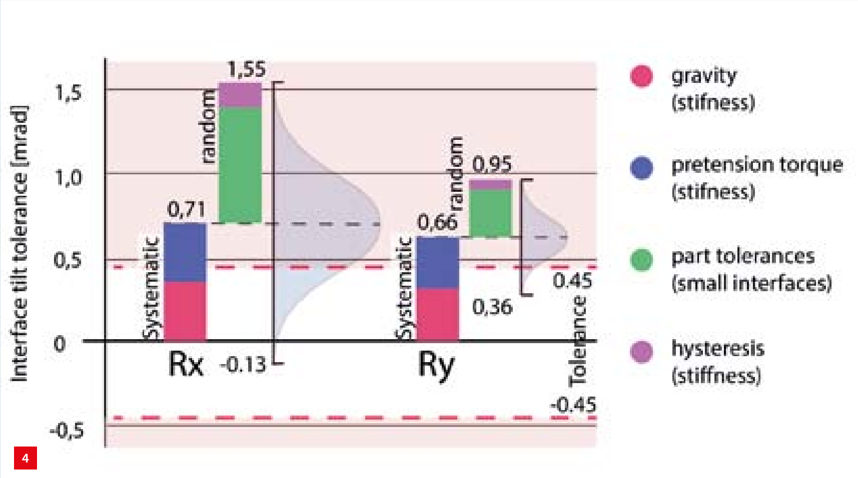


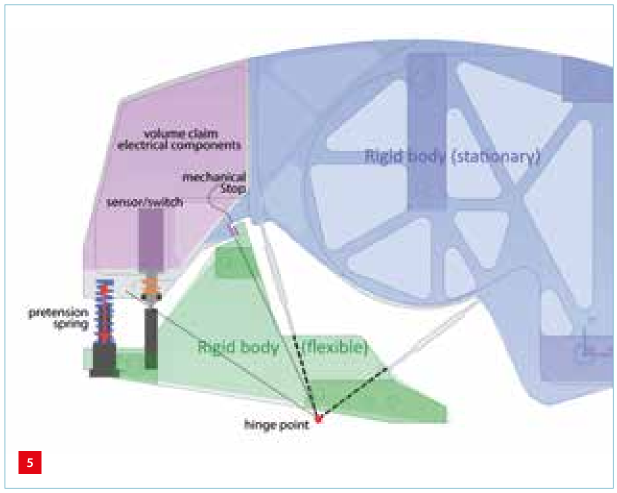
1 *Robot arm including a sensing device for calibrating the robot position in order to compensate for manufacturing tolerances.*



2 *Analysis of the current design.*

3 *Degrees of freedom of a leaf spring. The other directions are stiff.*





4 *Possible range of tilt in the current design with respect to the tolerance.*

5 *Redesign concept.*

6 *Printed plastic mock-up. Nice to know: this plastic version of the redesign outperformed the current metal design in absolute stiffness. Concept feasibility has not yet been proven in aluminium prototype, although the expectations are positive.*

7 *Illustration of how the development environment may be driven by design principles and intuition instead of by disturbances from complexity and uncertainty.*

add up to a tilt deviation of 1.11 mrad (*Rx*) and 0.41 mrad (*Ry*). Figure 4 visualises the possible range of tilt, by adding up the error sources. This clearly indicates that stiffness and part tolerance put a spanner in the works.

Redesign

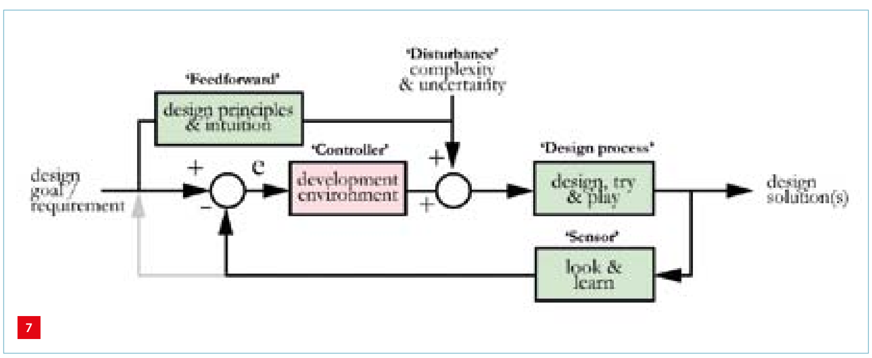
The analysis of the current design shows that the issues will be solved when stiffness is increased and the effect of manufacturing tolerances is reduced. Figure 5 illustrates the bottom view of the chosen concept. The hinge and its connecting frame parts are made out of one piece of material (monolithic aluminium). This is reducing the number of parts, which in turn reduces the tilt depending on manufacturing tolerances down to ± 0.34 mrad (*Rx*) and 0.18 mrad (*Ry*). The dedicated qualification tooling for the assembly is replaced by highly accurate standard measurement tools in part manufacturing.

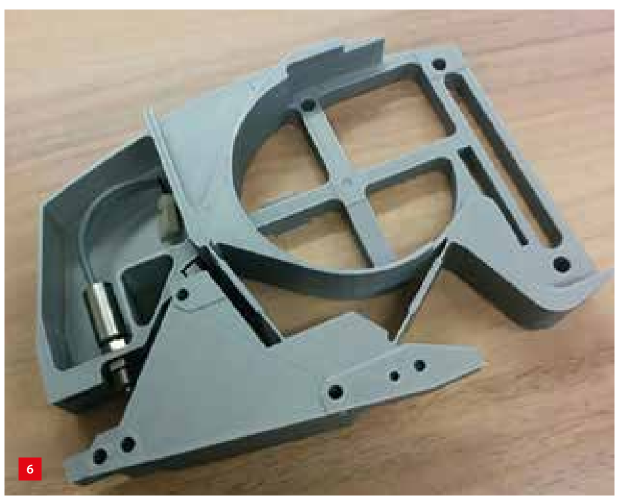
Higher stiffness-to-mass ratio is obtained by 'blowing up' the design, using hollow 'box constructions' and putting material on the outer bounds of the available space.
The two 'rigid bodies' (blue and green) are connected by two leaf springs. The mass is reduced to 50%, stiffness increased to 600%, costs reduced to 60%, number of parts reduced to 80% and assembly time to be reduced to approx. 40%. Figure 6 shows a printed plastic mock-up.

Personal reflection

At an early stage of the project I saw the inherent drawbacks of the current design, as referred to above. However, I had no evidence except for my design intuition. I started gathering and analysing data, and as the research evolved, my intuition, based on design principles, was confirmed again and again. In the end, I concluded that developing the redesign could have started earlier, without extensive measurements, calculations and reporting about the existing design. Playing it safe, 'searching absolute certainty', was a waste of time. I was inspired to illustrate this experience by using a classic control loop, see Figure 7, which shows how the development environment may be driven by design principles and intuition instead of by disturbances from complexity and uncertainty.

To conclude, I want to encourage you (designers) to follow your intuition based on design principles, by trying, learning and developing more! ■





HOW DO YOU INSTRUCT A ROBOT-WORKER?

When working with temporary employees, it is normal to assume that it won't take long to teach them their new work. It may take a while before they can perform their task without errors, but generally within an hour workers are already competent in many tasks. How does this work when you're starting with robots as workers? Do you have to employ a robot programmer to enable these 'metalectrical' workers to work flexibly?

HEICO SANDEE

AUTHOR'S NOTE

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"Klaas, could you stack these cases from production line 1 on pallets today? And make sure they don't stick out over the edge, ok?" Foreman Jaap points to the end of production line 1, which is today producing the bags of chips that will be on special at Lidl.

For a person, it is relatively easy to interpret high-level instructions like these and convert them into concrete actions to accomplish the task. Especially when it is a job we have done before, we barely even need to think about it; we just get started right away. With a new job, usually we try and see what works best for us in achieving the optimal result. Naturally we can then be adjusted a little if something different was intended. After a few hours though, we will have the knack and the boxes will be stacked onto pallets with ease.

One of the reasons that we can learn so quickly is that we do not have to think about our exact movements; we have already learnt them. For picking up a box, as children we learnt to clasp our fingers tightly around a Lego brick, so it does not fall out of our hands. These are basic skills that underpin many actions in everyday life.


1 *Temporary robot workers waiting to be deployed at Smart Robotics.*

Skills

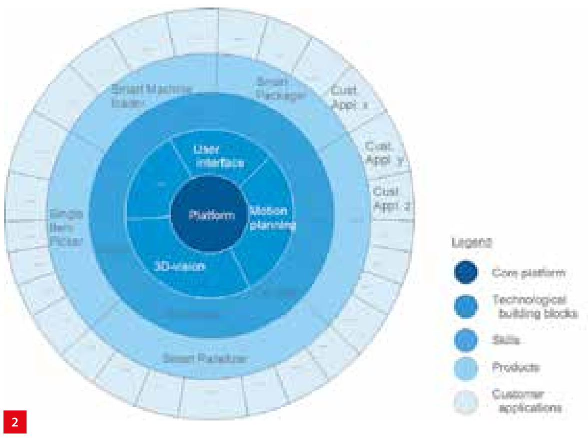
Many research groups in robotics are working hard to integrate this way of working in robotics. It is needed urgently, because often a trained robot programmer can take weeks to program a robot for a specific task. This means that many robots are therefore very inflexible in practice; manufactured to spend their entire 'life' on one specific task.

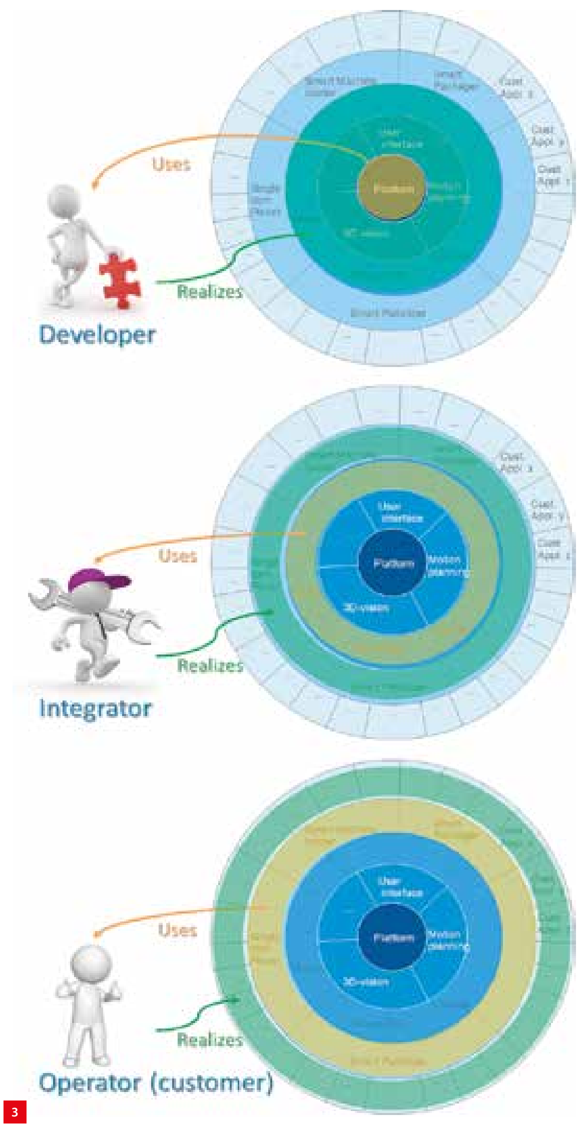
These competencies are typically called 'skills'. Robot skills include: picking up, locating, moving or discarding. A specific task such as palletizing consists of a number of these skills in the correct order: locate pallet, locate product, pick up product, move product to the pallet, place product on the pallet.

To achieve this, the robot must have the intelligence to perform these subtasks. The movements of the robot are not hard pre-programmed in advance; the robot will have to work out for itself how it should move its joints in order to accomplish the task. And all this without colliding with anything. Here advanced technology such as motion planning and obstacle avoidance is essential, as is vision technology that functions without being precisely calibrated in advance for the situation. A fine challenge that robot employment agency Smart Robotics (Figure 1) has seized with both hands, because this is exactly what is needed to make the so-called fourth industrial revolution a reality.

Architecture

The architecture used by Smart Robotics for this is shown in Figure 2. At the centre, a platform has been implemented upon which a set of instructions can be easily built by using





standard interfaces. The Robotic Operating System (ROS) was selected for this, because many robotics developers already have experience with it. On the platform, the modules/nodes run that form the building blocks for skills. With these skills 'products' are made, on the basis of which the client applications are realised.

Different stakeholders are involved at each of the different levels in this architecture (see Figure 3). Developers use the platform to realise the modules and skills. The integration team uses the skills to create products. The operator in the factory then uses the product to make specific applications. This operator – an employee of Smart Robotics' customer – can thus configure the Smart Palletizer for another box, another pallet or to operate the robot in a different place, for example.

The platform communicates with the hardware (robot, camera, gripper, etc.) via a defined interface. This means the platform is hardware-independent and it makes changing hardware modules relatively simple. Often you see that skills begin to align with the specific characteristics of the hardware, whereby this uniform interchangeability requires more changes in practice. It is actually not very different than with a person; it will take a while before you learn to walk again after getting fitted with an artificial limb.

To achieve flexibility with a temporary robot worker, working with skills is a must. However, every advantage also has its disadvantage. The modularity is often achieved at the expense of efficiency and thus cycle time. This is because a specific skill is not optimised for a specific task. This often requires a close look at how the skills can be used more intelligently in order to meet the required cycle time. For example, when two boxes need to be palletized, being able to pick them up simultaneously. Also, a limited set of skills can lead to a limited set of accomplished tasks. Here the robot's surroundings will occasionally need to be modified, for example by putting the supply of boxes in an area that is easily accessible for the robot, so that no special moves are necessary.

Programming

One step further, which many research groups are working on, is automatically generating tasks based on skills. For this, the skills should be put in a standardised format. This in effect makes them the 'words' that, with a chosen 'grammar', turn into a 'language' with which robot tasks can be described and 'reasoned' with. This happens in a so-called 'ontology'. One platform that is already very far along is called KnowRob (www.knowrob.org/knowrob). Such a platform also offers the possibility of robots learning from each other.

2 *Architecture for Smart Robotics' temporary robot-worker.*

3 *The stakeholders at the different levels of the architecture.*

Working on the basis of skills represents a turning point for automation with robotics. It is the key to achieving the flexible deployment of robots that can be easily configured by non-experts (Figure 4), where complex functions such as motion planning and advanced vision algorithms are accessible to non-specialist end users. Working with skills enables simple solutions to complex problems.

4 *'Programming' a temporary robot-worker.*

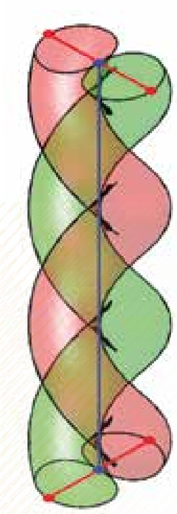
New robot academy

Smart Robotics is engaged in setting up a 'robot academy' with support from the government and universities. The intention is to train 30,000 people annually in dealing with robots. The programme, launched this year, is a three-day robotics training primarily intended for production workers. "People on the factory floor are really the ones who come into contact with robots. They have to work with them, they are more affected than their superiors", said founder Mark Menting, Managing Director of Smart Robotics.

Employees receive more than just training on how to work with the robots; they are also reassured. "We also want trainees to learn that robots do not need to be a threat, but can rather save their jobs", so Menting. "If you no longer need to stack boxes, you have more time to do other things in the workplace."

WWW.SMART-ROBOTICS.NL

A TRANSMISSION PRINCIPLE FOR ROBOTIC DEVICES



The device that is usually called a twisted string actuator is in fact a transmission which converts a rotating motion into a translation. It does this by twisting two or more strings around each other, which shortens their effective length. Due to its compactness, low cost, low noise and high transmission ratio it is suitable for applications in robotic devices, e.g. robotic fingers. But there are disadvantages as well. An overview describing test set-ups and results achieved in a collaborative project of two Dutch Universities of Applied Sciences, Avans and Saxion.

RINI ZWIKKER AND ERIC KIVITS

Introduction

To add to the confusion between 'actuator' and 'transmission', the word 'string' is also used in several entirely different meanings, e.g. in physics and mathematics. The words 'cord', 'wire' or 'rope' might be used as well. In the context of the twisted string actuator (TSA), a string is a cord made of multiple threads or filaments twisted together. The principle of the TSA is very old. Patents date back to at least 1932, but in ancient cultures and on medieval sailing ships ropes were already twisted to generate large forces. The development of robotic devices during the last decades generated new interest in the principle, and this led to research in several countries worldwide. The following article in this issue, "Actuators with a twist – Concise overview of IROS 2016 workshop on TSAs for robotic applications", presents the state of the art.

AUTHORS' NOTE

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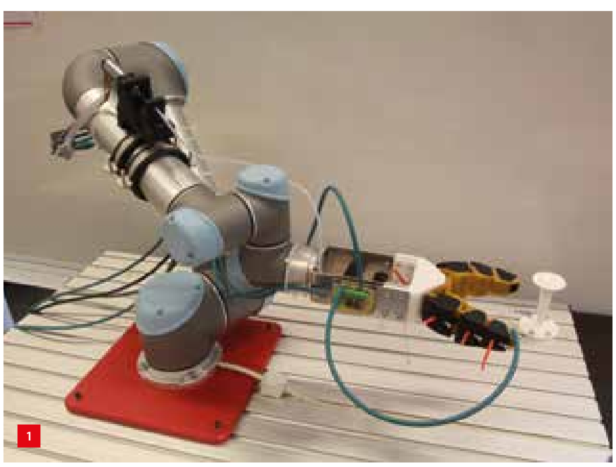


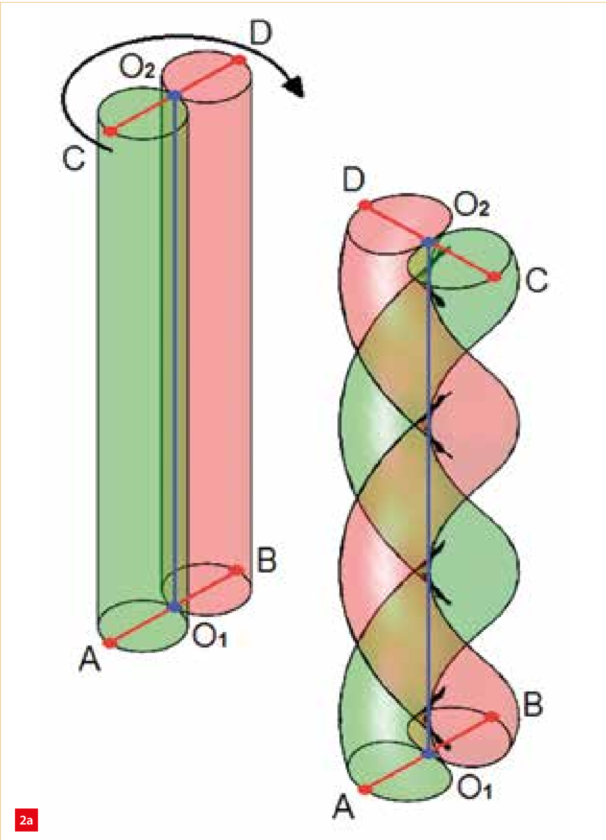
1 *Integrated test set-up of Avans: twisted-string-actuated tactile gripper on a UR5 robot (details shown below in Figure 9).*

The TSA can be used in light service robots or in active exoskeletons for foot, knee, arm or fingers. But it might be suitable for other applications as well, where compactness, low cost, low noise and/or high transmission ratio are important. Depending on the dimensioning and type of string used, the transmission is more or less compliant, and applicable to 'soft robotics'.

From November 2012 to June 2017, the Universities of Applied Sciences Avans and Saxion plus a group of companies have been, and still are, collaborating in the RAAK-Pro project Medical Robotics. Part of this project is to investigate and test functional and technical modules – both hardware and software – with which different robotic devices can be configured, mainly focussing on care applications to enhance autonomy and quality of life of patients or elderly people. These modules include navigation, compliant gripping and vision. Within the topic of compliant gripping work has been done on several sub-topics: robotic fingers, robotic grippers, slip sensing, control algorithms, and the subject of this article, the TSA. Figure 1 shows a test set-up at Avans where all these elements have been integrated on a UR5 robotic arm.

Principle and characteristics

When two initially parallel strings of equal length are twisted around each other, their end-to-end distance decreases (Figure 2a). When the input ends of the string are attached to a rotating motor, and the output ends are attached to a translating load (Figure 2b), then a transmission from rotation to translation is realised: the TSA.



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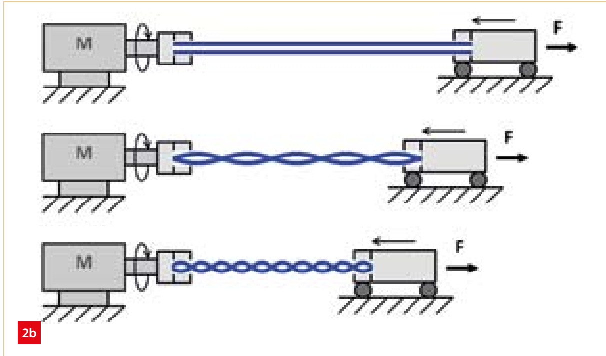


2b

2 *Principle of the TSA (see text for explanation).*

3 *TSA geometry.*
(a) Cross-section with path of string centre.
(b) Geometric relation for transmission ratio.

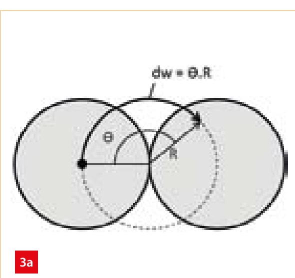
4 *Load displacement as a function of motor rotation angle.*

The circular distance *dw* covered by the motor end of the centre of one string can be expressed using the rotation angle θ or number of rotations *n* of the motor, with *R* being the radius of the string cross-section (Figure 3a):

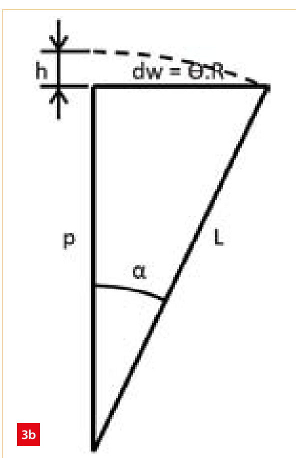
$$dw = \theta \cdot R \text{ or } dw = n \cdot 2 \cdot \pi \cdot R \quad \text{[mm]}$$

This rotation distance can be folded out to create a triangle (Figure 3b). In this triangle, *L* is the length of the string and *p* is the distance between the end points. Their relation is given by the Pythagorean theorem:

$$p = \sqrt{\{ L^2 - (\theta \cdot R)^2 \}} \quad \text{[mm]}$$



3a



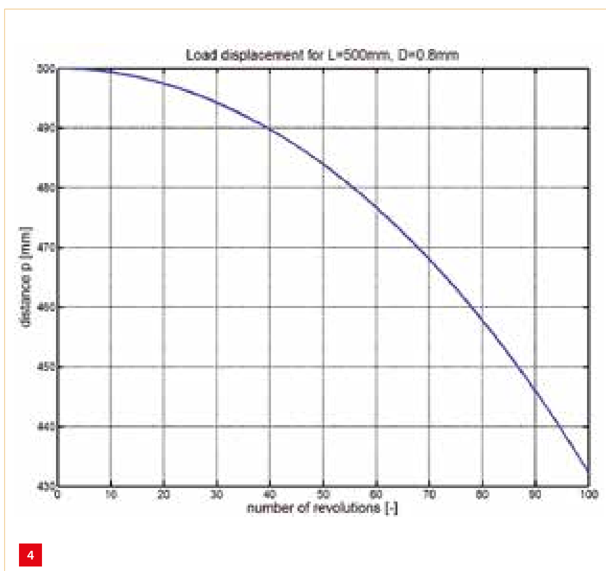
3b

The relation between input angle θ of the motor and linear end displacement *h* (= *L* – *p*) of the load then forms the transmission ratio. This is a non-linear function, starting at zero. Figure 4 shows the (complementary) relation between the number of revolutions *n* of the motor and the distance *p*.

At the same time, the torque T_m from the motor is converted into a pulling force F_s on the strings. The transmission ratio *i* from motor torque to total force for all strings (in our case two) is given in several literature sources, e.g. [1], as:

$$i = F_s / T_m = \sqrt{\{ L^2 - (\theta \cdot R)^2 \}} / (\theta \cdot R^2)$$

The transmission ratio – of any transmission – can be calculated either from displacements or from forces. Due to the law of conservation of energy one ratio must be the inverse of the other. Different literature sources on TSAs either use the one or the other approach. During writing of this article, it was discovered that these do not fully match, due to a linearisation at larger rotation angles. But the results of the tests below will show that there is a much greater difference between the above geometrical 'kinetostatic' theory and the measured characteristics. The first cause of this is that the above theory assumes



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non-deformable strings with constant radius. The following article in this issue will show some of the considerable research efforts in recent years to understand these effects and include them in modelling. The second cause is that gain and offset change over the lifetime of the string is due to wear and 'knitting' effects, as will be shown below.

Test set-ups

In this project, the focus was not on detailed theoretical modelling but rather on testing. Two different types of tests are relevant: functional and endurance testing. A type of test set-up has been designed and built with which both can be performed (Figure 5). With this test set-up the motion cycle of twisting and untwisting the pair of strings can be executed repetitively for a given amplitude, speed and load.

Several groups of students were involved in this process of designing, building and testing. Two similar set-ups were built, at both Saxion and Avans, which were aimed at application in underactuated robotic hands able to pick up objects of about 1 kg. The set-up at Saxion [2] focuses on thin wires and small forces, up to 50 N, while the set-up at Avans allows up to 360 N. Both use the same basic principle which will be explained using Figure 6.

The motor side consists of a DC-motor with encoder which is mounted on the base plate via a flexure guiding. For the Saxion set-up this is a parallel guiding fitted with strain gauges to measure the axial force, and for the Avans set-up a radial guiding fitted with a load cell to measure the reaction torque. The twin strings are attached to the motor shaft via a flexible coupling and axial thrust bearing. An attachment head has been 3D-printed in which the string is looped around a pin. This proved to be adequate to ensure that during endurance testing the string never broke at that point, but always somewhere in between the attachments.

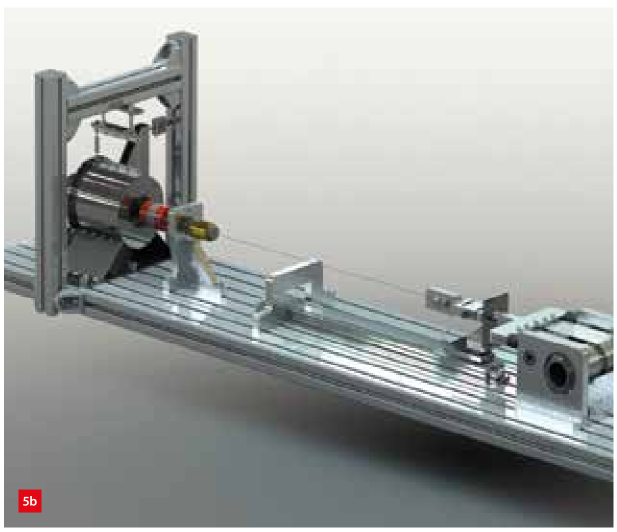
The load side of the test set-up consists of a linear guidance with plain bearing. The friction force of this guidance was measured to be less than 0.5 N. On one side of the carriage the string is attached, again looped around a pin. On the other side a constant tensile load is applied. This is done with a constant-force spring (Avans) or a mass which is attached via a toothed belt (Saxion). The force can be adapted by changing the spring (Avans) or the mass (Saxion). In the Avans set-up the load force is measured during twisting. The displacement of the carriage is measured with a linear encoder (Avans) or a rotational encoder on a toothed belt pulley (Saxion).

A user interface has been made in LabView, with command buttons, numerical output and three graphs for pulling force, motor current and load movement vs motor rotations. It contains manual, automatic and calibration modes. In automatic mode it cycles with user-defined speed and amplitude, to do endurance testing. A cycle storage interval can be set for which multiple points of one motion cycle are stored for post-processing. Of course, the total number of motion cycles is displayed and stored as well.

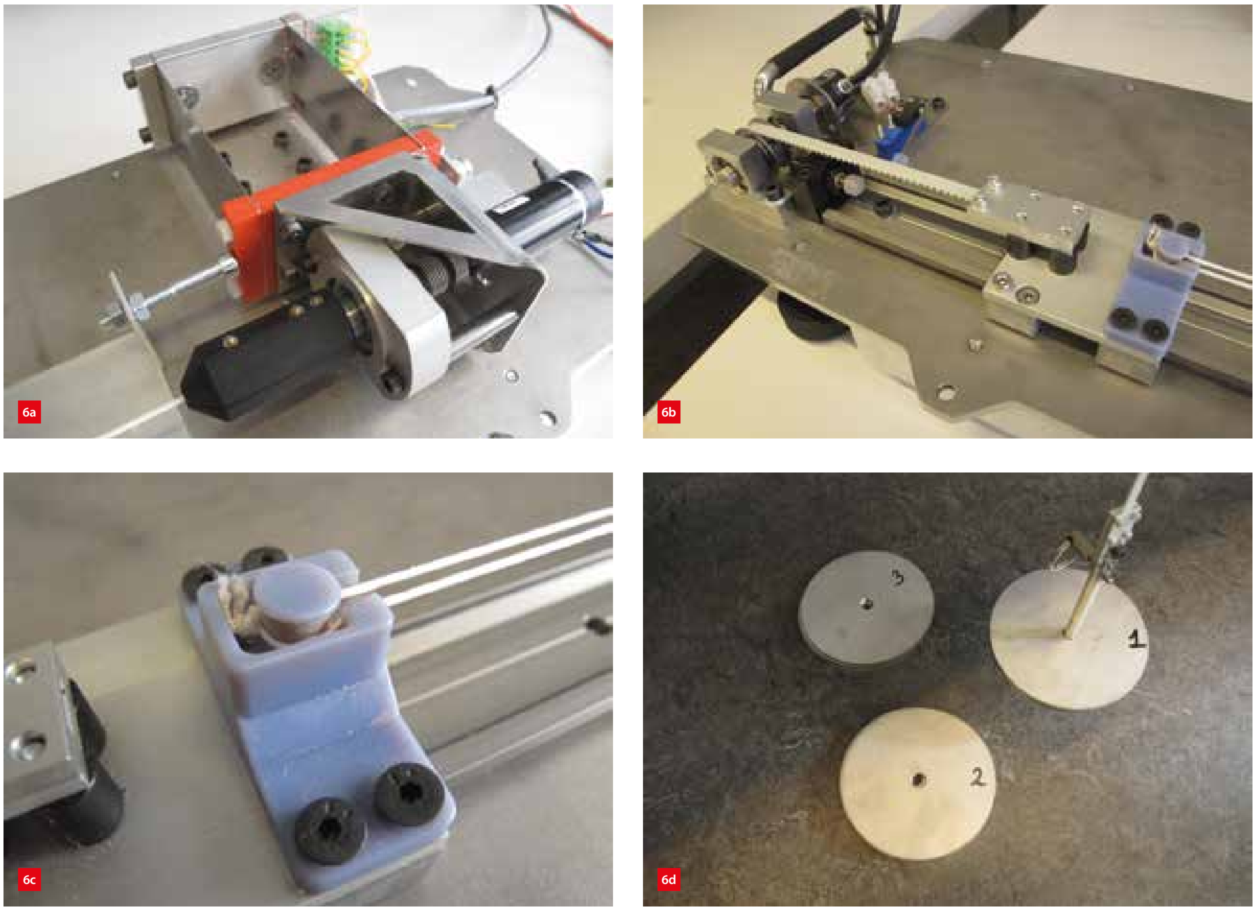
Test procedure

The test starts with cutting the test string to length and creating a closed loop by knotting the ends together. A length of about 1.1 m is used to create a pin-to-pin loop of 500 mm. This is fitted in the test set-up, with the knot behind one of the end pins. The string is rotated manually roughly five turns, to prevent going 'through zero', where the two strings would be parallel, after settling or wear. Initial tests quickly discovered that the twisting is to be done in one direction only, which must be the same as the main twisting direction of the string strands.

When twisted in the wrong direction or going 'through zero' the lifetime of the string is extremely limited, and the



5 *Top view of the TSA test set-ups of the two research partners.*
(a) Saxion.
(b) Avans.



6 *Main components of Saxion test set-up.*
(a) Motor side with flexure guiding and thrust bearing.
(b) Load side with carriage, toothed belt, encoder, end stop and end switch.
(c) String attachment to carriage.
(d) Load disks.

length curve (Figure 4) has a peak at a non-zero number of revolutions, i.e. it gets longer first. Next the load is applied by mass (Saxion) or spring (Avans). This causes straightening and stretching of the string to its 'zero' length, as reported before [3]. It proved to be necessary to do about one hundred motion cycles first to assist this settling. In practice this can only be done after the next step, determining the maximum possible amplitude.

The last step in the preparation is setting the amplitude, which is a fixed number of motor rotations for each test. First, the maximum 'operational' amplitude is to be determined. The maximum 'technical' amplitude is the number of revolutions at which loop knots begin to appear in the string. Some margin to this point is respected: when knots start to appear at e.g. 120 revolutions, then the maximum operational amplitude is set at 100.

Endurance tests are done at this 100% operational amplitude, but also at 33% and 67%. The theory on Design of Experiments (DoE) is being used to determine a number of combinations of load and amplitude which give maximum information from a minimum number of tests. Furthermore, three levels are tested for the load. Including test repeats this is a time-consuming process. Probably, additional tests are still running after the publication of this Mikroniek issue.

After these preparation steps the test can be started. The motor repeats cycles from zero to the maximum number of revolutions and back in about ten seconds at a constant rotation speed, with 'inclined sine' decelerating and accelerating near the turning point to avoid jerks. This was a feature which was added later, but proved not to have much influence. Once in every 1,000 cycles all signals from a full cycle are stored (6 parameters at 36 points). When the string breaks the carriage hits an end switch and the test stops.

String materials and structure

All initial testing to gain experience with the test set-up has been done – cheaply and conveniently – with 0.70 mm multifilament badminton strings. The string filaments are made of Polyamide (Nylon®) embedded in a resin, with sometimes an outer shield of e.g. titanium. The standard 0.70 mm diameter proved to be a good compromise between transfer ratio and relative stroke. A lower diameter gives too low a transfer ratio, resulting in very high motor speeds. A higher diameter limits the relative stroke; we now achieved about 20%, i.e. from 500 to 400 mm, before loop knots started to appear.

But the lifetime of these Nylon strings proved to be too low. Depending on the load and amplitude these strings only lasted several thousands to maximum 20,000 cycles, equivalent to weeks or months of using a robot hand. Most international TSA research now uses Dyneema® as a material, which is an ultrahigh-molecular-weight Polyethylene (UHMWPE). The Dutch company Eurocord can supply a large variety of these strings, and their 0.80 mm DHPS100 line (100 daN breaking strength) was subsequently used here.

Not only the yield strength, but also the stiffness of Dyneema is much higher than that of Nylon: Young's modulus 110-130 GPa, as compared to 2-4 GPa. For a servo-controlled robotic hand this makes it possible to achieve a higher servo bandwidth, while tuning the 'servo spring' still enables compliant gripping strategies.

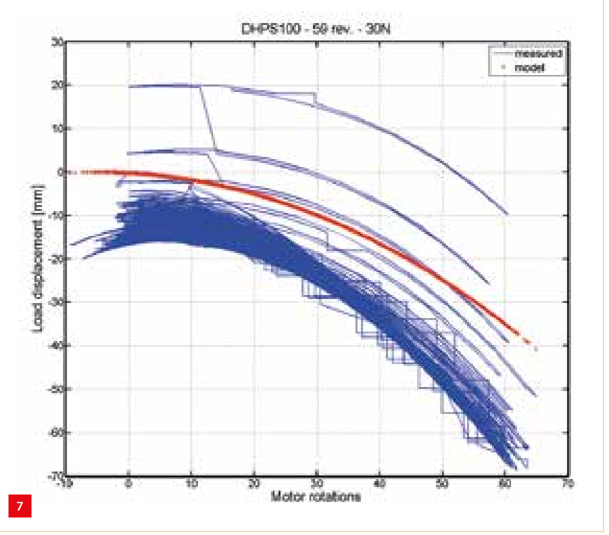
A note about the structure of the string: this must be twined from multiple thin filaments. If a single solid rod were used in the TSA then the torsional stress would be much higher. It can be calculated that a theoretical 500 mm long and 0.8 mm diameter Dyneema torsion rod would have broken long before the typical 80 rotations of the test set-up were reached.

Test results

Tests were performed with a number of combinations of three load levels and three amplitude levels. Aim of the tests was to investigate both the functional and the endurance behaviour of the TSA. A load force of up to 50 N was applied, and a load amplitude up to 100 mm. These figures were chosen with the primary application in mind, for use in an underactuated robotic gripper for care tasks, with one or two TSAs actuating all phalanges. A second transmission ratio of 1:5 between TSA and finger was assumed in the design of that gripper, so that 50 N through the TSA gives a 10 N gripping force. This second transmission will reduce the dimensions of the gripper design.

Figure 7 shows the result for load amplitude versus motor rotations of a typical endurance test. The thin (blue) lines are measured data; the thicker (red) curve is the theoretical model. Initially, the match between measurements and model was worse. Two causes were found for this: horizontal offset and gain. The horizontal offset error is caused by the five turns of pre-rotation described above. The gain error is caused by an effect described by several researchers: when the two strings are twisted they shorten, but at the same time their diameter must increase because the volume stays more or less constant. The initial vertical offset between model and test data is only a matter of zeroing, and hence not relevant.

The measurements directly show the main functional disadvantage of the TSA: a significant drift of up to 30 mm over the lifetime of the string, which is 30/5 = 6 mm at the



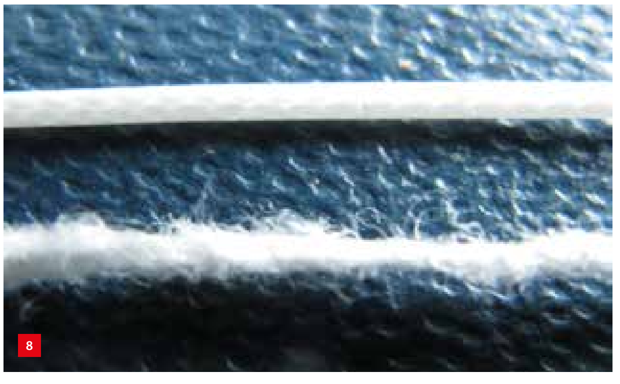
7 *Result of typical endurance test: measured load amplitude versus motor rotations. The model curve is after offset and gain correction. Tested with middle load and amplitude values (30 N, 60 revolutions); string broken after 99,000 cycles.*

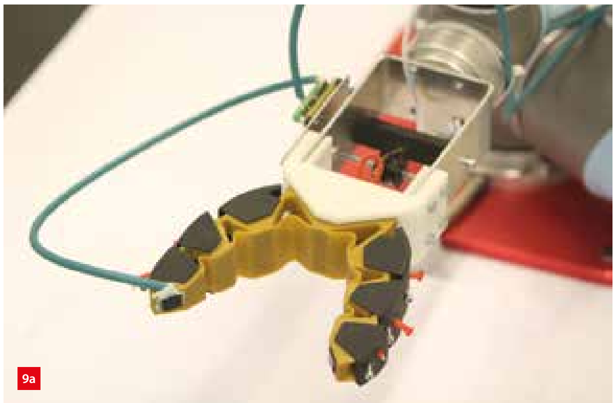
8 *Dyneema string before (above) and after endurance test.*

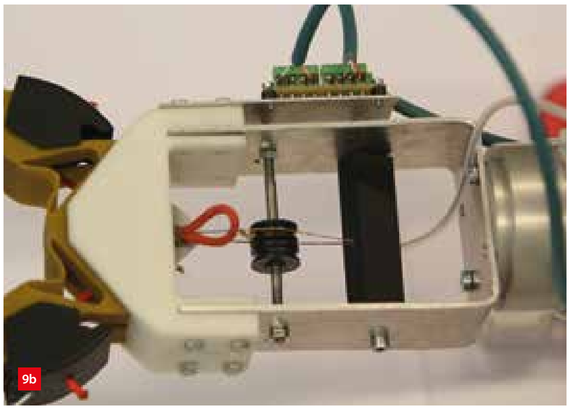
finger tip. During the first 75% of the endurance test the string shortens slightly due to increased 'knitting' of the filaments, causing the blue lines to go downwards. After that it starts to lengthen again when filaments start to break. The highest blue lines in the graph are the last few cycles, when the string is nearly broken. This lengthening may be used to signal that end of life is approaching. Figure 8 shows a Dyneema string before and after testing.

The Nylon badminton strings showed far less drift than the Dyneema strings, so this effect may be reduced with further development of string materials or filament structure. With the present drift regular zeroing or load position feedback will be necessary to achieve acceptable performance with 1-2 mm position reproducibility at the finger tip.

The number of cycles until the DHPS100 Dyneema string broke varied between 20,000 and 200,000 for the different combinations of load and amplitude that were tested. For application in a care robot gripper this is still quite low. If one assumes that a user makes 1,000 gripping actions per day, then the average lifetime of 100,000 cycles is still only 100 days of use. So, force and amplitude will have to be limited further in relation to length and diameter of the string to increase the lifetime.







9 *Details of integrated test set-up of Avans.*
(a) Monolithic gripper with microslip sensor feedback to grab objects with the least required force.
(b) Connection of twisted string with gripper tendon.
(c) TSA motor mounted at a distance from the gripper on UR5, the strings entering a Teflon tube.

Evaluation

The TSA has a number of disadvantages:

- An unsafe situation may occur when the string breaks, which is not unlikely given its limited lifetime.
- The string can only transfer forces in one direction. No push-pull or pre-tensioning is possible to increase stiffness or compensate for backlash. If a return-spring is added then more energy is used.
- The non-linear transmission ratio is progressive, i.e. with increasing stroke of the TSA the output speed increases and force decreases. This can be a disadvantage but also an advantage: a digressive characteristic would be preferable to limit contact speeds with a gripped object, but a progressive characteristic gives lower contact forces.

Note: some of these disadvantages also apply to other transmission principles, like the Bowden cable (invented as a bicycle brake cable), a type of flexible cable used to transmit mechanical force or energy by the translational movement of an inner cable relative to a hollow outer cable housing (according to Wikipedia).

However, whether or not these disadvantages outweigh the many advantages depends entirely on the application and design constraints. The TSA principle does uniquely offer a cheap, light, compact, bendable and silent transmission with a high transmission ratio.

The only alternative which is similar, from both a technical and functional point of view, is the Bowden cable. The main technical difference with the TSA is that the Bowden cable – usually made of steel – is used in tension only, not in a combination of tension and torsion. Therefore, the lifetime of the Bowden cable will certainly be much higher. The main functional difference with the TSA is that the Bowden cable does not provide an integrated transmission ratio. Unlike the TSA the Bowden cable is already used in commercial robot systems like the Intuitive Surgical Da Vinci and the Shadow robot hand. These are complex and expensive systems with joints that can be controlled individually.

Looking at the advantages and disadvantages of the TSA, it appears to be most suited for much cheaper robot grippers, costing only a few 100 Euros. This can be an underactuated gripper with just one TSA, or a life-size multi-finger gripper where each finger is to be actuated individually. Figure 9 shows details of the gripper in the integrated set-up of Avans already shown in Figure 1. This gripper was designed to be cheap and simple, with just a single TSA. In order to determine the string dimensions for sufficient lifetime more testing is needed.

The most important results from this project are that test set-ups have been realised to do these lifetime tests, and insight has been gained in the parameters which influence the functional and endurance properties. The fact that the TSA is not yet commercially used does not mean it is not viable. So, if there are companies out there with ideas for applications they are invited to contact the authors. ■

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UPCOMING **EVENTS**

18-19 May 2017, Aachen (GE)

29th Aachen Machine Tool Colloquium

Since 1948, the Aachen Machine Tool Colloquium has given trend-setting impulses for production technology in a 3-year cycle. The general topic of AWK 2017 is "Internet of Production for Agile Enterprises".

WWW.AWK-AACHEN.DE

29 May - 2 June 2017, Hannover (GE)

Euspen's 17th International Conference & Exhibition

This event will once again showcase the latest advances in traditional precision engineering fields such as metrology, ultra-precision machining, additive and replication processes, precision mechatronic systems & control and precision cutting processes. Furthermore, new topics will be addressed covering the revision of the SI and applications of precision in biomedical sciences.

WWW.EUSPEN.EU

31 May - 1 June 2017, Veldhoven (NL)

Materials 2017, engineering & technology

Trade fair, with exhibition and lecture programme, targeted at product developers, constructors and engineers. The focus is on properties - applications - solutions.

WWW.MATERIALS.NL

14-15 June 2017, Veldhoven (NL)

Vision, Robotics & Mechatronics 2017 / Photonics 2017

Combination of two events organised by Mikrocentrum (Photonics only on 14 June).

WWW.VISION-ROBOTICS.NL
WWW.PHOTONICS-EVENT.NL

20 June 2017, Veldhoven (NL)

Meten 2017

Seminar on measuring organised by Mikrocentrum. Topics include measurement strategy, measurement uncertainty, form and position tolerances, reading drawings, and normalisation/standaardisation.

WWW.MIKROCENTRUM.NL

20-22 June 2017, Erfurt (GE)

Rapid.Tech

International trade fair and conference on additive manufacturing.

WWW.RAPIDTECH.DE

29 June 2017, Enschede (NL)

Medical and Modular Robotics

Mechatronics Forum organised by the Saxion Research Group Mechatronics. Presentation of the results from the RAAK PRO project Medical Robotics, in which Saxion and Avans Universities of Applied Sciences, Roessingh Research & Development and University of Twente collaborated with Mecon Engineering, Demcon and Focal Meditech on developing knowledge for the building blocks of a mobile robotic platform for elderly care.

WWW.SAXION.NL/MECHATRONICA

4 October 2017, Bussum (NL)

15th National Cleanroom Day

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

WWW.VCCN.NL

10-12 October 2017, Leuven (BE)

Special Interest Group Meeting: Additive Manufacturing

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

WWW.EUSPEN.EU

10-12 October 2017, Karlsruhe (GE)

DeburringEXPO

Second edition of trade fair for deburring technology and precision surface finishing.

WWW.DEBURRING-EXPO.COM

23-26 October 2017, Aachen (GE)

Optics & Optomechanics Week

A unique collaboration by Dutch, German and international organisations comprising the DSPE Optics and Optomechanics Symposium & Fair on 23 October, the Optomechanics course by Dan Vukobratovich on 24-25 October, and the Course on Optical Design of Imaging Systems on 24-26 October.

WWW.OPTICSWEEK.NL

24-26 October, Stuttgart (GE)

Parts2clean 2017

International trade fair for industrial parts and surface cleaning.

WWW.PARTS2CLEAN.COM

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

32th ASPE Annual Meeting

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

ASPE.NET

ACTUATORS WITH A TWIST

(Source: IROS 2016)

One of the workshops of the 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2016, 9-14 October, Deajeon, Korea) was specially devoted to twisted string actuators, or TSAs. The workshop brought together researchers working on twisted string actuation, engineers from industry, and scientists with experience in the areas of mechanism design as well as compliant and flexible actuators.

ERIC KIVITS

The main target of the workshop was to present the current state of the art and the future trends in modelling, control and applications in the area of twisted string-based actuators and transmission mechanisms. The workshop also aimed to instigate knowledge sharing inside the engineering and research communities and to outline main future directions and issues of the novel mechanisms. For an introduction into TSAs, refer to the preceeding article: "Twisted String Actuator – A transmission principle for robotic devices".

Michael Stevens from US-based SRI International presented the use of TSAs in soft exosuits for human augmentation, i.e. conformal robotic clothing to reduce fatigue and enhance strength [1]. The intended applications are within the fields of healthcare, rehabilitation, and elderly and child care as well as in the military. One characteristic of their FlexDrive (Figure 1), a TSA-based linear actuator, is that it is lighter than a conventional ball-screw actuator at less than 0.4 kg, yet can produce 1,000 N of force and withstand 300 W of peak work.

The continuous work consumed by the system averages 65 W per actuator, which is ample for the application of human augmentation. Nonetheless, the same fibre drive can run at very low power levels and maintain high efficiency (> 90%), making it ideal for reducing metabolic cost while walking under a heavy load. For more dynamic situations in heavier load cases, another actuator was designed for use on exosuits capable of running and jumping. These requirements pushed the design of a new TSA capable of handling over 2,000 W of peak power and producing 2,900 N of force for less than 1 kg in weight. SRI claims that these actuators (Figure 2) have shown lifetimes of over one million cycles.

Kyung-Soo Kim from the Korea Advanced Institute of Science & Technology presented a dual-mode twisting actuation mechanism (Figure 3) [2]. Two TSAs are combined in a compact superposition mechanism having two transmission ratios, one for 'speed mode' and the other for 'force mode', applied in a robotic hand. The return motion is forced by a spring via an antagonistic cable.

AUTHOR'S NOTE

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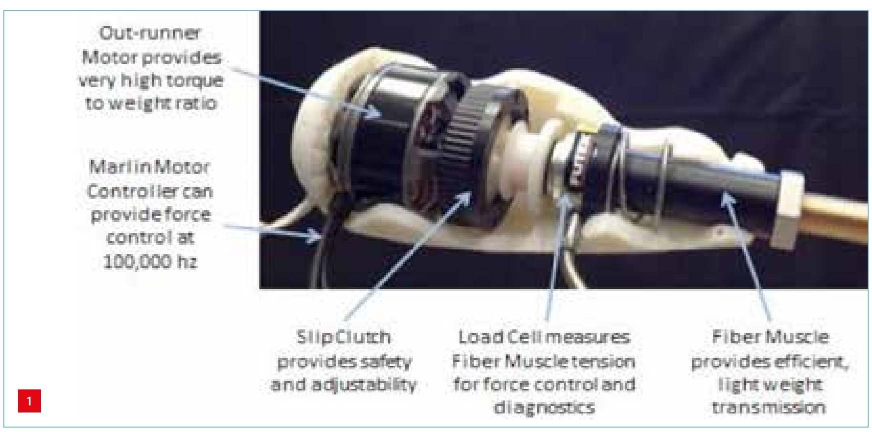
1 *Flexdrive 1.0: single-motor TSA design with slip clutch, force sensor, and return spring. [1]*

2 *Evolution of TSAs on exosuits. [1]*



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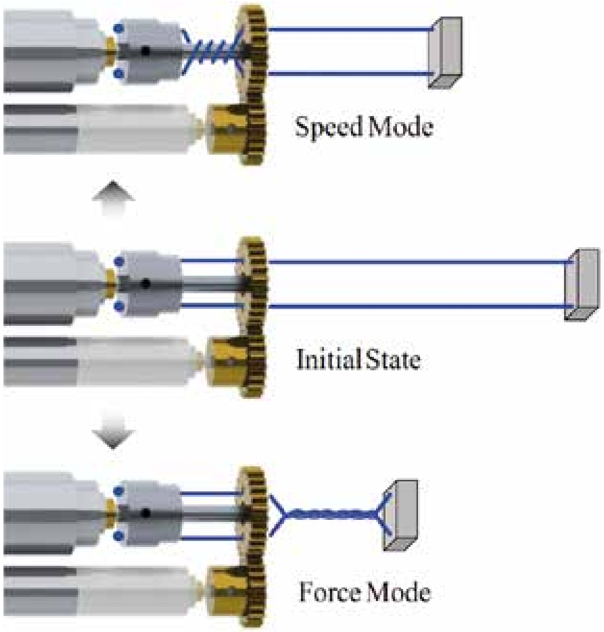

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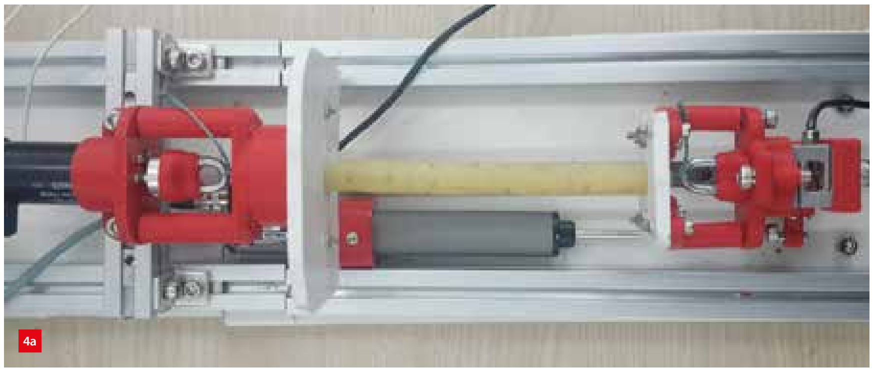

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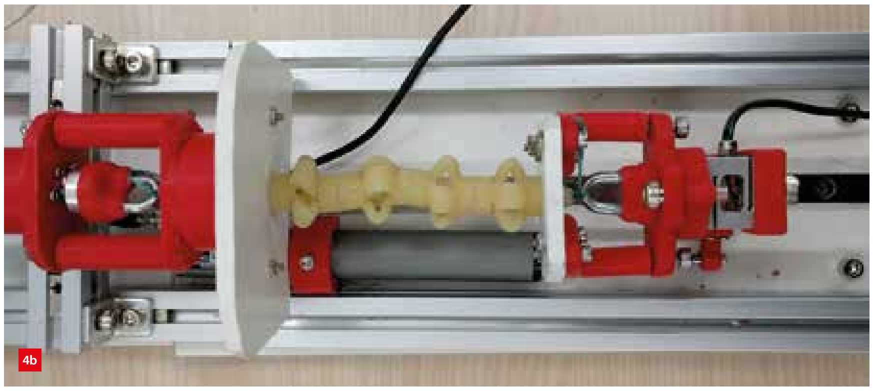

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3 *Dual-mode twisting actuation mechanism. [2]*

4 *Soft-buckling bidirectional TSA in operation. [3] (a) Extension. (b) Contraction.*

5 *Schematic representation of the rotative joint with two twisted string transmission systems. [5]*

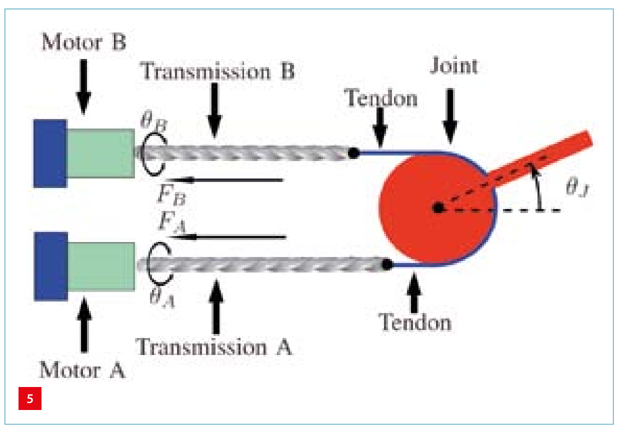
Igor Gaponov and Jee-Hwan Ryu from the Korea University of Technology and Education presented studies on several topics: the lifecycle of TSAs; twisting inside a Bowden cable; and a bidirectional TSA [3]. They are currently formulating a mathematical model which will describe the lifecycle of the TSA depending on the properties of the strings as well as environmental and working conditions. Having such a model will alleviate the need to conduct extensive experimentation for each new string and will hopefully allow to predict the lifecycle of the strings if all parameters are known.
Another field of their research is the behaviour of a twisted string inside a Bowden cable housing (jacket). Hysteresis caused by friction of a translating string inside a Bowden cable housing severely restricts the use in applications where large misalignments between the actuator and load side are present. This is also the case when twisting such strings inside a Bowden cable housing; however, first results show that the virtual play of the load position seems to be somewhat lower than without twisting.

Due to the non-linear nature of string twisting, two twisted strings cannot be connected to the same motor for bidirectional actuation. To solve this issue, they presented an idea to passively return a TSA by means of a buckling structure with a constant returning force, allowing for a bidirectional positioning of a load driven by one motor (Figure 4). The resulting mechanism is more compact than an antagonistically placed cable around a capstan.

The author briefly presented the work in progress at Avans University of Applied Sciences, The Netherlands, as described in the preceeding article.

Takahiro Inoue and Shinichi Hirai of Okayama Prefectural University, Japan, discussed their work on a novel joint mechanism composed of an antagonistically-twisted round-belt actuator, which is able to make a rotating motion by means of contraction forces induced by twisting small-diameter elastically-deformable round-belts [4]. They discovered that a traditional simple proportional controller is stable enough for force feedback strategy to achieve positive results. The negative physical properties of round-belts do not influence the control performance.

Gianluca Palli showed the results of the TSA research activities at the University of Bologna, Italy [5]. First, the stiffness variability in robotic joints actuated by two TSAs in antagonistic configuration has been analysed and the practical implications on the control of these devices were studied (Figure 5). Second, to overcome the limitation of



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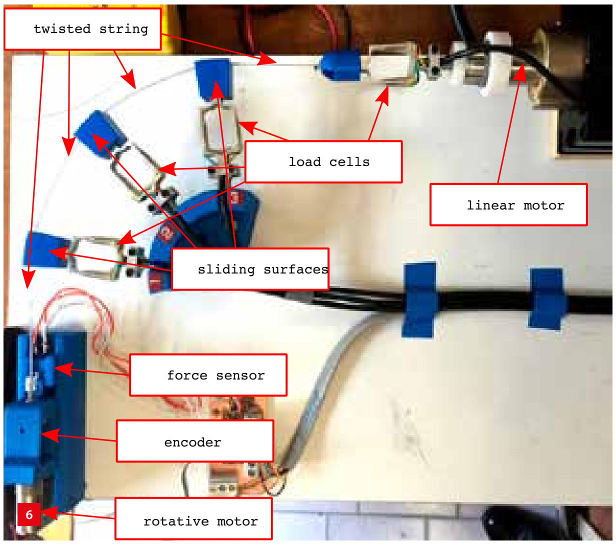

6 *Experimental set-up of the TSA guided by Teflon tube and environmental constraints. [5]*

7 *High-speed twisted string actuated applications. [6] (a) Stereo camera. (b) Robotic hand.*

keeping the twisted strings arranged in free space and in straight configuration, i.e. without any contact with the environment, the effects of friction on the string twisting and transmission system behaviour have been investigated by means of both mathematical modelling and experimental validation (Figure 6).

Ivan Godler of Twist Drive Technologies from Japan presented a paper on the basic findings in modelling of twisted string actuation [6]. The kinematic relation between motor angle and driving distance was derived, and a suggestion to improve nonlinearity in a robotic joint was presented. Various materials of strings were tested for durability, showing UHMWPE having the longest life span. Applications of twisted strings actuation to a robotic hand, to a fast-moving stereo camera, and in a high-precision angular positioning device were presented (Figure 7).

Disney Research also showed interest in the application of TSAs in robotic muscles, mainly because of the lack of noise during operation, which may prevent breaking the spell of spectators [7].

Conclusion

All participants agreed that the main challenges to focus on in the coming years are the further improvement of the mathematical model and the durability of TSAs. The advantages of TSAs especially in robot applications are encouraging enough to keep up the good work. ■

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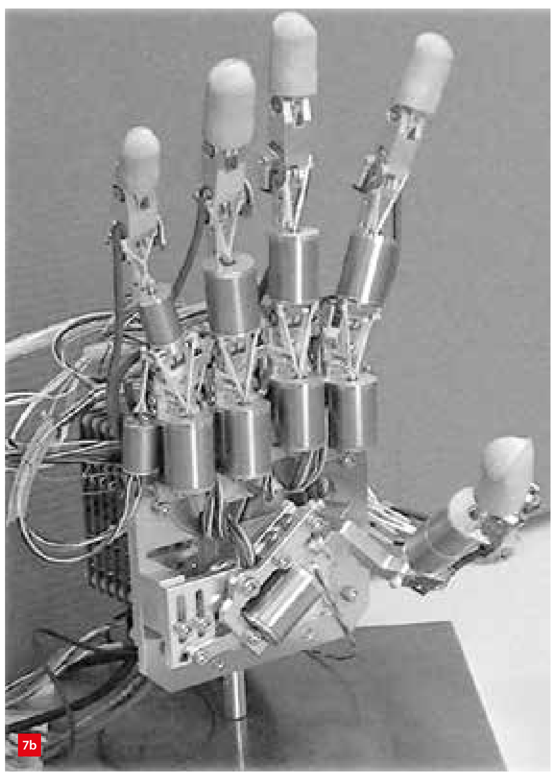

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IROS 2017

The 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2017) will be held in Vancouver, Canada, September 24–28, 2017.

WWW.IROS2017.ORG

INFORMATION

WWW.IROS2016.ORG

ROBOTICS SEEN FROM A HUMAN PERSPECTIVE

"Living and Working With Robots" was the overall theme of the European Robotics Forum 2017. European robotics research is now creating robots that are leaving the lab and entering the real world. The aim of ERF was to be not just a technical conference, but to bring together everyone interested in robots and examine how they will interact with business and society. This account will highlight notable presentations and discussions that concerned the human perspective in robotics.

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The European Robotics Forum (ERF) is the annual meeting organised by SPARC, the public-private partnership of the European Commission and the euRobotics Association. One of the aims of SPARC is to develop and implement a Strategic Research Agenda, leading to a Multi-Annual Roadmap (MAR) which includes topics such as seamless human-robot interaction. The Robotics 2020 MAR is referenced in the European Horizon 2020 programme. ERF 2017 was held in Edinburgh, Scotland, from 22 to 24 March, attracting some 850 participants (Figure 1).

1 *Venue for ERF 2017 was the Edinburgh International Conference Centre. (Photo: David Barbour)*

Standardisation

One of the workshops at ERF 2017 was dedicated to standards and standardisation for robots, organised by the euRobotics Topic Group Standardisation and the H2020 coordination action RockEU 2, and presented by Theo Jacobs of Fraunhofer IPA. The information came from the ISO TC299 technical committee. Safety standards reduce the legal risks for manufacturers and enable the development of new, innovative robotic products. Additional standards, e.g. for performance measurement and interoperability, foster sustainable market growth.

Despite their great importance, awareness of standards and willingness to participate in standardisation are rather low in the European robotics community.

Key points from the discussion (taken from the workshop report):

- For the safety of software, existing standards like IEC 62061 or IEC 61508-3 are considered outdated, as they do not include new programming paradigms.
- Software security is an increasingly important topic. However, traditional safety standardisation working groups exclude the topic from their scope.
- Interaction with standardisation committees from other domains should be sought. The automotive industry is now fast developing towards autonomous systems and is also experimenting with AI (artificial intelligence). Other interesting domains are AGVs (automatic guided vehicles) and IoT (internet of things).
- Teaching students how to use standards and how to perform a risk assessment, should receive more attention. However, the theory is often "boring students to death". Better guides to standards would be welcome. [At Fontys, experiences with teaching robot security are more positive; companies appreciate the effort, and students enjoy – after a short theoretical introduction – working on practical assignments.]
- Also for SMEs, simplified guides to safety standards, possibly containing example applications and videos, would be helpful.

Social robotics

The session on social robots featured a large number of robots that operate in public areas like shopping malls, airports or hospitals. Presentations included robots like Pepper (of Japanese company SoftBank Robotics) and Spencer (Social situation-aware PErceptioN and action for CognitivE Robots, developed in an EU-funded project and tested at Amsterdam-Schiphol Airport), projects like Mummer (Multi-modal mall entertainment robot), and R&D companies like MetraLabs (developer of professional mobile service robots, from Ilmenau, Germany; Figure 2) and PAL Robotics (Barcelona-based "Leading humanoid robotics research for the real world").

The discussion made clear that there is considerable demand for insights and knowledge concerning normal human behaviour. For instance, how people interact with social robots, and why children want to play with robots not intended for play. TRL (Technology Readiness Level) is lower than people expect. Humans usually see robots as animate (theory of mind, anthropomorphism). The robot design can increase such expectations unintentionally, e.g. by using humanoid features like limbs or eyes. We should be aware that 'social' does not equal 'humanoid', and that communication does not only take place through language.

Furthermore, the purpose or relevance of social robots should be considered more than it is at present. Instead of being used for entertainment, meaningful uses may be highlighted like social robots as assistive technology for the elderly. Last but not least, talking with and involving end-users of robot technology is important. We should ask them what they actually want or need and how they experience robot technology.

In the session on empathic human-robot interaction the main issue concerned the minimal signals humans need to interpret robot behaviour. Models from cognitive science and psychology should be used to help roboticists predict what will work or not and what will facilitate interaction. The question was raised why empathy is deemed necessary. Maybe it is not so much about empathy as it is about well-being and ease of use. From the discussion it became clear that safety will still take precedence over empathy during the coming few years. Nevertheless, it is important to consider 'good' robot behaviour, e.g. a co-bot (collaborative robot) asking for screws, when running out of them, in a nice manner.

2 *MetraLabs produces professional mobile robot platforms and implements service robot installations.*

Elisabeth Schärtl of KUKA, the German robot manufacturer, discussed the influence of industrial robots on human beings, going beyond technical requirements. KUKA's research includes interviews with the end-users. KUKA is especially interested in who is using robots and what will change when co-bots are introduced on a large scale. At the moment, it is mainly people helping and serving the robot, but changes are to be expected with co-bots.

Ethics

"Should society be afraid of robots?" This question was raised by Vincent Müller (University of Leeds). "The emergence of new technologies, such as robotics and artificial intelligence, causes a vast amount of discussion and even fears about the consequences of their usage and appearance." He pointed out that ethics is a branch of philosophy, with robot ethics being a subcategory within ethics.

Alan Winfield, Bristol Robotics Lab, talked on the IEEE global initiative for ethical considerations in the design of autonomous systems. Every technologist should be trained to prioritise ethical considerations in the design of autonomous and intelligent systems. He stated that we should be moving from benefit towards well-being and that the concept of 'success' should include ethical values.

The need for an ethical framework, as advocated by the European Parliament in 2015, was discussed. Human privacy and frailty should be considered. Therefore, transparency in the programming of robotic systems is required, which can be achieved by reflective design.

A presentation was given of the REELER initiative, Responsible Ethical Learning with Robotics, which specifically focuses on the alignment of roboticists' visions with empirically-based knowledge of human needs and societal concerns. REELER uses an anthropological approach to the design of robots. In this way human-robot interaction is studied from a wider perspective and takes into account a diversity of affected stakeholders. It was stressed that the design process should include the end-users and this not just from a strictly functional point of view.

Artificial intelligence

Raia Hadsell of London-based DeepMind, a leader in artificial intelligence (AI) research and part of Alphabet (Google) since 2014, delivered a keynote speech on deep learning. She discussed the recent history of deep learning as well as recent developments such as the Deep Net and the possibilities of reinforcement learning. Finally, she suggested two methods to speed up deep reinforcement learning for robots: training in simulation, then transfer to the real robot, and progressive neural networks. Her presentation made good use of what we know on human learning and can be used to make progress in the area of machine learning.

Technologies like AI have the promise of making robots smarter and more autonomous to support people. In order to make robots robustly adaptive to the environment, a hot topic is to integrate (more) AI and internet of things applications with robotics. The EU recently started an initiative to anticipate future developments in this area. The focus would be on the ethical and legal issues involved (with AI), the tools, and the creation of a platform for sharing research/tools in this area. What is missing in this initiative is a compositional framework/architecture for robotics where these AI-related tools would fit in.

Regarding the application of AI in industrial robotics, a large number of priorities were listed:
- Safe operation
- High-level instruction and context-aware task execution
- Knowledge acquisition and generalisation
- Adaptive planning
- Personalised instruction
- Self-assessment
- Learning from demonstration
- Evaluating safety of actions
- Development and self-optimisation
- Knowledge transfer
- Communicating intention and collaborative action

Conclusion
It was to be expected that the European Robotics Forum 2017 would mainly be focused on current technical challenges. For instance, safety is mainly seen as a technical and physical issue. Questions posed concerned, for instance, the force a robot may apply in the presence of humans or which are our most vulnerable body parts. Nevertheless, there also was some attention for the human perspective and user experience issues. Though technical perspectives remain important, robotics is clearly in need of more input from the social sciences. And a lot of human intelligence will still be required.

Horizon 2020: ROS-Industrial

One of the ERF 2017 sessions included presentations of sixteen Horizon 2020 projects, covering a variety of fields: healthcare, manufacturing, civil, commercial, logistics/transport, and community service/coordination. The latter category featured the recently launched ROSIN project (ROS-Industrial quality-assured robot software components).

Open-source software for robots is a de-facto standard in academia, and its advantages can benefit industrial applications as well. The worldwide ROS-Industrial initiative has been using ROS, the Robot Operating System, to this end. In order to consolidate Europe's dominance in advanced manufacturing, ROSIN will push the role of the EU within ROS-Industrial to a leading position, through three main actions on ROS: ensuring industrial-grade software quality; promoting new business-relevant applications; supporting educational activities for students and industry professionals.

The partners need to answer two questions on the suitability of open-source software for manufacturing. The first one is about software quality, which has to conform to industrial requirements. To ensure this, ROSIN introduces a break-through innovation in automated code quality testing, complemented with quality assurance measures including novel model-in-the-loop continuous integration testing with ABB robots. The second question focuses on the level of industrial interest in Europe towards open-source software and the opportunity to further invest in it.

The ROSIN project is coordinated by TU Delft (the Netherlands), and further partners besides Fraunhofer IPA (Germany) are the IT University of Copenhagen (Denmark), the FH Aachen University of Applied Sciences (Germany), Fundacion Tecnalia Research & Innovation (Spain) and ABB (Sweden). A considerable part of ROSIN's budget (in excess of 3 million Euros) is reserved for co-financing Focused Technical Projects (FTPs) for developing ROS applications. The call is open.

ROSin

WWW.ROSIN-PROJECT.EU

INFORMATION
WWW.ERF2017.EU
WWW.EU-ROBOTICS.NET

AUTONOMOUS MOBILE ROBOTS IN MANUFACTURING AND CARE

Whether it be in industrial companies or hospitals, goods need to be moved around. In almost all cases, humans either push or pull a trolley, or carry the goods themselves. These are examples of where we will investigate a systematic implementation of autonomous mobile robots. Our vision is that autonomous robotics will change internal logistics drastically in the coming years. Personnel will still be needed, however – in a different, albeit natural, role of managing the mobile robot fleets.

HENK KIELA

We all are familiar with the way goods are moved around in hospitals and industrial companies. One typical characteristic is that in almost all cases, humans push or pull a trolley, or carry trays or the goods themselves. The trolleys are often specially designed to carry patient meals or to have bins with parts for a production order. They also often carry many items, in order to have some stock in production to minimise movement. Sometimes the destination is a fixed location, such as a manufacturing machine, or there may be many locations where the goods are delivered or served, such as in a hospital.

Quite a few companies now develop mobile robot systems for use in industrial companies and service organisations. Knapp in Austria supplies small autonomous mobile robots and large pallet movers in combination with their fully automated storage systems for industry and warehouses. MiR, Omron/Adept and TUG offer more-or-less standard solutions for various payloads, mostly in a range of 50-80 kg. Then there are suppliers of OEM solutions for autonomous navigation and fleet management, like Blue Botics and Navitec. From these varied offerings, system integrators like Probotics can select a suitable solution for each individual customer.

Mobile robot logistics and fleet management for mobile robots are a new modality to connect isolated locations to form a flexible and integrated manufacturing environment or service operation, where professionals can be relieved from moving goods.

Internal logistics

When observing the movement of goods in an organisation, the internal logistics in (SME) manufacturing companies, hospitals, elderly homes and logistics centres can be compared.

Industrial SMEs

In most larger companies with large-scale production and limited variation in products, fixed mechanisation has often been realised with belt- and conveyer-systems. In many smaller companies, the product mix is larger and production volumes per order are generally lower. Goods in this kind of industry are often moved by people, in many cases by the machine operators who prepare their machine and workplace for a new work order. These companies need flexibility to move from one production order to another. Investing in mechanised transport systems like belts and industrial automation is often not economically viable, so goods are moved by the operators, forklift operators or logistic employees.

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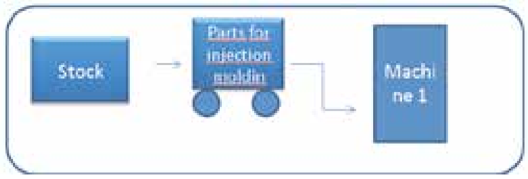
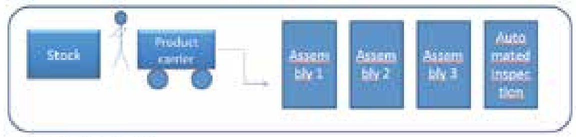


1 *Logistics for a single production step.*



- Loading parts (semi-)automatically on a robot carrying a product holder.
- Driving the robot with product holder to first assembly station.
- Processing on station 1.
- Repeating steps for other work stations, including inspections.
- Returning finished product to stock.

2 *Logistics for multiple production/assembly steps.*

Take the example of a metal part that has to be moulded into a plastic part in an injection moulding machine (Figure 1). To start a production order, raw materials, parts and probably tooling need to move from stock locations to the machine. The operator collects the parts and tools at the central store near the shop floor. The tooling has to be mounted on the machine by the operator. The machine settings must be loaded and tested, and some test parts will be produced to confirm everything.

Then production can start. Every 20 seconds, a metal part has to be taken from a bin, put into the machine, a button pressed and then 20 seconds later the completed part can be taken out of the machine and thrown in another bin. After two hours, the bin with bare metal parts is empty and the receiving bins are full. The machine is halted for 15 minutes to swap bins with the central store.

Two cases for mobile robots can be observed here, to increase operator productivity and to enrich the work of the operator:

1. Mobile robots could bring new parts to the workstation and take completed parts at more frequent intervals than two hours, relieving the operator from routine work and increasing machine run-time. Another benefit would be the possibility of checking the quality of the finished products every 30 minutes, rather than once every two hours, thus improving quality assurance.
2. The operator's action, of putting a metal part from the bin into the machine and 20 seconds later taking that part to put into another bin, could be easily automated with robot arms that only need to be configured once by the operator for bin picking, etc.

What would this mean to the operator? Would he lose his job? Or does his role merely change to that of a supervisor, in charge of setting up the process on a machine and overviewing the automated supply and handling of parts? Although today's technology offers a lot more than a few years ago, the operator will still need to 'fix things' every now and then. Nevertheless, the operator would now have the time to, for example, set up another moulding machine for a second production order. He would spend most of his time on what he is good at, i.e. setting up equipment and processes.

In practice, most products are manufactured in more than one production step, which means that parts have to be moved to another production location instead of to stock (Figure 2).

Using mobile robots to transport goods offers another benefit over classic production. Because smaller quantities can be moved from one station to another, overall lead times can be reduced, improving performance in delivery time to the customer.

Hospitals

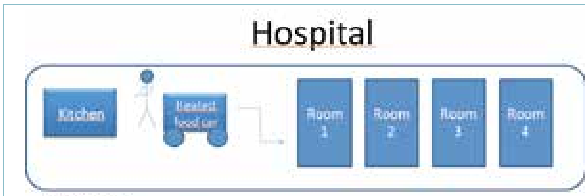
A service organisation such as a hospital faces different challenges to those of industry. Food distribution, for example, must be achieved within a certain time frame, taking into account freshness, temperature, and individual wishes and menu choices.

Mobile robotics can help to improve the speed and quality of food distribution, because portions can be split over smaller robotised carts. The distribution system on the cart can be filled in the kitchen on an individual basis per patient/client (Figure 3). As food is distributed more quickly, the time that food carts are moving on the floor is reduced.

Similar benefits can be seen for linen and medicine distribution. Scheduling goods movement to clients and bed locations would be easy to implement with mobile robots, leaving less room for errors in medicine distribution and fewer carts on the floor for linen distribution. More research will be done with hospitals to investigate in more detail how internal logistics, service to clients and quality of work for personnel would benefit from the deployment of mobile robots.

Economic benefits

In Western Europe, we generally recognise the need to improve our productivity to keep up with global competition. More work needs to be done by the same number of people. Cost of services and goods have to



- Manual loading in kitchen according to order list.
- Driving the trolley to the first location.
- Distributing various meal orders to room after room using delivery list.
- Returning empty trolley to kitchen.

3 *Logistics for food distribution in a hospital.*

go down. At the same time, it becomes harder to attract sufficient skilled people. In Europe, an estimated 20-30% of precious professional labour time is spent (or wasted) on logistics movements inherent in the execution of the work that really needs be done.

Suppose autonomous robots could take over half of the logistic tasks currently done by workers; this would result in a productivity increase of 5-10%. Of course, walking around with a trolley can provide some freedom and an opportunity for social interaction for staff. However, having logistic tasks done by robots can also provide more freedom and social interaction time.

Currently, however, all these logistic movements do have a few unwanted side effects that introduce hidden costs and reduce flexibility, such as higher floor space claims for temporay storage of goods, health risks for workers due to overloading trolleys for efficiency reasons, and safety risks due to incidents with a trolley.

State-of-the-art logistic robotics

The same technology that enables electric cars and autonomous driving functions in cars also pushes autonomous mobile robot technology. Mobile robot applications now suddenly appear feasible for a number of reasons:

- Sufficient embedded calculation power has become available at a reasonable price.
- Sensor technology has increased greatly in the past five years. An example is intelligent vision systems with embedded processing capable of scanning the mobile robot's environment to navigate and avoid obstacles.
- Mobile power, i.e. battery technology, has improved dramatically the last three years.
- New safety regulations for service robots (ISO 13482) provide guidance to robot designers. Although this standard is intended for a rather new category of service robots, it may be used as well in other domains, like industry and care, as long as specific standards for service robots in those areas have not yet been published.

Business case

The first question a solution provider has to answer for a potential customer – based on a study of actual goods movements – is whether there is a business case for mobile robot deployment, including:

- the integration of mobile robots with their destinations and pick-up locations;
- the integration of the mobile robot fleet into a planning system;
- the integration of the mobile robot fleet with a variety of building-specific elements like automatic doors, elevators, crossings with other traffic, etc.

It should be kept in mind that customers are not aware of the hidden logistic cost in their operation. Every logistic movement of goods, whether a single bolt or nut or a whole pallet, costs on average an estimated five to 10 euros. When a single mobile robot costs between five and 20 euros per hour, only a few robotised goods movements are needed to break even. The case will, of course, be more complicated in practice. Robots in a fleet can easily do more jobs in an hour, but on the other hand, big quantities of goods would need to be broken up into smaller chunks to be transported by mobile robots. Doing a simulation of robot fleets and routes in a production environment can prove useful in detecting bottlenecks in the routing, determining the required size of the fleet and providing evidence for the degree of service in various production scenarios.

Integration of robot and docking station

The basic function of a robot is to take goods from A to B. The first challenge is how to get the parts on board and drop them off at the destination. It seems very unlikely, even undesirable, for a human to be present at both locations, so the robot system needs to have an automatic on/off loading mechanism that hooks on to the docking stations at the pick-up and delivery location. Examples of standard robots for these tasks (Figure 4) generally are capable of carrying up to 50 or 100 kg of payload.

The selection of one or more standard-sized bins and pallets for transport of parts in production and automated storage may provide the first moment for a customer to change his way of thinking about internal logistics. Choosing a standard pallet may result in transport with partially filled trays, which might seem suboptimal, but these standard pallets can be moved and stored anywhere in the production using automated storage and mobile robots. Now, a product or production order can 'find' its own way in production by 'directing' a mobile robot to the next workstation.

4 *Robots for goods pick-up and delivery.*

All currently available mobile robots have a limited accuracy for docking (Figure 5). In general, the standard repeatability of a mobile robot equipped with odometry (position determination by velocity integration) and a standard lidar (laser imaging detection and ranging) is best case +/–2 cm, or in some cases +/–1 cm, depending on the amount of variation in the environment. Most robot systems have additional means to improve accuracy, such as magnetic or geometric alignment marks or triggers that control movement (for example, optical sensors can help to stop the robot within mm accuracy with respect to a fixed loader).

Integration with shop-floor planning

Deploying a fleet of autonomous logistic robots requires an automated system that generates drive orders (missions). In a manufacturing environment, these missions are best generated in the MES (Manufacturing Execution System). The MES triggers execution of processes at individual machines, workstations and operators, based on information about which parts are ready for transport to a next location and which locations need materials, semi-finished parts and tools. The fleet may consist of various types of robots for different payloads, different product sizes, special docking station adaptations or product holders, or different environments (a smooth indoor floor, outdoor paved area, etc.).

With the great variety of manufacturing companies and their requirements for robots and the MES systems they use, a connection to a fleet management system will have to be custom-defined and -built. Fortunately, today the interfaces for dropping missions into a fleet manager are relatively simple and often well documented.

Integration

A standard method has been developed to benchmark individual organisations to define a useful business case, a possible introduction process and relevant integration aspects regarding the organisation and operation. For example, most companies will operate their mobile robot fleet in connection to their internal planning software to automatically plan and schedule tasks for various classes of mobile robots. This requires the integration of mobile robot fleet management with their production planning process and software.

Customers probably prefer to start with a small experiment to see the benefits and validate the interaction between robot mobile logistics and the rest of their operation, including – last but not least – their personnel.

Safety will be an integral part of the requirements analysis; a proposal should reflect the way safety has to be realised, and to what levels intended and unintended users of the mobile robots will be protected and by what measures. In most cases, a fleet supervisor has to keep track of orders and deviations. Ultimately, he has to decide on rush orders and take action in case of calamities.

Requirements analysis

A checklist, shared with the customer in advance, can be used to investigate the material flow situation and production environment, as well as the customer's expectations, for analysing his current situation and assessing the potential for mobile robot deployment. The service criteria (key performance indicators, KPIs) of the customer have to be studied and the current (detailed and integral) costs of logistics have to be estimated. Also, the building elements involved with deploying a robot fleet have to be studied. If a door cannot be opened automatically by a robot or fleet manager, there is a potential problem.

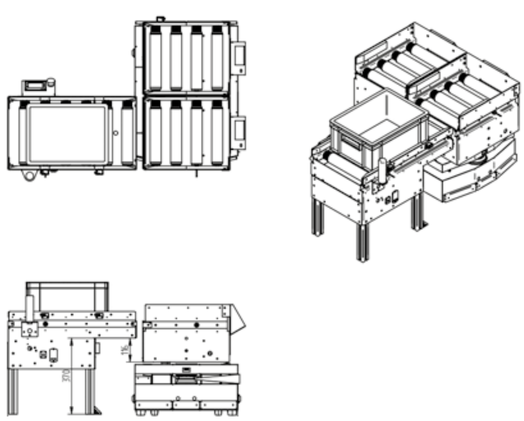
Proposal

When making a proposal, the solution provider has to match its portfolio of robot products and that of its partners with the customer's KPIs. A proposal should include the following 'integration' aspects:

- integration with docking at various locations;
- integration with (production) planning systems (ERP/MES) and special software interfaces;
- simulation of various scenarios to validate the KPIs and customer expectations;
- deployment plan including changes to infrastructure to secure navigation and localisation of mobile robots as much as possible;
- training robot fleet supervisors and personnel;
- safety.

Conclusion

Autonomous robotics has the potential to drastically change internal logistics in the coming years. However, personnel will still be needed, if only to manage the fleets of mobile robots. ■



5 *Currently available mobile robots have a limited accuracy for docking.*

THE GAUSSMOUNT

Advances in semiconductor manufacturing equipment demand for continuous vibration isolation system improvements, including vacuum compatibility. At Eindhoven University of Technology, therefore, a non-contact, non-fluid or non-gas, permanent magnet-based vibration isolation system has been modelled, designed and constructed, capable of levitating and isolating a mass of 730 kg.

DAVE VAN CASTEREN

AUTHOR'S NOTE

Dave van Casteren performed his research within the Electromechanics and Power Electronics group at Eindhoven University of Technology, the Netherlands. He completed his Ph.D. thesis under the supervision of prof. E.A. Lomonova and dr. J.J.H. Paulides. His research project was performed in close cooperation with ASML Netherlands.

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Introduction

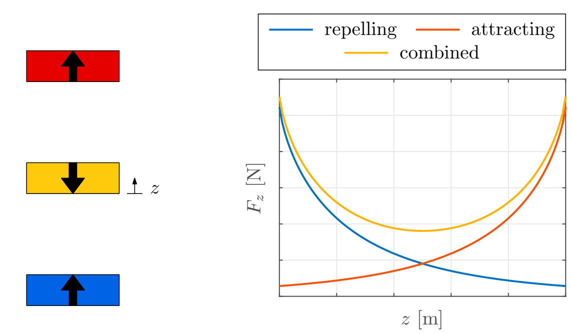
In 1975, Gordon Moore speculated that the semiconductor complexity would double annually until about 1980 after which it would decrease to a rate of doubling every two years, known as Moore's law [1]. This exponential improvement described how the crude home computers of the 1970s could transform into the sophisticated machines in the 1980s and 1990s, and currently give rise to high-speed internet, smartphones and other 'smart' devices. Initially, Moore's law was based on observation and forecast. Later, however, chipmakers deliberately chose to follow Moore's law, making it a 'self-fulfilling prophecy'.

The production of silicon-based integrated circuits (ICs) entails several steps [2] [3]. In short, UV-light is used to create a circuit pattern onto a wafer. By creating multiple layers and interconnecting multiple circuits, ICs are created. The complexity of an IC is mainly determined by the feature size in the pattern and the accuracy of the placement of the different patterns (overlay). Among others, the accuracy is affected by vibrations (e.g. floor vibrations). Lithographic systems, therefore, include a base frame which is supported on the ground and a vibration-isolated frame, often referred to as metro-frame, on which the lenses are positioned, and which is used as a reference for wafer and reticle stage control.

To date, vibrations can often be adequately reduced by using air mounts in combination with actuators. Magnetic levitation and vibration isolation systems are, however, becoming more important due to their inherent high control bandwidth and accuracy [4]. Furthermore, permanent-magnet-based systems have preferable features such as cleanliness, noiseless, maintenance-free, vacuum compatibility, etc. Especially the latter is important for the new extreme ultraviolet (EUV) lithography systems, as they are operated in vacuum environments.

Principle

The main component of a magnetic vibration isolation system is a magnetic gravity compensator, which levitates an isolated mass. The quality of the isolation system is greatly determined by its stiffness (i.e. force variations due to relative movements). A low stiffness indicates a weak connection between the floor and the isolated mass, hence a high isolation quality. To obtain a low stiffness whilst maintaining a high force output, which is required to levitate a significant mass, attracting and repelling magnets are used.



1 *Passive attraction and repelling forces using high-grade permanent magnet material.*

This principle is easily observed when looking at two individual magnets. Figure 1 shows two fixed magnets and one free magnet. The free magnet is repelled by the bottom magnet and attracted by the top magnet. When isolating the repelling or attracting force, it can be seen that a large force is accompanied by a large stiffness and a small stiffness is accompanied by a small force. To combine both a large force and a small stiffness, the two forces are combined in a magnetic gravity vibration isolator.

Earnshaw's theorem [5] states that it is not possible to obtain a passively stable permanent-magnet-based device along all its directions simultaneously. This theorem can be translated to: The summation of the stiffnesses in the horizontal directions, K_{xx} and K_{yy}, and vertical direction, K_{zz}, is equal to zero. In short:

$$K_{xx} + K_{yy} + K_{zz} = 0$$

Therefore, a negative stiffness will always be present when utilising passive levitation for vibration isolation, making the system unstable. This necessitates the presence of actuators, force-producing magnetic devices, in a magnetic vibration isolation system. Besides only passive isolation, this also makes it possible to achieve active isolation, while minimising the electrical input power requirement due to the high bandwidth of these actuators.

To design the compensator, it is important to accurately calculate the magnetic forces. Because of the unbounded nature of the problem and the airgap size with respect to the volume, numerical methods are not suitable due to the required computational load. Therefore, an analytical technique is required, such as the charge method [6], which represents parallel magnetised permanent magnets with magnetic charges on the surface of the magnet. The charge density, σ, is calculated using:

$$\sigma = \vec{M} \cdot \vec{n}$$

Here, $\vec{M}$ is the magnetisation vector and $\vec{n}$ denotes the outward unit normal to the surface. In the traditional method a relative permeability of 1 is assumed. The magnetisation vector is, therefore, only dependent on the remanent magnetisation of the permanent magnet:

$$\vec{M} = \frac{\vec{B}_r}{\mu_0}$$

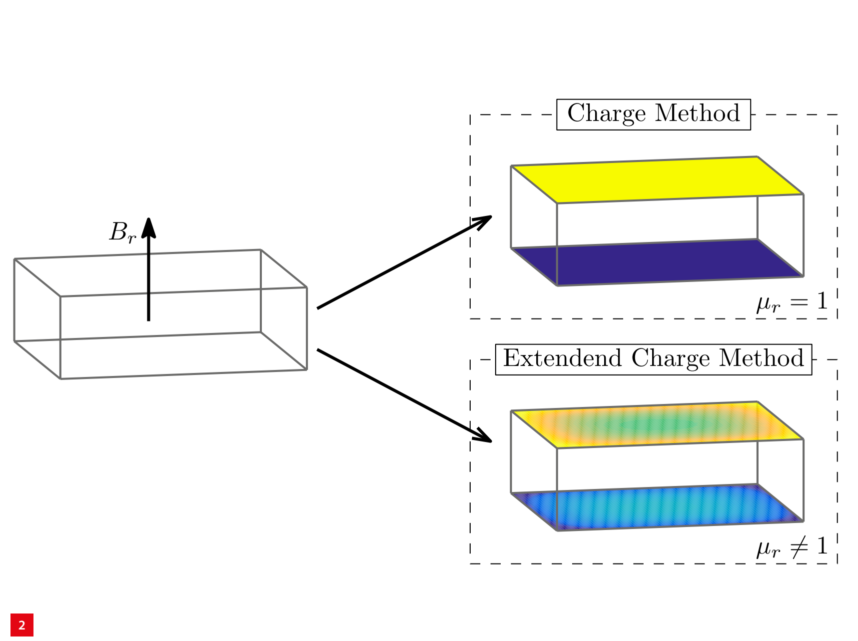
This results in a constant charge density, as can be seen in Figure 2. Relative permeability indicates the relative ability of a specific material to guide magnetic field with respect to free space, i.e. pure vacuum. Rare-earth permanent magnets usually have a relative permeability around 1.05. Therefore, in this research, the extended charge method is proposed which accounts for this non-unity relative permeability, hence also other magnetic materials could be considered [7, 8]. It does so by taking into account the influence of the magnetic field in the magnetisation vector:

$$\vec{M} = (\mu_r - 1)\vec{H} + \frac{\vec{B}_r}{\mu_0}$$

This leads to a position-dependent charge density distribution with higher concentrations at the edge of the material, as can be seen in Figure 2. Note that the magnetic field strength, $\vec{H}$, is calculated by:

$$\vec{H}(\vec{r}) = \frac{1}{4\pi} \oiint_S \frac{\sigma(\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3} \mathrm{d}S'$$

Here, $\vec{r}'$ and $\vec{r}$ are the source point and observation point, respectively. Which means that the charge density on a surface is dependent on itself and on the charge of the other surfaces in the volume. This dependency is taken into account by solving the charge density distribution iteratively.

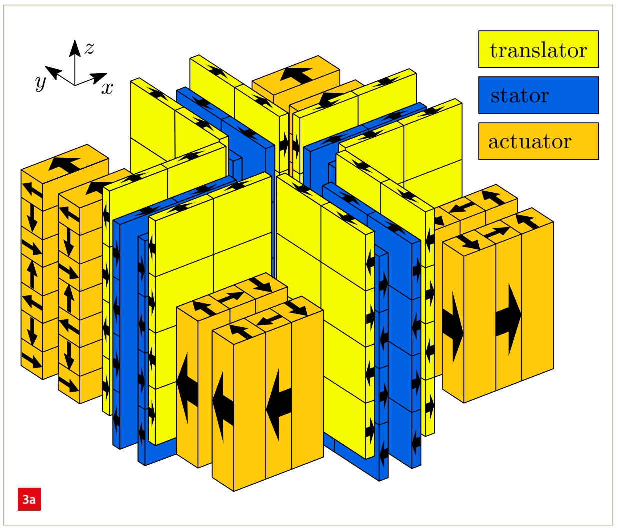


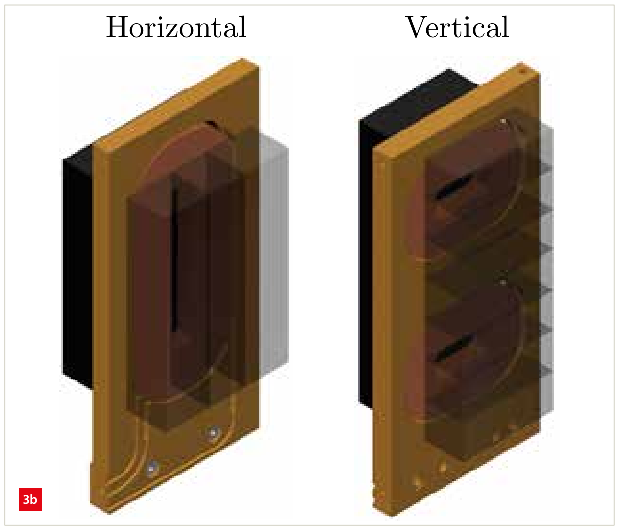
2 *Artistic representation of the magnetic charge density on the top and bottom of a cuboidal permanent magnet.*

In this work it is assumed that a complete vibration isolation system will consist out of three units which deliver a passive force and an active force by a gravity compensator and multiple actuators. An optimisation among different magnet topologies which incorporate attracting and repelling magnets results in a configuration for a single unit as illustrated in Figure 3. Here, a 6-DoF magnetic gravity compensator is shown in combination with four 2-DoF actuators (DoF = degree of freedom).

The 6-DoF gravity compensation is realised by the magnets which form a cross, called the outer cross and the inner cross for the translator and stator, respectively. The space in the corners of the inner and outer cross are used to locate the actuators. To avoid moving wires and increase the capability to remove any heat produced in the coils, the coils are placed on the stator and the magnets are located on the translator.

In total there are two horizontal actuators and two vertical actuators. This means that each unit consists of a 6-DoF gravity compensator and a 2-DoF actuator. By placing three of these units in a triangle, each 120° rotated, a 6-DoF controlled system can be realised. Using the traditional charge method, this topology is capable of lifting 7,537 N, while the extended charge method calculates a lifting capability of 7,000 N for a $\mu_r = 1.05$. This means the relative permeability of the magnets decreases the vertical force by 7%.





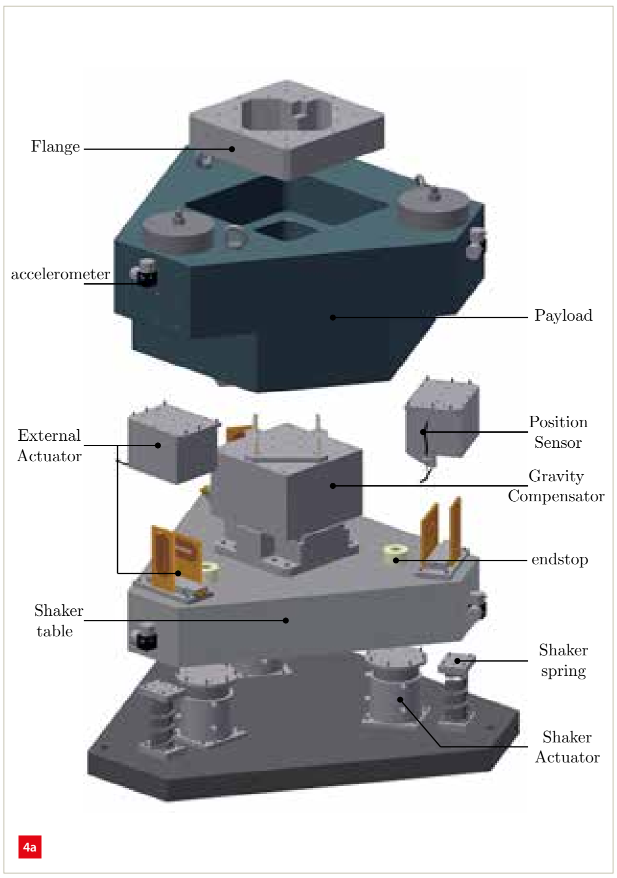
3 *Magnetic topology of the vibration isolation system.*
(a) Schematic representation.
(b) Detailed view of the horizontal and vertical actuator.

4 *The Gaussmount, a testing environment to validate the vibration isolation system.*
(a) Design.
(b) Realisation.

Prototype

To test the capabilities of the designed isolator, a test rig called the Gaussmount, shown in Figure 4, was built. Instead of manufacturing three units for a complete vibration isolation system, only one unit was realised. For the magnets special care was taken to minimise variations in the remanence and magnetisation angle. Furthermore, since a large vertical force is required, also large forces are present on the individual magnets in the system. The manufacturing of a magnetic isolation system is, therefore, not that easy. To simplify the glueing of the magnets on the supporting structure, the inner and outer cross were divided into four parts. These four parts are connected to each other before sliding the inner cross into the outer cross. Due to the nature of the magnetisation, the sliding mechanism should be able to withstand both pulling and pushing forces.

Although a single unit is capable of generating the levitation force to compensate a certain mass, the 2-DoF actuators are insufficient to guarantee stable operation. Therefore, external actuators are necessary to ensure 6-DoF actuation which is required to stabilise the system and to actively reduce the vibrations, as shown in Figure 4.



The cumulative mass of the isolated platform has been chosen such that the difference between the passive vertical Gaussmount force and the gravity force of the isolated platform is as small as possible. Given the modeling inaccuracies and manufacturing tolerances, the payload mass was chosen to be smaller than the calculated mass. Any necessary additional mass is obtained by placing stainless steel disks on top of the payload. To limit the movement of the isolated mass, which prevents the magnets from touching, end stops are present. Table 1 specifies the mass for the main components.

Table 1. The individual masses for the main components in the Gaussmount.

Component	Material	Mass (kg)
Payload	Granite	574
Flange	Aluminium	25.5
Disks	Stainless steel	42.0
Outer cross	Aluminium/Vacodym 854	42.2
Inner cross	Aluminium/Vacodym 854	32.2
Shaker table	Aluminium	286

The isolator and the external actuators are mounted on top of the so-called shaker table, which acts as an artificial floor. This shaker table is capable of generating controlled vibrations, which can be used to measure the transmissibility. The shake table rests on top of mechanical coil springs and is excited by three commercially available LA50-65-001Z voice-coil actuators driven by PADC Quad 260/50 current amplifiers, allowing 3-DoF controllability. For static and compliance measurements, the shaker table can be fixed into position by placing leaf springs parallel to the coil springs.

To stabilise the vibration isolator, the relative position between the payload and the shaker table must be known. Optical sensors (RC100-AELN) have been chosen to measure this distance because of their excellent resolution for large strokes and their minimal influence on the magnetic field. To measure the acceleration of the payload and shaker table, 1-DoF capacitive accelerometers (8330M04) are used. As a result of their capacitance-based measurement principle, these accelerometers are capable of measuring a large range of frequencies, ranging from sub-Hertz to 1 kHz.

To minimise the structural interference on the magnetic field and thus the force, non-magnetic materials are utilised. The payload is made from granite and the supporting structure of the isolator, actuators, shaker table, and flange are made from aluminium (Al 6082).

Although aluminium has a relative permeability of close to 1 (1.000022 to be exact), it does have a large electric conductivity, $\sigma_e = 36 \cdot 10^6$ S/m. This means that for static fields, the forces are not influenced by the aluminium parts.

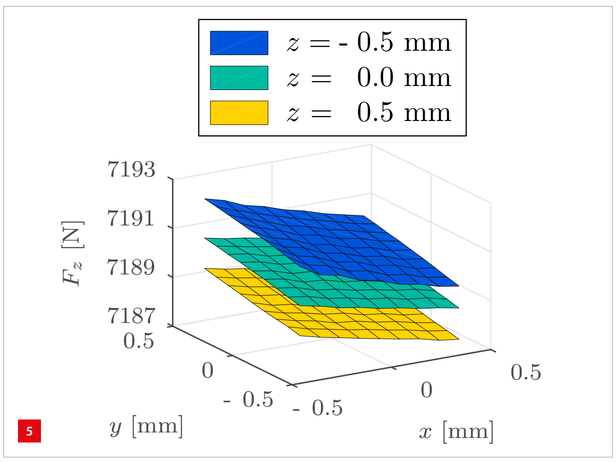
For time-variant fields, however, there is an influence. Due to the high conductivity, eddy-currents flow in the aluminium causing additional fields and forces in the system, which act like a damper. These eddy-currents increase with the variation in magnetic flux density. Since the field of the coils can vary rapidly, the mounting blocks for the coils are made out of a non-magnetic and non-conducting material.

Measurement results

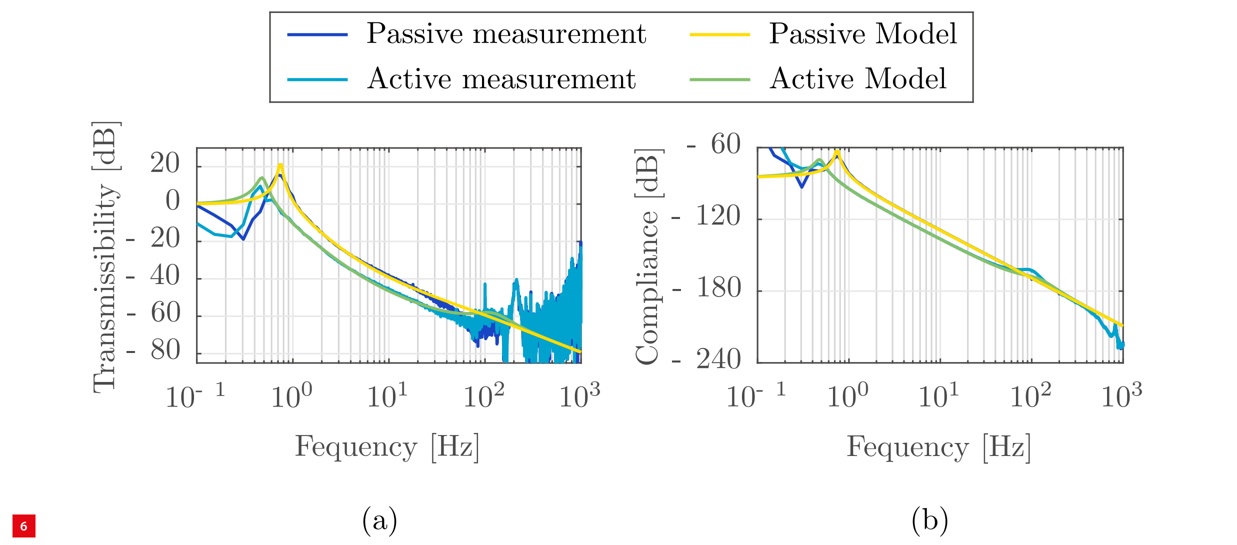
To determine the characteristics of the gravity compensator, two types of measurements have been performed. Firstly, static measurements for the calculation of the stiffness and secondly, dynamic measurements to determine the isolation capabilities.

The results of the static measurements are shown in Figure 5. Since no force sensors are present, as they would introduce contact, the gravity compensator force cannot be measured directly. Therefore, to determine this compensator force, F_C, the force delivered by the actuators, F_A, is used, which is calculated using the applied current and motor constant. The current is measured by averaging over 5 s with a 5 kHz sampling rate. By subtracting the actuator force from the gravitational force of the mass, the vertical force is estimated. Using this measurement the vertical stiffness is calculated to be 2.5 N/mm.

Figure 6 shows the results of the dynamic measurements, which were performed to determine the Frequency Response Function (FRF) of the transmissibility and compliance of the designed isolator. The transmissibility describes the ability of the system to isolate the mass from floor vibrations, while the compliance describes the ability to reject vibrations originating from direct forces on the mass.



5 *Force characteristics in the working envelope of the gravity compensator in the z-direction. The variation in color indicates the movement in z.*



6 *Frequency response of the active and passive vibration isolator.*
(a) Transmissibility.
(b) Compliance.

For the transmissibility measurements, coloured noise vibrations (0.5-300 Hz) are inserted into the system by three Shaker Voice Coil Actuators (SVCAs) located underneath the shaker table. To calculate the transmissibility, the shaker table acceleration and the isolated mass acceleration are recorded as input and output signals, respectively, during 50 s with a sampling frequency of 5 kHz. By comparing the measured FRF to the transmissibility based on a model, the mass and damping coefficient are determined as 730 kg and 500 Ns/m, respectively. This mass is within 2% of the calculated value using the extended charge method, with respect to a 5% difference using the original charge method [9].

Discrepancies for low and high frequencies are visible between the model and the measurements. At low frequencies, the excitation signal does not have a large input power, resulting in a low coherence and therefore in discrepancies. At higher frequencies, > 50 Hz, the measured FRF starts to deviate from the modeled FRF, due to the damping coefficient which reduces for higher frequencies. For the compliance measurements, the disturbance force is generated by the actuators used for stabilisation. It can be seen that the FRF is very similar to the modelled compliance. Measurements show a resonance peak at 800 Hz, which coincides with the calculated mechanical resonance frequency of the translator.

A passive system always makes a trade-off between transmissibility and compliance. The low stiffness design of the isolator results in a low transmissibility but increases the compliance. To reduce both the transmissibility and compliance an active system is required. By using a simple PI controller, which uses the payload's acceleration as input, a decrease in both transmissibility and compliance can already be achieved as can be seen in Figure 6. Here a decrease of 10 dB is obtained in a range from 1 to 50 Hz for both FRFs.

Closing

The scientific work described here has resulted in a method which is capable of describing the forces between magnets with a high accuracy. Based on this work, magnet topologies for permanent magnet based systems, e.g. vibration isolation systems, can be designed and constructed, where the main challenge is to achieve accurate force prediction. ■

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THAT'S HOW YOU **MAKE** IT

Demoweek 2017 centred around the question: "How do you make it?" The answer to that question will vary from company to company, but that automation and robotics will be a core part of their operations, seems pretty clear. That was underscored by a visit to the companies participating in the Demoweek.

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During the recent Demoweek (28 to 31 March 2017), eight companies in the Ede-Veenendaal region, the Netherlands, again opened their doors to the metalworking industry. Held biennially in odd years, the event recently concluded its fourteenth edition. The signature of the participating companies is very diverse, as can be seen in the overview below (from machines to software and tools), but the one common denominator among them is that they operate in the machining sector. The one thing that makes this event unique is that it attracts a community of directly involved and like-minded individuals (Figure 1).

Whenever anyone mentions Veenendaal and automation, the conversation inevitably turns to Cellro, the robotic systems company that has long been an international billboard for our country. Cellro's well-known standard product, the Xcelerate, is a robot system that automatically loads and unloads workpieces and allows for unattended machining.

The robot is positioned on a table-top with drawers for storage of raw and machined products. A universal product inlay with adjustable formats can be placed in the drawer for storing products with a wide variety of shapes and dimensions. The Xcelerate comes with a control unit you can use to configure the system to accommodate the products to be handled. A compartment, installed on top of the robot, holds customer-specific grippers with six groups of tool changers. A handy option comes in the form of the reversing station, which allows machining a product in a single pass.

The Xcelerate was specially developed to lower the automation threshold for suppliers (Figure 2). "Suppliers often have to deal with a wide variety of products in smaller quantities. This requires a robot system that can be quickly and flexibly adjusted to a specific situation", says sales manager Elise de Koning. Thanks to its universal character, the Xcelerate is very versatile in use.

1 *The one thing that makes the Demoweek unique is that it attracts a community of very like-minded and directly involved individuals. (Photo: Cellro)*

2 *Cellro specially developed the Xcelerate to lower the automation threshold for suppliers, who usually have to deal with a wide variety of products in smaller quantities. (Photo: Jan Oonk)*

In addition, Cellro has special departments such as Specials and Projects. Specials, for example, features a laser marking system for handling and marking components for artificial hips, which could be admired during the Demoweek. Projects offers systems that use both Cellro and customer-specific modules. Increasing user-friendliness and adding functionalities is the future of automation, according to De Koning.

Connected Machining

Ensuring a flawless, automated and unmanned production process is not just about using the right hardware. It also requires the right software. That is why Heidenhain has developed various software packages, under the denominator of Connected Machining, which link the control system of a CNC machine directly to the network of all production-supporting departments. "A machine is no longer an island, it is fully integrated into the operations", according to sales manager Nico Schuitemaker. "All essential information can be accessed at any given time." The status of an order, for example, can be viewed whenever required, while options are also available for monitoring the machinery.

Conversely, the operator also has direct access to all information relevant to the process. In a nutshell, collating pieces of information into a single view makes the production process much more efficient and transparent, especially if it involves a large range of small series (Figure 3). Schuitemaker: "Machining companies can then manufacture their products faster, more flexibly and with higher accuracy."

As international developer of measuring and control technology, Heidenhain markets the CNC control systems TNC 640 and TNC 620. The TNC 640 is considered the all-rounder and is designed for complex machining operations on milling and milling/turning centres with multiple axes. The more compact TNC 620 is optimised for three- to five-axis machining operations.

3 *Integrating a machine within the operations makes manufacturing of products faster, more flexible and more accurate. (Image: Heidenhain)*

Software vendor Bemet has also devoted its resources to optimisation of production processes as a whole. Enabling machines, products and software systems to communicate with each other allows for a more rapid exchange of data. This is not just limited to internal (business) processes (such as CAD/CAM, ERP and tool management), but it also extends to the relationship with the customer. All with the aim of reducing lead times, reducing the margins of error, organising stock management and providing faster service to customers. Thinking in terms of total solutions is critical in that regard, according to Bemet.

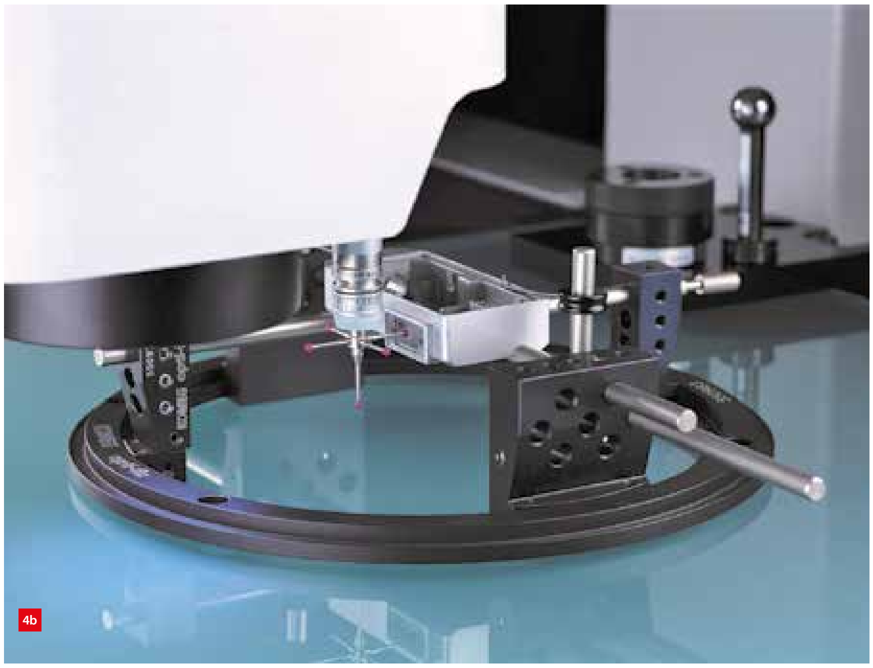
CMM programming software

MiCat Planner software by Mitutoyo delivers dramatic time savings during the entire production process. According to the company, it can save up to 90 percent time by automatically generating measuring programs for coordinate-measuring machines (CMMs) based on the CAD file. MiCat Planner optimises the measurement cycle by reducing the number of probe changes and movements. The only thing the programmer needs to do is select the measuring machine, a CAD file (with or without geometric dimensioning and tolerancing data), and the measurement strategy is automatically generated and translated into a measuring program in MCOSMOS (Mitutoyo CMM software).

Mitutoyo's portfolio featured a new function, the Quick Vision Active measuring unit. It uses an integrated high-resolution camera, where light (exposure) is provided through the table or the lens or via LED ring light. The ring light consists of four segments which can be set separately. The different light sources ensure accurate edge detection for correct and precise measurement at all times. Thanks to the 'search pattern' function, the shape of the workpiece is automatically recognised, so rough positioning will suffice. Adjustment of the light intensity and focus will allow all kinds of surfaces – from black to reflective (stainless steel) and transparent (glass) – to be measured. This is especially relevant for complex products in which various materials are processed.

In addition to the camera, the Quick Vision Active measuring unit can also be equipped with a probe (Figure 4), which can be used for deep cavities, for example, or when there are complex contours on the side of a product. Thus, this all-in-one solution provides added flexibility.

4a



4b

High pull

Three other machine suppliers also participated in the Demoweek, Dymato, Bendertechniek and DMG Mori. Dymato presented the world premiere of the XF2000 machining centre of Hyundai Wia, a machine that was completely developed within the European Development and Design Center (EDDC) in Raunheim, Germany. The XF2000 (with a Siemens 840D SL control) comes with a 200 mm pan/tilt table and 300 mm x 300 mm x 200 mm linear working range. With up to 50 m/min traverse speed and 2 g acceleration, the machine can be called highly dynamic. More importantly, the machine configuration is so robust and stable that this acceleration is actually achieved, as Marc Sieber of the EDDC explained. The machine therefore allows for an extremely high pull. In the standard version, the XF2000 is equipped with a built-in, high-performance spindle with up to 40,000 rpm.

The new machining centre was specially developed for 24/7 automated production of small precision parts, where the chips must not disrupt the process. The horizontal spindle and chip conveyor directly below the spindle ensure efficient chip management. A robot can be loaded onto the XF2000 from the side, leaving the machining area at the front visible and accessible for the operator.

High-tech

An interesting piece of news about DMG Mori is that the company has purchased 50.1% of the shares of Realizer, German manufacturer of 3D metal printers with selective laser melting (SLM) technology. DMG Mori has long been building hybrid machines through its subsidiary Lasertec and it will strengthen its position in the additive manufacturing industry with the recent acquisition of Realizer.

Bendertechniek showcased machines from Brother (compact machining centres), and Muratec (multi-axis lathe and milling machines in combination with loader/unloader systems). These two brands have been added to Bendertechniek's delivery programme last year. Brother machines lend themselves well to automation. Muratec supplies lathes with kissing and frontal spindles which, integrated with the gantry loader, create production cells with high dimensional accuracy.

Dormer Pramet, global manufacturer and supplier of cutting tools to the metal cutting industry, was also exhibiting at the Demoweek. "Reliability of tools is critical to 24/7 production", underscores technical consultant Martin Gerritsen. The choice of tool is also crucial to achieving maximum efficiency from a process; it requires using the right tool for the right machining application. Dormer Pramet supplies over 20,000 tool variants, and according to Gerritsen, today's tools are so high-tech that, in practice, the machine is usually the limiting factor. ■

INFORMATION
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4 *The Quick Vision Active. (Photos: Mitutoyo)*
(a) Light can be provided through the lens or via the side of the lens. In the latter case, the product can be exposed to light from the lens and measured from different sides.
(b) The equipment may, in addition to the camera, also include a probe for measuring deep cavities or complex contours on the side of a product.

PRECISION IN GLASS, CERAMICS AND ASSEMBLIES

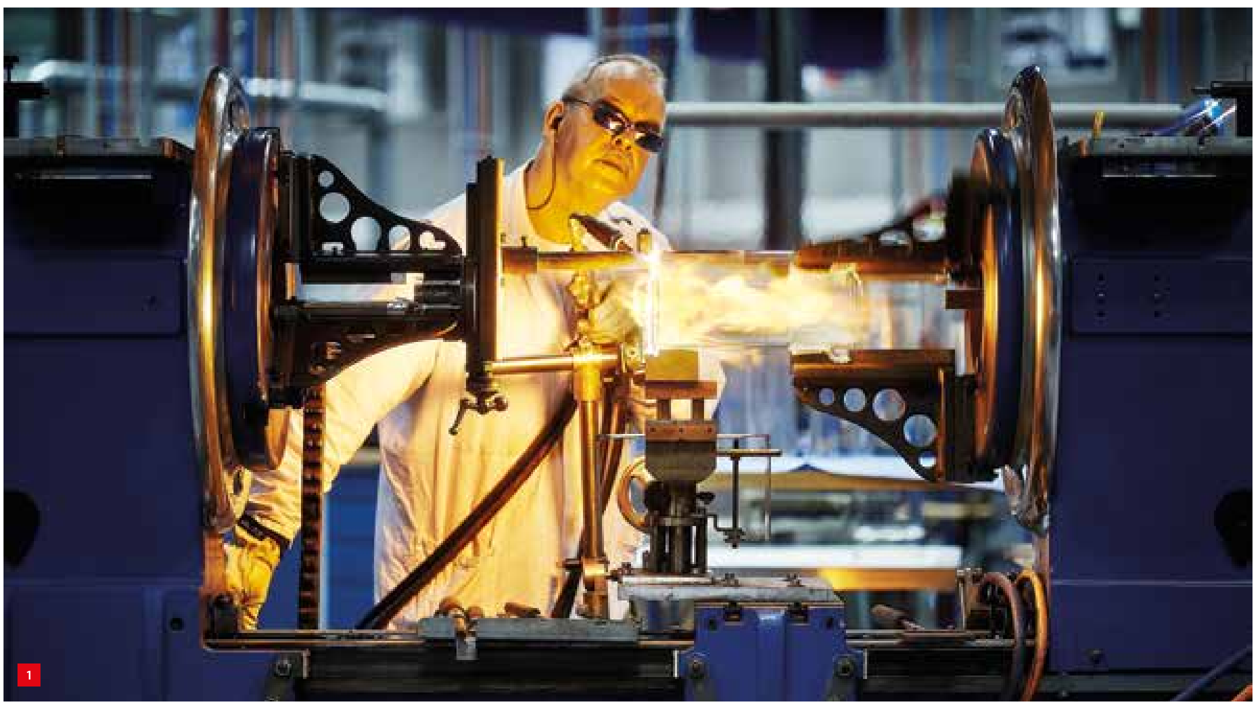
In 2012, Dutch companies Louwers Glastechniek in Hapert and Pulles & Hanique in Veldhoven merged to form a new company, LouwersHanique. Now the quartz processing expertise of Pulles & Hanique complements the glass, metal and ceramics machining and joining expertise of Louwers Glastechniek. Both companies were established during the nineteen-fifties, emerging from the glass-processing expertise of the incandescent lamp and radio tube industry in the Eindhoven area.

FRANS ZUURVEEN

Process control, accuracy mindfulness and quality awareness are the most important characteristics of the versatile craftsmanship shown by LouwersHanique's workforce of more than one hundred employees. With ten of these employees involved in fundamental research, many of LouwersHanique's R&D activities involve cooperating intensively with various partners, institutes and technology centres, such as Philips Innovation Services (PINS) at the High Tech Campus in Eindhoven, the Netherlands. PINS originates from the earlier Philips activities NatLab and CFT, i.e. "Natuurkundig Laboratorium" (Research) and "Centrum voor Fabricage-technieken" (Centre For Manufacturing Technologies), respectively.

LouwersHanique's quality awareness is evident from its ISO 9001:2015 certification and the other international quality monitoring standards it has attained, regarding World Class Manufacturing, for instance. Accuracy mindfulness is apparent in its stringent procedures for its extensive cleanroom facilities and cleaning processes.

The company's modern premises in Hapert are divided into several buildings, according to the three fundamental disciplines of LouwersHanique: thermal processing (see Figure 1), mechanical precision machining and highly accurate assembly. This division also reflects the traditional differences between 'hot' and 'cold' glass technology, along with the present processing of ceramics and other unique materials.



1 *The thermal machining of glass.*

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2 *Creating a complex glass assembly including a vacuum-tight double-walled tube for a CO_2 laser.*

3 *A high-precision quartz torch for critical ICP analysis (Inductively Coupled Plasma mass spectrometry).*

4 *High-power glass-to-metal feedthroughs for lithography applications requiring extreme cleanliness.*

5 *Adjusting a workpiece on a Hermle machining centre with a centring microscope.*

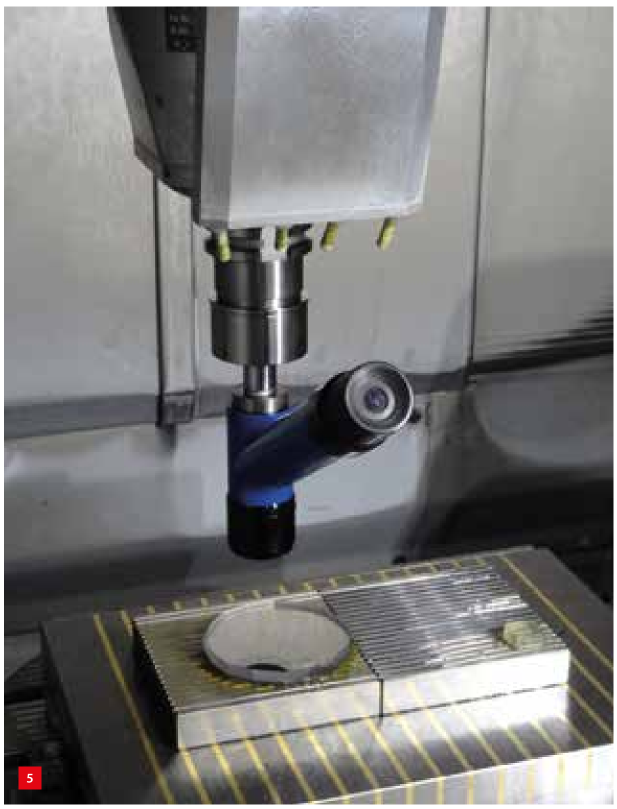
Thermal processing

The thermal processing department includes the manufacturing of precision parts for high-end semiconductor equipment and more traditional laboratory glass products (see Figure 2). This processing starts with the heating of glass materials sourced from leading-edge suppliers like Schott, Heraeus, Momentive and Corning. The required thermal conditions are achieved by gas-oxygen burners, inductive heating or laser technology.

The most widely used glass materials are borosilicate 3.3 and quartz glass. Borosilicate glass is preferred for analytical applications because of its optical transparency and thermal shock resistance. Quartz glass is more difficult to process and more expensive to acquire, but is widely used for special applications which ask for high purity, excellent UV transmission, high temperature resistance and/or low thermal expansion (see Figure 3). Quartz materials, including fused silica glass, are preferred for high-purity, high-temperature processes. These ask for clean environments and extremely clean infrastructure, equipment, tools and gases, according to LouwersHanique's precision-assembly specialisms (Figure 4).

Mechanical machining

The mechanical machining department houses many high-precision CNC-controlled machining centres, mainly from German milling specialist Hermle. These machines are supplemented by different types of precision grinding, lathing, lapping and polishing machines (see Figure 5). The materials being processed in this temperature- and humidity-controlled department are quartz, technical glass and advanced ceramics. Precision metal parts that are also widely used by LouwersHanique are provided from acknowledged third-party supply-chain partners.



Diamond is the only material that effectively machines carbides, nitrides and those oxides that are nearly as hard as the hardest material itself. Examples of these are SiC, B_4C, Si_3N_4, BN, ZrO_2 and Al_2O_3. Less hard materials include glass ceramics like Macor from Corning and Zerodur from Schott. These materials, however, also need tightly controlled diamond grinding in order to achieve the critical surface properties and vacuum cleanliness that are often needed. Using softer grinding materials frequently results in surface or even subsurface damage.

Macor is made of borosilicate glass with mica and is stable up to 800 °C. Zerodur consists of SiO_2 with TiO_2 and has a thermal expansion coefficient of nearly zero. That is why Zerodur is applied in optical precision instruments (see Figure 6), as well as Corning ULE, a titania-silicate glass with near-zero expansion characteristics. These special materials are used in machine tool reference blocks and interferometer reference mirrors, for example.

Precision assembly

LouwersHanique's assembly activities are at the same level as the company's unique joining expertise in the combining of glass with glass, glass with metal, or glass with ceramics. It can also mutually combine ceramics, as well as ceramics can with metal and with optical components.

For these combinations of dissimilar materials, LouwersHanique uses various joining techniques, such as monolithic direct bonding (see Figure 7), precision glueing and high-quality glass joining. A special method of combining such materials can be seen in the design and manufacturing of ultra-high-vacuum feedthroughs based on glass-to-metal joining (see Figure 8). This method is the result of more than sixty years of Louwers Glastechniek experience. Such direct glass-metal joinings, without virtual leaks, provide minimal outgassing and maximum integration levels, purity and reliability. Their traditional know-how on the matching of materials includes expertise on expansion coefficients, viscosity, chemical bonding and other joining conditions.

Obviously these processes need to be performed in high-level cleanroom assembly environments, which also involve cleanroom-grade cleaning procedures. That's why LouwersHanique uses elaborate Class 1.000 cleanroom facilities, supplemented by proficiency in UHV/Grade 2 cleaning processes as well as RGA (Residual Gas Analysing) qualifications.

Below, high-precision assembly and manufacturing examples are used to illustrate LouwersHanique's precision engineering expertise.

6 *A high-precision Zerodur chuck with µm-tolerances and sub-µm flatness for an nm-accuracy metrology application.*

7 *Monolithically bonded glass for an in-vitro fertilisation cell.*

8 *A combination of different kinds of glass-to-metal feedthroughs according to LEMO, Harting and sub-D standards.*

9 A complete set-up for the precision calibration of glass tubes. At the right the stainless steel mandrel.

Precision glass tubes

When standard glass tubes are required to have more precision in their internal diameter, the tubes need to be calibrated. LouwersHanique's calibration process is based on the controlled shrinking of two materials with different thermal expansion, i.e. glass and stainless steel. The process for tubes from borosilicate glass 3.3 (Schott Duran, for example) applies an accurately machined mandrel from stainless steel with ±1 µm outside diameter tolerance (see Figure 9).

The coefficients of thermal expansion are properly defined from both the mandrel material and the borosilicate glass. At the start of the process, an oversized glass tube is positioned around the mandrel and subsequently heated to a temperature which makes the glass sufficiently malleable. Next, a vacuum is created between the mandrel and the glass tube, which causes close contact between glass and steel. This vacuum condition also prevents oxidation of the mandrel material.

Essential for the calibration process is the greater shrinkage of the mandrel in relation to the shrinkage of the tube when cooling down, which is due to the difference in expansion coefficients. This results in loosening of the glass tube from the mandrel.

When calculating the required mandrel diameter at room temperature, all parameters for the thermal process have to be taken into account. For this calculation, the shrinkage of the glass down from the annealing temperature (560 °C for Duran) is supposed to proceed linearly as a function of temperature. Also, the cooling down speed has to be controlled accurately to prevent internal stresses.

Force-controlled precision glueing

XYZTEC in Panningen, the Netherlands, specialises in the design and production of bond-testing precision equipment. Their testers include an XYZ-stage with facilities to apply push, pull or shear forces on bonds to be inspected.

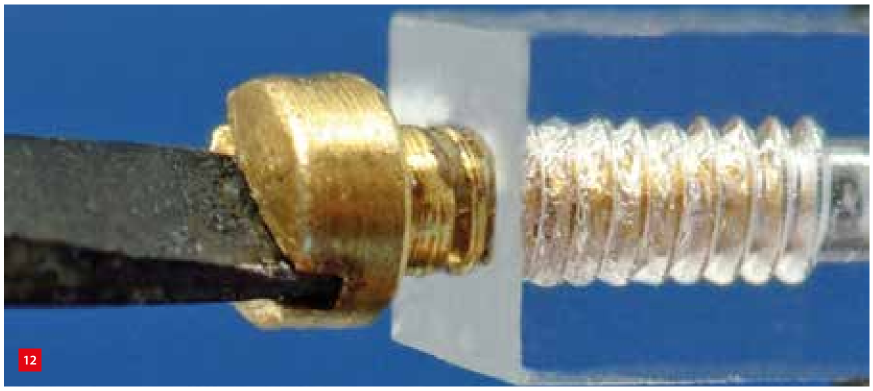
Together with XYZTEC, LouwersHanique has modified a bond tester to assemble and bond tiny components on a glass or ceramic substrate with an accuracy of about ±10 µm (see Figure 10). This was helped greatly by the accuracy of the X-, Y-, and Z-slides of the bonding test stage – 30 nm resolution, 0.5 µm repeatability. LouwersHanique added a glue dispenser to the XYZTEC tester, which enabled the accurate deposition of a droplet of UV-hardening glue on the substrate. This droplet has a diameter of only 300 µm. The accuracy of the tester guarantees a droplet position accuracy of a few µm.

The next step in the assembly process is the force-controlled deposition of the component on the substrate. To that end, LouwersHanique has integrated a robot-like, vision-controlled gripper in the tester. This gripper picks up the component and moves it exactly to the position of the glue droplet, then presses it down with a controlled and well-defined force. The last step in this assembling procedure is the application of UV light to set the glue.

Selective Laser Etching

The most common fluid used for etching glasses is HF, hydrogen fluoride. This is a dangerous and very aggressive chemical, to be handled with extreme caution. That's why LouwersHanique was happy to discover that the Fraunhofer Institute for Laser Technology (ILT) in Aachen, Germany, uses a process that instead etches glass with KOH, potassium hydroxide. This process has been introduced to the market via LightFab, a company founded by researchers from RWTH Aachen University. The company builds the fast LightFab subtractive 3D printers, which turn the complete process into real precision technology, enabling the creation of extremely narrow channels in glass with a precision of ±1 µm.

10 A force-controlled precision-glueing instrument based on a XYZTEC bond tester. The system is equipped with a gripper, programmable for rotation, opening angle and gripping force. The upper screen displays the deposition of tiny ceramic blocks on a substrate.



The secret of the Selective Laser Etching (SLE) process is modifying the structure of borosilicate glass, quartz or sapphire using an extremely small laser spot. This structural modification on the micron scale facilitates the relatively easy local etching of the material. Selectivity is characteristic in this process: the ratio of the etching rate of the locally modified material to the etching rate of the untreated bulk material. This ratio equals 500:1 for quartz, for example.

When creating a long cylindrical channel by modifying the material using the laser spot, the difference in etching rates means that some conicity arises in the formed channel. This conicity is due to the fact that at the point where etching of the treated material started, subsequently a little bit of additional (untreated) material is removed at the corresponding, much lower etching rate. This conicity can however be compensated for by adapting the CAD/CAM model which defines the structures to be produced. Other highly complicated structures can likewise be etched with KOH, with the single condition that this etching agent can protrude into the material.

Figure 11 shows the accurate LightFab subtractive 3D printer for the direct laser writing of transparent material. Transparency is a necessary condition for the SLE process, meaning the component has to have at least one transparently polished plane for admitting the laser beam into the material.

The LightFab machine for fast 3D printing from CAD/CAM software includes an accurate 3D product positioning system, a laser focusing module, microscope objectives with a camera and a femtosecond-laser for 1030 nm or 515 nm wavelength and 4 W or 2 W power, respectively. At an XYZ-travel range of 120 x 80 x 25 mm^3, LightFab specifies an XY-resolution of 50 nm and a Z-resolution of 100 nm at a repeatability of 1 µm. The printer is also provided with a 3D Microscanner, a steering device for the fast writing of microvectors. The Microscanner enables the fast writing of complicated microstructures (see Figures 12 and 13).

Today, LouwersHanique uses LightFab's jobshop service to produce 3D precision glass structures. In the near future, it will acquire one or more LightFab 3D printers.

To conclude

In 1891, Gerard Philips began the difficult process of producing incandescent light bulbs. His first problem was to make carbon filaments that were sufficiently durable. Some decades later, his brother Anton imported machines from the United States to manufacture lamp filaments from tungsten. By the start of the Second World War, their Eindhoven-based company had become a world player on the market for radio tubes. In all these products, electrical connections had to pass through the glass wall that separates the outside from the internal vacuum or inert gas atmosphere. Thus a huge amount of knowledge arose in and around Eindhoven concerning the creation of reliable glass feedthroughs.

This knowledge ultimately led to a high-tech industry for the precision machining and joining of glass, quartz, special ceramics and metals. LouwersHanique is perfectly right to be proud of this expertise based on a long technical history. ■

INFORMATION
WWW.LOUWERSHANIQUE.COM
WWW.LIGHTFAB.DE
WWW.XYZTEC.COM

11 *The LightFab subtractive 3D printer for the direct laser writing in transparent material. The printer is provided with a µm-accurate 3-axis system with a range of 120 x 80 x 25 mm^3.*

12 *A 1 mm diameter threaded hole in quartz glass manufactured with the LightFab SLE-system; a tiny M1 screw has been inserted to demonstrate the potential of this manufacturing method.*

13 *Channels in quartz with variable cross-sections for a microfluidic system, printed directly from CAD data. Minimum channel width is 10 µm.*

KALEIDOSCOPE OF HIGH-TECH IN THE WEST NETHERLANDS

By its own admission, Corpus in Leiden, the Netherlands, offers a 'spectacular voyage through Man'. To that, on 28 March 2017, Holland Instrumentation (HI) added a kaleidoscopic 'voyage through the high-tech West Netherlands': ZIE-2017. With a scintillating lecture on the new economy and high-tech, a company fair and innovation market including the presentation of 'Slim Gemaakt in Zuid-Holland' (Smart Industry in Zuid-Holland). For those daring to take the plunge, there were four parallel sessions on various high-tech topics.

ANTON DUISTERWINKEL

Jan Rotmans, professor of Transitions and Transition Management at the Erasmus University Rotterdam, shook the public with a visionary view of the 'Next Economy'. This concerns not only digitalisation, but also fully-sustainable energy generation and, therefore, full electrification. Plus circularity, the re-use of raw materials. "We are living not in an era of change, but in a change of eras", said Rotmans.

For the high-tech industry, this presents numerous opportunities for energy storage and conversion, for example. And for smart, digital systems for collecting, separating and processing waste. It is actually high-tech that is facilitating sustainability and circularity. All this has far-reaching consequences for society and for the economy in the West Netherlands, which is still highly dependent on fossil fuels and outdated organisation forms. Rotmans challenged visitors to not let that hold them back. "Everyone thought it was impossible until someone came along who didn't know that."

1 *Corpus, venue of ZIE-2017.*

AUTHOR'S NOTE

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LeidsePlein

ZIE was organised for the first time in Leiden, sponsored by the municipality. The LeidsePlein, part of the company market, featured presentations by aerospace firms AirbusDS and cosine and machine and module developers such as West End, Code-P West, Lencon Engineering and De Roovers. Munisense, supplier of sensor networks, was also present, as were DeltaPatents (IP services) and LiS (Leiden Instrument Makers School), the only such school in the Netherlands. Leiden-based drone builder AvioniCS brought ECOntroller, an air pollution meter that can be installed on drones. The Dutch Optics Centre, from Delft, demonstrated a sensor system for a portable kidney dialysis machine.

The autonomy of systems was the one other theme at the innovation market. Tryst from Rotterdam-based Tweetonig and Kinergizer extract energy from sunlight and vibrations, enabling sensors to operate without batteries or cables. Accerion is launching a precision positioning system for robots. And Delft Robotics is developing applications for self-learning robots.

Fantastic beasts

Robotics is a hot topic, as was demonstrated by the crowds at the lively parallel session HI organised together with

RoboValley. Chris Verhoeven, of Delft University of Technology (TU Delft), opened the session with a number of provocative statements. He compared modern robots that use sensor information to respond to their surroundings with animals and talked about fantastic beasts. As an example, Verhoeven cited the rag and bone man's horse: an autonomous vehicle that knew its own route, picked its way over obstacles and adjusted to the rag and bone man's tempo.

The message is clear: an irreversible evolution is underway in robotics. Robots are becoming autonomous and self-learning. A company such as Delft Robotics is using self-learning algorithms to develop vision systems with which robots can recognise and pick up highly varying objects. Together with TU Delft, this company won the Amazon Picking Challenge, against competition such as MIT and Japanese universities. Such technology is bringing TU Delft's professor Martijn Wisse's dream of a 'factory in a day' ever-closer to reality.

Let us, as the Netherlands, take full advantage of this by joining forces. That was the message of Willem Endhoven, director of High Tech NL. Together with RoboValley's Arthur de Crook, he presented 'Holland Robotics'. A new initiative aimed at putting the Netherlands on the international map as a robotics country. Not only the knowledge institutes, but also the companies. Holland Robotics therefore has the ambition of setting up a national, industry-driven science programme.

This fits in perfectly with the ambitions of RoboValley, which wants to harvest the universities' knowledge and encourage commercial applications, by means of an investment fund, a robotic service centre, accommodation for start-ups in RoboQuarter, a robot master team for advising companies, an international masterclass and other publications.

Together with InnovationQuarter (IQ), the Zuid-Holland development agency, RoboValley is also developing RoboHouse: a physical place where robots are demonstrated and developed, where hands-on education can take place and where standardisation will be encouraged. RoboHouse will be based in Delft and offers companies the opportunity to showcase their latest products, develop their workforce and find partners for developing new applications.

2 *At iTanks' stand, visitors were able to visit a second, virtual fair with a hololens.*

Smart industry

Robots with embedded artificial intelligence are a schoolbook example of smart industry, the digitalisation of industry. But smart industry is far more and includes the internet of things, for example, machine-to-machine interaction, big data and new business models based on these. More and more businesses are realising the importance of these developments and recognising the opportunities they present. The question of where to begin and how to tackle the issue, however, becomes more pressing with each new development and publication.

To involve more businesses in these developments and provide them with concrete tools for getting started, the 'Slim Gemaakt in Zuid-Holland' action agenda has been compiled by a partnership of eight organisations (Delft, FME, HI, IQ, the Chamber of Commerce, Metaalunie, the province of Zuid-Holland and TNO). This action agenda shows concrete examples of businesses that are already involved in smart industry, as inspiration for others. It is also full of concrete regional initiatives for scans, resources, field labs and financing tools.

To give good examples more acknowledgement and visibility, a series of 'hidden champions' is being spotlighted. These are small and medium-sized businesses that supply to other companies and are at the top in their niche in Europe or even further afield, but virtually unknown to the public at large. These companies are at the top because they are innovative and often apply aspects of smart industry.

The series of films on hidden champions was begun during ZIE. The honour of this opening went to tbp electronics, from Dirksland. An innovative supplier of electronics, which has already introduced far-reaching automation into its production, warehouse, purchasing and even invoicing. The next step requires machine-to-machine communication. Easier said than done, as the production machines come from various suppliers and are not really prepared to this. In a short film and accompanying inter-view, Ton Plooy, director and owner of tbp electronics, tells how he nevertheless aims to take a step in this direction.

And there's more

The annual ZIE company fair is also a good opportunity for getting to know other hidden champions from the West Netherlands. There also were a couple of good examples in the three other parallel sessions, from other regions as well.

3 *Cor Heijwegen, president and owner of Hittech Group, thanked the ZIE sponsors during his last lecture as president of Holland Instrumentation.*

The session HI organised with Brainport Industries presented high-end flow meter manufacturer Bronkhorst High-Tech from Ruurlo and vision & robotics supplier Beltech from Eindhoven. Clean Tech Delta presented Parhelion from Rotterdam, who are working with smart, energy-efficient lighting, and Chess-Wise from Haarlem, who are experts on connectivity. Finally, The Hague Security Delta, S&T (Delft) and Tensing Safety & Security (Waardenburg) presented two examples of innovative companies in the field of safety and (cyber) security. Six examples of smart industry in practice.

Holland Instrumentation

ZIE is organised by Holland Instrumentation (HI), the West Netherlands high-tech platform. HI supports the regional network of high-tech companies, knowledge institutions and governments across sectors, as high-tech occurs in all sectors where technological innovation plays a role, presenting multiple mutual learning opportunities. HI therefore also co-operates with many other organisations. Putting the high-tech network on the map is also a major objective.

This year, five years after its establishment, HI underwent a major makeover. A new logo, a new website and the expansion from South Holland to West Holland have opened up new roads. At ZIE-2017, Cor Heijwegen, Hittech, who helped set up and shape HI, stepped down as president. His successor is André Boer, general manager of Krohne Altometer.

WWW.HOLLANDINSTRUMENTATION.NL

PRACTICAL UNDERSTANDING OF COMPLEX MECHATRONIC SYSTEMS

This spring, Mikrocentrum will start a new course for higher educated engineers. During the five-day courses, Sven Hol, Ph.D., will discuss the theoretical aspects of the various disciplines within the field of mechatronics, after which the participants will familiarise themselves with modelling, simulating and controlling mechatronic systems.

AD SPIJKERS

Even though the Applied Mechatronics course is suitable for every branch of the industry, it focuses mainly on those manufacturing processes that require increased dynamics and precision. This counts for the actual manufacturing of (parts of) the product, but also for assembly, pick & place, and handling systems.

Need for mechatronic know-how

Mechatronics is an engineering discipline that combines mechanics, electronics, control engineering and computer science. This combination prevents creating suboptimal solutions to a control problem in a single discipline. Factors such as thermal management, friction, stability and performance are taken into account as well.

An increasing number of companies eventually has to deal with different disciplines through their original discipline (particularly in the case of mechanical/precision engineering). Often the knowledge of and experience in these other disciplines are lacking. Moreover, there seems to be much to gain from the integration of the various disciplines. Sven Hol and Mikrocentrum noticed that a practically focused, high-level course revolving around these aspects was much needed. In consultation with Mikrocentrum, which wanted to include a practical aspect, Sven Hol developed the current course.

Target group

The training is aimed at people in the industry who are already familiar with mechatronics, such as system architects, mechatronic designers, machine engineers, electrical engineers, software and firmware developers. The training assumes a higher education level (HBO+ or university) and at least two years of work experience with mechatronics. It has been constructed in such a way that a specialist in one discipline can still understand the theory and practice of the other disciplines. After the course, he/she will be able to combine these less familiar disciplines with his/her own know-how.

Mikrocentrum's intended audience for the course are companies that deal with mechatronic systems for which they require precise and controlled motion and strive for increased speed and productivity. Next to high-tech companies, these can be manufacturers of office equipment (e.g. copiers), packaging, sorting or assembly machines, and medical equipment as well. But also their suppliers seem to feel the need for more knowledge, in order to understand what their customers are working on.

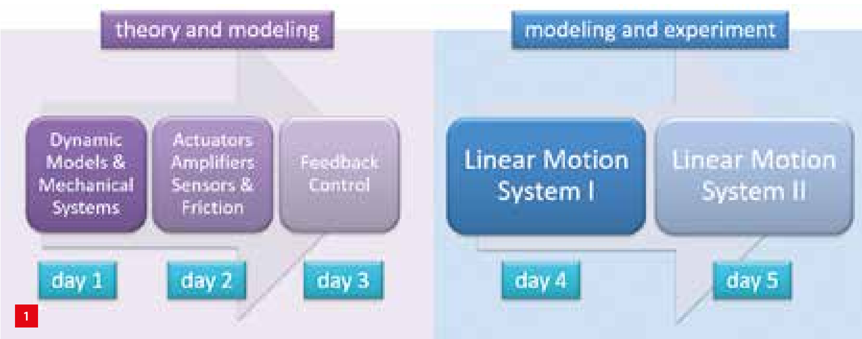
The course is also relevant when it comes to heavy machinery (such as (road) construction equipment, agricultural machinery, recycling systems or internal transportation). A higher positioning accuracy often is not relevant here. But these companies often do aim for higher productivity, lower environmental taxes, lower energy consumption and data recording. Mechatronics can play a significant part in attaining those objectives.

Set-up

The course lasts five days (Figure 1): three days for mostly theory, modelling and simulating, followed by two days of practice. During the first three days, the various disciplines will be discussed including their mathematical models. These will eventually be merged in one complete model. The objective of the theoretical part is making the model for a demo system, which will then be tested during the two practical days and used for calculations and measurement.

AUTHOR'S NOTE

This article was contributed by Mikrocentrum. Ad Spijkers is a freelance writer and former editor-in-chief at Eisma Industrialmedia and Reed Business.



1 *Course content.*

2 *Sven Hol showing the demo system that course participants can work on.*

On the first day, mostly mechanics will be discussed. Participants will learn the meaning of mechanical quantities and of mass, stiffness and damping and how to put them into models. Sensors and actuators are the topic of the second day. A closer look will be taken at different kinds of drives, sensors and amplifiers and how these match the intended application and performance. The participants will make models in the frequency domain (where they will learn how to interpret and deal with resonances, among other artifacts) and in the time domain (how a process develops through time).

On the third day, PID control, feedback and feedforward will be discussed. The participants will make and implement their own mechanism and test its validity. The focus will also be on the response, sensitivity and stability (margin) of the controller and the performance of the complete system. With the various building blocks the participants will finally build one complete model. The modelling process will be realised with mathematical computing tools, MatLab and Simulink. The models and tools are such that newcomers can use them as well. Lastly, practical implementation and fine-tuning will be discussed.

On the fourth and fifth day, both the theory and the constructed system will be assessed by means of a demo system that Sven Hol has developed himself and built with the aid of Mikrocentum and a number or partners.

Experimenting

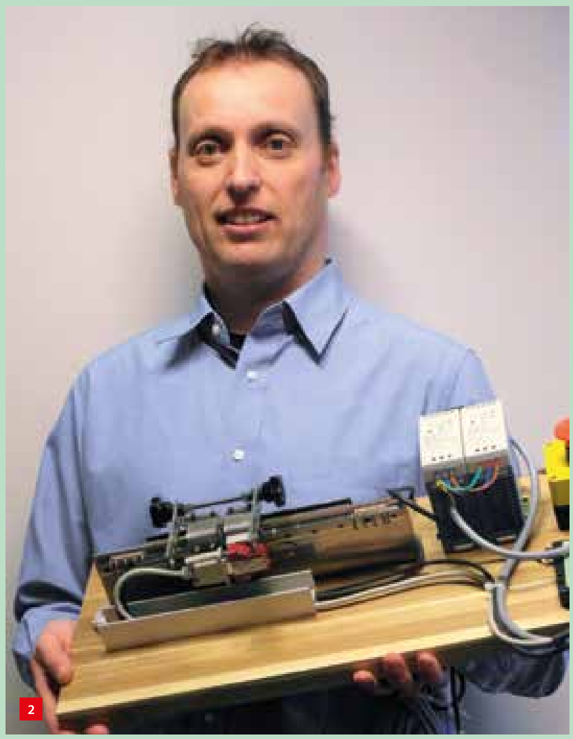
Participants can work on a demo system, i.e. a single-axis linear system. Multiple axes will obviously make a system more complex; however, every axis can be modelled in the same way. In order for the system to work properly, a coupled control strategy is then needed, for instance, a master-slave system with a multiple-axis controller.

The mechanism consists of a guidance track with two so-called 'stages' that can move independently. Behind, there is an array of magnets, which creates a linear motor. The stages contain a small three-phase coil system and when activated, the stages can move along the magnet array. A linear encoder is placed on the guidance track in order to determine the position of the stages accurately.

The two stages are connected by a fixed rod, which can be placed in several positions between two leaf springs. In this way, different degrees of stiffness (from a very stiff transfer to a very weak one) can be accomplished. The stiffness between the actuated stage and the measurement stage influences the performance and stability of the entire system. During the practical part, the participants will experience how the demo system reacts to changes in stiffness and motor control. In this way, a very realistic experiment for the participants will lead to a solid understanding of complex mechatronic systems.

Teacher

Sven Hol studied Mechanical and Automation Engineering at the University of Twente, the Netherlands, and received his Ph.D. in Mechatronic Design at the Eindhoven University of Technology, the Netherlands. At ASML he held several functions, including electro-mechanical designer, customer service manager at ASML Japan, and researcher. Currently, he is a mechatronic architect at ASML and works as an independent consultant helping other companies with mechatronic challenges.



INFORMATION

The course starts on 30 May 2017 at Mikrocentrum's training centre in Veldhoven, the Netherlands.
Contact: Wouter Lintsen, +31 40 296 99 33 (tel.).
WWW.MIKROCENTRUM.NL

IIOT, AI, MEDTECH AND OEM CHALLENGES

The fifth edition of High-Tech Systems was organised by Techwatch as a one-day conference and exhibition with the focus on high-tech systems and key enabling technologies. HTS 2017 took place last month in Eindhoven, the Netherlands, and featured four tracks: Industrial Internet of Things (IIoT), Artificial Intelligence (AI), Medical Technology, and OEM Challenges. DSPE was one of the partners of the event.

Keynote

The keynote was delivered by Lars Idema, Department Head Mechanical Development at Océ R&D, Océ-Technologies. He addressed two challenges of tech companies: multiple product specs, and 'development beliefs'. "We try to unify both of them by modelling. Stop building machines, start model-based product development."

In mature markets, competition is about total cost of ownership rather than just cost, productivity in stead of speed. In total, maybe 25+ product aspects have to be managed during development. In the architectural phase, Océ, part of the Canon group, tries to connect product-level specs to technical models. This raises a lot of new questions on working methods, tooling and skills.

Regarding 'tech churches' defending 'development beliefs', Idema distinguished the Ironmen – "building is what we do" – and the Sims, "going virtual all the way". "Both are right in their own way, but how to harvest both their paradigms in product and even platform development?" Perhaps a virtual twin manifesto is needed: "Physical prototypes are essential but virtual ones will make the difference."

Idema illustrated the two key challenges with examples from the printing industry, which is moving from printing *on* things towards printing *of* things.

IIoT consortium

Georgio Angelis, Fellow of the High Tech Systems Center at Eindhoven University of Technology, introduced the initiative of building an IIoT consortium. "The IIoT shows every sign of a rapidly transforming industry. Gathering, analysing and sharing of meaningful and actionable data between systems to improve productivity and quality will unlock a lot of value. Our offer is to put industry's key technological challenges in this area on our research agenda." Angelis showed an IIoT technology map which will be used as a starting point to guide parties through the technological challenges.

Late last year, during the HTSC TU/e Consortium Day, areas of common interest for IIoT research were identified. Next, on 11 May 2017, a full-day IIoT consortium building workshop will be organised to facilitate industry-academia collaboration. Angelis invited interested parties to join this initiative. The new IIoT consortium will address applications, technologies and business models (Figure 1).

Social robotics

In the Artificial Intelligence track, Gwenn Englebienne, Assistant Professor in the Human Media Interaction group at University of Twente, talked about machine learning in social robotics. "As humans, we exhibit very complex and varied behaviour, which is adapted to our physical environment, our social environment, the context we are in, etc. Computers are only beginning to scratch the surface of this exciting world. Yet as they become more pervasive in our environment, correctly assessing the humans' context and social situation is becoming crucial to the interfacing between humans and computers." Englebienne discussed the use of machine learning and computer vision techniques for accurately recognising this context.

Co-development of medical devices

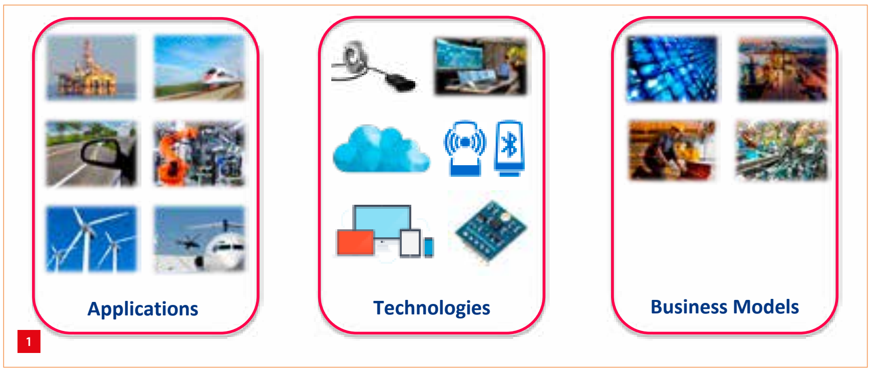
Joris Jaspers, Head of the UMC Utrecht Department of Medical Technology Innovation, gave an overview of high-tech medical equipment used in hospitals, their claims and the clinical evidence available. The common technology-driven approach delivers devices which sometimes have a very small diagnostic or therapeutic bandwidth, often come on top of the existing devices and increase healthcare cost. As an alternative, Jaspers provided some insights and examples regarding the development of medical devices from a clinical-driven approach and how these devices meet clinical needs. In his vision medical devices should be co-developed in close relation between engineers, hospitals and the industry, for the benefit of patients and healthcare workers.

Advanced packaging

Start-up company Liteq, based in Eindhoven, promises to unlock the full potential of lithography for advanced packaging. That was the message of CEO Gerrit van der Beek's presentation at HTS 2017. Liteq has developed a lithographic system for the advanced packaging market starting with the specific requirements of this market in mind, unlike other lithography providers that modified existing systems resulting in solutions with lots of compromises.

"The advanced packaging market is on the move since front-end lithography is no longer capable of following Moore's law in a cost-effective way. Instead the world has discovered the solutions that advanced packaging is offering to support the ever-increasing demand for integrated functionality in the form of small and thin devices with low power consumption, high bandwidth, low latency and against low cost. Here, lithography is the enabling technology", according to Van der Beek (Figure 3).

Liteq developed a dedicated lithography stepper for the advanced packaging market. Special attention has been given to advanced-packaging-specific functionality such as warped wafer handling, contamination control and wafer edge processing supporting modern plating process technology. The Liteq system's architecture is highly modular and is designed to support upgrades in the field of all new developed options and functionality. ■



1 *The new IIoT consortium will address applications, technologies and business models.*

2 *Co-development required. For non-technical experts: strength and stiffness are crucial mechanical properties of many 'constructions'. For non-medical experts: the fibula is the calf bone in the human leg.*

3 *Gerrit van de Beek, CEO of Liteq: "We employ lithography as the enabling technology for advanced packaging." (Photo: Techwatch)*

INFORMATION
WWW.HIGHTECHSYSTEMS.EU
WWW.OCE.COM
WWW.TUE.NL/HTSC
HMI.EWI.UTWENTE.NL
WWW.UMCUTRECHT.NL
WWW.LITEQ.NL

STUDENT-SUPPLIER COLLABORATION

The solution to stabilising the soldering process for assembling a small temperature sensor lay in automation, but the time available for developing such a solution was very limited. Using Festo's standard H-gantry combined with a standard soldering machine and a self-developed product container, mechatronics student Michael van Dam succeeded in designing and building a working system in eleven weeks.

EDITORIAL NOTE

This article has been contributed by Festo Nederland, supplier of automation technology, based in Delft (NL).

www.festo.nl

Much of the work at assembly company CentWerk in Delft, the Netherlands, is performed manually, but automation is increasingly developed for the assembly of large quantities, in this case, several hundred thousand to over one million, says Gerben Romberg of CentWerk. "Achieving a faster process and a more consistent quality product is just one of the many compelling reasons for automating part of a process."

Temperature sensor

Thus, a decision was made to automate the soldering processes involved in assembling a temperature sensor for boilers, among other things. This product consists of a connector housing with two metal pins to which the two wires of the temperature sensor are soldered. A large number of parameters go into making a good solder joint. For example, the amount of solder, the distance from the soldering iron to the product and the number of seconds the soldering iron is in contact with the solder.

Given the complexity of this manual process, CentWerk regularly had to contend with solder joints of variable quality. Which made the soldering process eligible for automation. A task that was assigned to trainee Michael van Dam, mechatronics student at The Hague University of Applied Sciences in Delft.

Clamping problem

"As it turned out, the problem was not in the soldering process itself, but in how you clamp the connector housing and connect it to the sensor," says Van Dam. He solved this problem by developing a product container into which the employees place the housings by hand. A mould with two small funnel-shaped openings, positioned exactly in front of the pins of the housing, is then placed on top of this. The sensor legs are inserted by hand into the openings, positioning them precisely above the pins.

When a product container is full, it is placed against a stop in the soldering unit; five containers fit in the current configuration. A soldering iron then automatically carries out all the steps required to make the solder joints, moving linearly across the product container and lowering briefly to make a solder joint at each spot where the product is applied. At the same time, 5 mm solder is automatically supplied from a standard solder feeder with stepper motor.

Standard

Because of the limited training time of eleven weeks, Van Dam did not have the opportunity to design and build from scratch a set-up made of stand-alone components. This led him to contact the automation technology supplier Festo, which is also based in Delft. Going off Van Dam's idea, Festo suggested using a standard H-gantry system, the compact handling system YXMx (see the box).

Van Dam believes this is a good solution. "The gantry is a standard product for a reasonable price. It is also a complete

1 *The automated soldering station at CentWerk.*

system that comes with a PLC control, software and vision – plug & play. The Codesys V3 programming software, for example, simplified the programming of such things as the soldering iron motion pattern as many of the functions were already available."

The soldering iron's movement was initially programmed as a sequence of straight-line movements: in the x-y-plane to the point above the connector housing and then in the z-direction towards the solder point. In the final solution, the soldering iron moves following an optimum curve – x, y and z are synchronised – directly to the solder point (soft motion functionality), reducing the lead time.

Conclusion

By using the standard H-gantry in conjunction with an existing solder feeder, Michael van Dam was able to successfully realise an automated soldering station (Figure 1) within eleven weeks. Festo was always available for questions, made a demo system of the gantry available for a quick start and offered a programming course.

Specifications of YXMx

The YXMx gantry system is a flat gantry-based system based on Festo's EXCM-30 axes. Two ServoLite motors (stepper motors with encoder and servo control) and a toothed belt enable the x- and y-movements. An auxiliary z-axis enables the movements to and from the underlying product.

Default range values are 100...700 mm (X), 110...510 mm (Y) and 75...125 mm (Z). The repeat positioning accuracy is 0.1 mm in the x- and y-direction, and even 0.01 mm for the z-direction, which is rather over-dimensioned for the application described here. Maximum speed and acceleration are 0.5 m/s and 10 m/s^2, respectively.
The cycle time for the cascade servo control is 2 or 4 ms.

INFORMATION
WWW.CENTWERK.NL
WWW.DEHAAGSEHOGESCHOOL.NL

GOOD VIBRATIONS AT MECAL

At the end of March, DSPE organised a Precision-in-Business day (i.e. afternoon) at Mecal in Eindhoven. Mecal is an independent engineering consultancy and design house providing a wide range of integrated OEM product solutions in the global Wind/Energy and High-tech/Systems markets. Mecal counts over 130 employees and has offices in the Netherlands (Enschede (HQ), Eindhoven and Groningen), Denmark, USA, China and Japan.

For an audience of about twenty, CTO Bernhard Bakker gave a brief introduction to Mecal. He talked about the transition of his firm, established in 1989, from an engineering consultancy to a technology company. Mecal – the name is short for mechanical calculations – started off with analytical services, using finite-element methods, and gradually expanded, adding (model-based) development, engineering, prototyping and series production to its portfolio.

In the process, Mecal has built a wide range of mechatronic competencies, including manufacturing, logistics and installation. An extended cleanroom facility will soon be added to the Eindhoven offices. IP licensing and OEM product sales today account for a significant part of the revenue. One of Mecal's products is a pedestal for high-end equipment in semiconductor fabs.

Predictive modelling

Walfred Maas, group leader Analysis at Mecal, then discussed the changing world of predictive modelling. He gave a brief overview of the evolution in his field, from mechanical calculations on single components using simple models in 1989, the birth year of Mecal, and more advanced finite-element simulations using more detailed system models, including thermal and flow behaviour, around 2000, to far more accurate, shorter-lead time analysis of complex system models featuring more degrees of freedom, including full geometry and multi-physics behaviour.

Due to the evolution of hardware (Moore's Law for computer chips) calculations can now be performed two to three orders of magnitude faster than twenty years ago. This in turn enables the development of more advanced equipment, e.g. EUV lithography machines, which allow for the manufacture of even more advanced hardware, facilitating even faster calculations, etc., etc.

Maas continued by touching upon new analytical trends instigated by the software and hardware advancements. These included new solutions in the design of accurate positioning stages – design by damping, and overdetermined actuation – as well as the inclusion of plasma physics in computational fluid dynamics models for EUV source development. In general, multi-physics is entering the field of analysis, although really multi-physical model studies are still far from commonplace. Another upcoming computational technique is topology optimisation, following the rise of 3D printing, which radically offers the full potential of freeform geometry.

Increasingly, simulations are used in real-time feedforward process control; model order reduction is then required to keep the computational effort within reasonable bounds. When more computing power is needed, improved parallelisation of solver algorithms offers a solution. Parallel/High-Performance Computing becomes increasingly accessible, thanks to companies offering this solution via the 'cloud'. Finally, simulations play their part in the model-based design of experiments; the exploration of parameters in design space can help to validate design choices and shorten the development process by reducing the need for physical prototyping.

Analytical software is not only becoming more and more advanced, it also gains in user friendliness, so that engineers can more confidently perform routine calculations themselves. Hence, the role of analytical service providers, such as Mecal, is changing. They have to focus on the more advanced jobs, customised analytical tooling, problem identification, and interpretation of results. This calls for customer intimacy, Maas concluded.

The Precision-in-business day was concluded with a tour of Mecal's prototyping workshop. Mecal's new vibration cancellation solution, the Equalizer, attracted considerable interest.

Vibration suppression

Bringing Mecal's technology to the market is the primary concern of Johan van Seggelen, business development manager at Mecal. He introduced one of Mecal's spearheads, active vibration isolation. Some ten years ago, Mecal, in collaboration with TNO, developed the Hummingbird platform in response to the growing need for highly effective, robust and affordable vibration reduction systems. It combined new and existing technologies, in order to significantly reduce floor vibrations and to suppress disturbances caused by machine movement, ranging from very low to high frequencies. The Hummingbird technology has been installed, for example, as a vibration filter between a ceiling and a microscope in an academic hospital, and in the pedestals which Mecal supplies to semiconductor fabs all over the world.

Mecal has recently introduced a new vibration reduction solution, which is named Equalizer, an active inertial cancellation system that is designed to counteract vibrations, especially in the 20-80 Hz frequency band. The Equalizer is capable of reducing vibrations over a large floor area by a factor of 3 to 5. It can easily be installed around precision machines or, for example, in buildings where vibrations from passing trains have to be suppressed. The Equalizer offers a scalable solution; Mecal's modelling competencies can help to determine the strategic locations of multiple Equalizers that yield the best, 'quietest' result.

WWW.MECAL.NL

Precision education at a high level: bronze ECP^2 certificate for Joris Looman (ASML)

Joris Looman, Lead Design Engineer Opto-Mechanics at ASML, has obtained the Bronze ECP^2 certificate for courses certified in the ECP^2 programme, the European certified precision engineering course programme (see also page 62). He participated in the Summerschool Opto-Mechatronics, a DSPE initiative, and took the post-graduate courses Design Principles Basics, Applied Optics, Mechatronics System Design - part 1 and part 2, and Thermal Effects in Mechatronic Systems at The High Tech Institute. With a total of 29.5 points (each point representing one course day), he easily met the certificate's condition of obtaining 25 points within five years. It made him the third engineer to receive the Bronze ECP^2 certificate since certifying precision engineering courses started in 2009. In 2015, the DSPE initiative was scaled up to the European level.

The courses mentioned represent a kind of standard curriculum for ASML engineers, says Edwin Krijnen, Manager Development Mechanics Sensors & Measurement. They certainly do for his group, of which Joris Looman is a member. "As a lead engineer, Joris is in charge of a specific NXE sensor. He does a lot of opto-mechanical work and, for instance, has to design stable opto-mechanical constructions. In developing the hardware for sensors and measuring systems, we draw upon the subjects of the courses every day in our group, because these sensors have to measure at the nanometer level. For our opto-mechanics group, the ECP^2-certified courses are a fairly complete offer. It's the combination of disciplines which makes this offer unique."

Joris Looman cutting the cake for his colleagues after receiving the Bronze ECP^2 certificate.

ECP² COURSE CALENDAR

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

ECP² program powered by euspen

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

ECP2EU.WPENGINE.COM

Course providers

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

Content partners

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

The world's first selective asparagus harvesting machine

In mid-April, on a field in Heeze, in the Dutch province of Noord-Brabant, Cerescon presented its asparagus harvesting machine. The machine is selective, as it only cuts harvest-ripe asparagus, with a better quality than that obtained by means of manual cutting, and it solves the problem of high labour costs in Western Europe. Cerescon is the company of CTO Ad Vermeer (freelance high-tech system designer, working for SoLayTec, Liteq and others), his wife and CEO Thérèse van Vinken (formerly engaged in project management and marketing (communications) at Philips, FEI and ASML) and private investor Cees Welten.

Ad Vermeer's brother Marc, asparagus producer, came up with the idea and acted as the driving force in the development. Sadly, he passed away late 2014 at the age of 51. According to him, asparagus production in Western Europe was threatened by German legislation that labourers from outside Germany should receive the minimum wage of 9 euros/hour instead of the usual 6 euros/hour. An asparagus harvesting machine could offer the solution and brother Ad was to invent it. To that end, Cerescon was established and large, innovation-keen producers were recruited for a user group.

First challenge: how does the machine find – 'see' – the asparagus to be cut? Moreover, harvesting asparagus that have appeared above the ground is not optimal, as violet discolouring due to sunlight decreases their value. Therefore, the machine should detect and harvest the asparagus underground. Radar did not appear to work, and X-ray had too many drawbacks. The next idea: little ultra-thin bars that gently 'plough' through the sand bed and are fitted with a touch sensor, can automatically determine the location of an asparagus, after which the coordinates are sent to an automatic cutting unit. The concept worked, but the user group wasn't convinced: the little bars would slightly damage the asparagus. Disturbing the sand bed, however, turned out not to be a problem.

Ad Vermeer: "That was the breakthrough. I only had to replace the touch sensor with a sensor which detects water, as an asparagus mainly consists of water. After that, thousands of technical, practical and organisational problems would pop up, but that would only be a matter of hard work to deal with them. The fundamental problem had been resolved."

Cerescon's asparagus harvesting machine, which will enter the market in 2019, has many advantages, such as much lower labour costs and higher revenue because of better quality. Perhaps the biggest advantage: because the machine can look deep into the ground, it can harvest asparagus that manual cutters can only spot tomorrow or the day after. Therefore, the machine can harvest in one round the same amount that 60-75 manual cutters achieve in three days.

A Brabant family thus developed the world's first asparagus harvesting machine, which can also select whether to cut or not. The fact that people are still required for picking tomatoes, strawberries or peppers, is not because machines are not able to pick tomatoes, etc., but because only humans are able to distinguish a ripe tomato from one that should be left hanging for a while. There's a world to be gained for selective harvesting machines.

WWW.CERESCON.COM

Thérèse van Vinken and Ad Vermeer of Cerescon with their asparagus harvesting machine.

Fontys conducts research into human-robot cooperation

The School of Engineering at Fontys University of Applied Sciences in Eindhoven, the Netherlands, is pursuing research into adaptive robotics and human-robot interaction in high-mix, low-volume, high-complexity processes. The research, titled "(G)een Moer Aan" (Nuts and Bolts of Robotics), is the brainchild of the Fontys Professor of Mechatronics & Robotics, Henk Kiela. Project partners include fellow universities of applied sciences, other research institutions, industry associations, the Municipality of Eindhoven and a number of SMEs. Funding comes from the RAAK-MKB (Regional Attention and Action for Knowledge Circulation - SME) scheme of the Nationaal Regieorgaan Praktijkgericht Onderzoek SIA (National Taskforce for Applied Research SIA).

In the ever-changing world of mass production, it is important to have people and robots working together within production systems so that they can adapt, quickly and at low start-up costs, to new production conditions. The primary aim of the research project is to make reconfiguration of a robot system for a new task in a production environment as simple as possible; just as simple as 'using a smartphone'. As per the request of the SME partners involved, the focus of the research is a repetitive manufacturing process, which is all too common in many sectors and is rather labour- and time-consuming: inserting nuts and bolts into an object.

The central research question is: "How can an operator easily, quickly and safely, teach a robot to perform assembly tasks so that it can fit nuts, bolts and washers to objects in a fast and robust manner?" "We have long been looking into how we can use robotics to take over routine tasks from staff", says Henk Kiela. "We are going to see if we can speed up these activities through robotisation."

The result of this field-based research project is a design methodology for the set-up of a user-friendly user interface of a bolt-inserting robot in the workplace. Smart use of integrated CAD product information, vision technology and

Robotic research at Fontys.

compliant gripping and placing technology will make it possible to pre-configure the robot automatically as much as possible. "But the operator will still continue to play an important role; he can perform other tasks during the time that is freed up. The research must also contribute to maintaining and improving employment in the manufacturing industry."

The research builds on existing systems and software. Over the next two years, the project group hopes to present a demonstrator that can automatically place nuts and bolts into an assembly using a CAD drawing.

WWW.FONTYS.NL

New: Holland Robotics

In late February, industry association High Tech NL undertook an initiative to bring together industrial companies and scientific institutions for ambitious robotic ventures. Holland Robotics must ensure that robotics knowledge is fully utilised in the Netherlands in order to strengthen its international competitiveness.

Holland Robotics, successor to the earlier initiative RoboNed, is a national robotics community that takes national collaboration between science, industry and robotics entities to a higher level. With High Tech NL as a catalyst, the four technical universities (Delft, Eindhoven, Enschede and Wageningen), the Vrije Universiteit Amsterdam and the University of Groningen have joined forces with industrial companies Demcon, VDL ETG, Philips, Lely and Vanderlande. Another dozen or so large industrial companies will also join the community; Holland Robotics is open to any company that wishes to contribute to this initiative.

"Holland Robotics is dedicated to addressing and meeting the needs of the scientific community", says Maarten Steinbuch, Scientific Director of the High Tech Systems Center at Eindhoven University of Technology. "It is important that RoboNed's legacy is gaining new momentum and that we will be fulfilling a scientific innovation agenda at national level." Dennis Schipper, Managing Director of Demcon, echoes that sentiment on behalf of the industry partners. "Thanks to this platform, the industry can take the lead in designing a serious technology roadmap in order to put the future of Dutch robotics on the agenda." Holland Robotics also paves the way for a formal research consortium of scientists and industry, which will conduct long-term research in applications that are important for the high-tech industry.

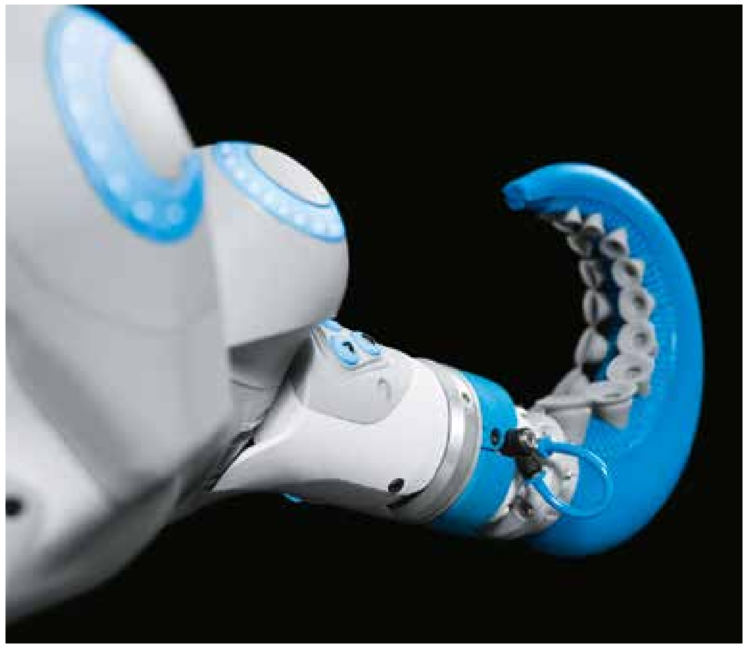
WWW.HIGHTECHNL.NL/INNOVATIE/HOLLAND-ROBOTICS

A bionic approach to robotics

Lightweight robots with pneumatic drives working in collaboration with humans, and a gripper modelled on the octopus's tentacles: the engineers from the Bionic Learning Network of Festo presented three future-oriented concepts at the Hannover Messe 2017 trade fair. While the BionicCobot is inspired by the natural movement of the human arm, the BionicMotionRobot is based on the elephant's trunk and the octopus's tentacles from the animal kingdom. A new bionic grasping device, the OctopusGripper, is likewise derived from the octopus. All three projects show what hazard-free, direct human-robot collaboration could look like in future.

Over ten years ago, Festo initiated the Bionic Learning Network, which is closely linked with the processes of innovation within the company. In cooperation with students, renowned universities, institutes and development companies, Festo sponsors projects, testbeds and technology platforms. The objective is to benefit from bionics as a source of inspiration for new technologies and to realise these in industrial automation.

Robots could be used as assistance systems for relieving the human operator above all in monotonous or dangerous work processes. The strict separation between the tasks of humans and those of robots is now increasingly making way for a collaborative working space. The new bionic lightweight robots are ideally suited for safe human-robot collaboration by reason of their natural movement patterns and their inherently flexible pneumatics. They can be a cost-efficient alternative to classic robot concepts in future.



■ *The OctopusGripper: grasping based on the model of the octopus's tentacles. (Photo: Festo)*

The movement patterns of the BionicCobot are modelled on those of the human arm, from the shoulder via the upper arm, elbow, radius and ulna down to its gripping hand. Each of its seven joints makes use of the natural operating mechanism of the biceps and triceps – the efficient interplay of flexor and extensor muscles. It can thus execute very delicate movements, just like its biological model, finely regulated so as to be either powerful and dynamic, or sensitive and readily yielding; the system therefore cannot endanger humans even in the case of a collision. This is made possible by the Festo Motion Terminal, a pneumatic automation platform that unites high-precision mechanics, sensors and complex control and measuring technology within a very small space. Depending on the task to be carried out, the BionicCobot can be fitted with different gripping systems.

The OctopusGripper consists of a soft silicone structure that can be pneumatically controlled. If compressed air is applied to it, the tentacle bends inwards and can wrap around the object being gripped in a form-fitting and gentle manner. Just as with its natural model, two rows of actively and passively controlled suction cups are arranged on the inside of the silicone tentacle. This enables the OctopusGripper to pick up and hold a large number of differently shaped objects. Thanks to its soft, inherently flexible structure, the OctopusGripper has great potential for use in collaborative working spaces in the future.

WWW.FESTO.COM/BIONICS

Release 2017a of MATLAB and Simulink

MathWorks recently introduced Release 2017a (R2017a) with a range of new capabilities in its mathematical computing software, MATLAB and Simulink. R2017a includes a new product, Automated Driving System Toolbox, which helps design, simulate, and test ADAS (advanced driver assistance systems) and autonomous driving systems. MATLAB updates also include additional deep learning algorithms and visualisation in the Neural Network Toolbox, and deep learning functionality in the Computer Vision System Toolbox.

WWW.MATHWORKS.COM

i-Botics: telerobotics and exoskeletons

The independent research centre i-Botics, an open innovation centre for R&D in interaction robotics, has been founded by TNO and University of Twente. Programmatic research and technology development will be combined with dedicated projects. Two research lines have been selected: telerobotics and exoskeletons.

Telerobotics is concerned with remotely controlled robots, possibly semi-autonomous, in which telepresence and teleoperations are combined. Telerobotics are used in operations for many applications and domains, like (petro)chemical industry, healthcare and defense, and by large asset owners on land, subsea and in space.

The i-Botics approach is to provide the human operator with full perceptual and manipulation capabilities to intuitively perceive the remote environment and act as if being present at the remote site, combining the cognitive ability of the human operator with the robotic capabilities at a distance. However, this poses big challenges, which i-Botics will address, like the 'situational awareness' of the human operator, 'robotic sensing' and 'adaptive automation' for partial autonomy.

An exoskeleton is a wearable user-guided robot that will become common practice in a diversity of applications. One type of exoskeleton application is telepresence: complex manipulations are performed by a person wearing an (arm-hand) exoskeleton, hereby intuitively steering a robot on a distance who does the job. Another type of application can be found in the medical, military and industrial field. Here, the man does the job and the exoskeleton provides mechanical power to the human body to give support in physical activities. Either to support disabled people, to empower soldiers, or to keep workers healthy.

Despite the vast interest in exoskeletons, several technological issues hinder the acceptance and use. The ambition of i-Botics is to bring easy-to-wear active exoskeletons for human enhancement a major step forward, i.e. make them flexible, fast and comfortable, as well as applicable, useful and accepted in practice.

WWW.I-BOTICS.COM

Telstar and Brecon sign collaboration agreement

The Telstar Group, headquartered in Barcelona, Spain, and part of the Japanese listed corporation AZBIL, has recently decided to cease its activities in the construction of cleanrooms (previously also known as LUWA) in the Benelux and to fully focus on its Life Science, Vacuum and Instruments solutions. Many Telstar products are utilised in a cleanroom environment. Obviously it remains very important for Telstar that the areas where its products are placed are of high quality and continue to meet the GMP requirements in full.

Brecon Cleanroom Systems, part of the Brecon Group in Etten-Leur, the Netherlands, has gained Telstar's full confidence for the construction of such an environment. Therefore, Telstar has formally transferred the cleanroom construction activities to Brecon in a partnership agreement. Telstar, in the Netherlands established in Utrecht, will continue to provide its services to existing customers for technical maintenance, after sales and/or validation, etc. However, for structural adjustments in cleanrooms built by Telstar and/or new construction projects, Telstar will from now on refer to its partner, Brecon.

Brecon specialises in the design and construction of dust-free, germ-proof cleanroom systems, for example more than 50,000 m^2 of cleanrooms at the ASML campus in Veldhoven, the Netherlands.
In addition to the semiconductor market, Brecon also serves the pharmaceutical, medical devices, food and other markets that operate in a GMP-regulated environment. Brecon is initiator of the PP4C concept, a partnership between specialised companies for turnkey cleanroom construction. On both the Dutch and the export market, the Brecon Group offers an all-in range of services and products (disposables, clothing, cleaning, training, furniture, etc.).

WWW.TELSTAR.COM

WWW.BRECON.NL

EBL2 commissioning

Since 2000, TNO has been active in EUV material interaction research, developing the second generation EUV exposure and in-situ surface analysis facility – dubbed EBL2 – to accommodate the ASML power roadmap. This system will give customers the opportunity to evaluate their materials/components in terms of EUV irradiation and environmental conditions in order to address contamination and lifetime challenges.

The EUV Beam Line 2 (EBL2) is the main facility for EUV development at TNO's International Centre for Contamination Control (ICCC) in Delft, the Netherlands. Late last month, EBL2 was officially commissioned. The compound system consists of a beam line for EUV exposure testing in a controlled environment, and an XPS for surface analysis. Samples can be transferred between beam line and XPS without any disruption to the vacuum.

The ICCC is dedicated to developing the highest standards and practices in contamination control to eliminate both particle and molecular contamination. The centre is equipped with the most advanced facilities, including ultra-clean handling equipment for EUV masks, inspection and analysis tools for both particle and molecular contamination, as well as various other inspection and cleaning equipment.

WWW.TNO.NL/ICCC

■ *View of the EBL2 set-up.*

Technobis launches the AeroGator

Technobis, the Alkmaar-based Dutch manufacturer of integrated photonics based fibre-sensing systems and devices, has launched its new miniature fibre-sensing product, the AeroGator, which has been specifically designed towards multi-parameter aerospace applications. "Full solid-state, multi-channel, fibre-sensing versatility, fitting into a miniature turnkey solution, has not been easy, but we made it work", says Program Manager Aeronautics and Space, Rolf Evenblij. "Aircraft manufacturers and avionics suppliers have been waiting a long time for airworthy devices to make fibre sensing technically and economically viable in aircraft."

Technobis has been developing and providing fibre-sensing systems since 2006 for a wide range of applications and environments. Starting with free-space optics, now since five years based on photonic integrated circuit (PIC) technology, Technobis has introduced sensing solutions providing up to sub-femtometer wavelength-shift detection resolution, sub-nanometer displacement sensing resolution and sampling rates up to 20 Mhz. Using miniature and high-performance acquisition and control electronics, combined with the ease of compatible PIC packages

replacement, allows multi-parameter fibre-sensing solutions, such as damage and impact detection, load monitoring, shape sensing, distributed fibre bragg grating sensing and more.

WWW.TECHNOBIS.COM

NEWS

Plug & play fibre connection for scan systems

Scanlab, a leading OEM manufacturer of scan solutions, based in Puchheim, Germany, has introduced a new collimation module for reliable connection of fibre-coupled lasers. This industrial-strength fibre coupler helps transform scan heads into a system that can be easily integrated in laser processing machines. When combined with disk or fibre lasers (particularly lasers of higher power classes up to 5 kW), cost-efficient welding and cutting applications can be realised, e.g. in car manufacturing and metal processing.

Scanlab's new collimation module transforms its larger-aperture scan systems – typically 30 mm – into flexible, combinable 2D scan solutions for welding and cutting processes. Compared to an integrated 3-axis system fibre-laser-based processing systems are substantially lower in cost. The new module's industrial suitability is underscored by a robust fibre-coupler housing with water-cooled stainless steel entrance aperture, as well as a replaceable window protecting the collimation optic. Additionally, the collimation optic is manually adjustable for very precisely setting the focal position to the working distance, and thus fully exploiting the benefits of scan head calibration.

WWW.SCANLAB.DE

ASML extends holistic patterning strategy

ASML has announced a partnership with US-based Cadence Design Systems to expand the capabilities of its holistic lithography product portfolio, further streamlining chipmakers' process flow from design to mask production. The collaboration will bring together ASML's computational lithography solutions and the Cadence physical design back-end tools, leading to enhanced design technology co-optimisation (DTCO) capabilities for advanced nodes, and other technologies.

As part of its holistic lithography approach, ASML has developed powerful lithography and patterning models that can simulate how a chip design is realised in silicon, representing the actual manufacturing processes. The integration of these design models into Cadence products enables DTCO to deliver optimal design scaling while securing manufacturability and yield. As the first result of their collaboration, the newly released Cadence® LPA PLUS enables engineers to simulate the manufacturability of their design at any time during implementation and sign-off, enabling more efficient delivery of high-quality designs.

ASML's partnership with Cadence represents another step toward realising a full end-to-end design-to-mask process flow. This adds to an earlier partnership which ASML established early 2016 with Nippon Control System, to integrate their products, from optical proximity correction (OPC) to mask data preparation (MDP), on a common platform, delivering improvements in mask tape-out productivity and patterning performance in wafer fabrication. According to an ASML press release, engineers can now leverage litho-aware design and mask data preparation on a seamlessly integrated platform.

WWW.ASML.COM

WWW.CADENCE.COM

WWW.NIPPON-CONTROL-SYSTEM.CO.JP/EN

New medium-load, ultra-precision hexapod

The newest member of Aerotech's HexGen family, the HEX300-230HL hexapod, is targeted at medium-load, ultra-precision applications ranging from sensor testing to synchrotron sample manipulation, with guaranteed positioning accuracy specifications below 5 µm.

The HEX300-230HL is actuated with six high-accuracy struts built with precision preloaded bearings, ball screws, and drive components. Unlike competitors utilising DC brush servomotors, this hexapod is driven by AC brushless, slotless servomotors that maximise its performance and longevity. Directly coupling the AC brushless servomotors to the ball screw results in increased drive stiffness, higher positioning accuracy, and better minimum incremental motion (20 nm in XYZ and 0.2 µrad for θxθyθz), compared to competitive designs using belts, gearheads, or compliant couplings. Specially-engineered strut pivot-joints provide low friction and high stiffness, enhancing the overall performance for a load capacity of up to 45 kg.

The platform and base can be easily modified with user-specific features or mounting patterns, and – like all Aerotech hexapods – this new version can be vacuum-prepared for demanding applications such as synchrotron sample or optics manipulation, semiconductor manufacturing and inspection, or satellite sensor testing.

WWW.AEROTECH.COM

Admetalflex 130 prints high-quality metal materials

Admatec Europe, supplier of printed components and 3D printing equipment for ceramics and metals, and ECN, the Netherlands' largest research institute for sustainable energy, have launched the Admetalflex 130. This new 3D printer delivers printed metal components with high-quality material properties and, compared to industry standards, low-surface roughness values, fine features and no residual stresses. The operating principle originates from DLP (digital light processing), using photosensitive resin, combined with debinding and sintering. The Admaflex key technology items such as the film technology and continuous material throughput system apply to the Admetalflex as well.

As Admatec and ECN have a good understanding of the powder metallurgy market, demonstrated by their previous ceramic 3D printer, it was always the aim to launch this new metal 3D printer, which serves the market for relatively small-sized, high-precision, high-performing printed metal components which are manufactured today by CNC machining or metal injection moulding.

WWW.ADMATEC.NL

WWW.ECN.NL

New piezo rotator for optics

Attocube systems presents an enhanced version of its stable piezo-driven rotation stage ECR5050. The new high-stability version ECR5050hs has a higher torque and a (large) aperture that can be used as a feedthrough for wires or for (optical) beams. It enables precise 360° endless rotation in both directions and is available for ambient conditions, high vacuum down to 10^{-8} mbar, and in a bakeable UHV version (pressure < 10^{-9} mbar). Its optional optoelectronic sensor allows for a resolution of 0.01 m° and a repeatability of 1 m°.

WWW.ATTOCUBE.COM

LiveDrive launched

At the Hannover Messe 2017, Genesis Robotics, based in Vancouver, Canada, launched the LiveDrive, a direct-drive actuator that can replace motor-gearbox actuators by eliminating the need for gears. The new device will make robots faster, safer and less expensive, according to CEO Mike Hilton in an interview published by the RoboValley website.

The LiveDrive design was instigated by the fact that the actuators in robot arms use technology that hasn't really changed for over a hundred years. "It is basically an electric motor and a gearbox", Hilton explains. " There have been improvements, but no foundational changes." The result is that robots are complex, heavy and expensive.

These characteristics make them dangerous to operate near people. Inertia hampers making an emergency stop, backlash and lost motion result in less precision and controllability issues. Genesis Robotics has solved these problems and got rid of the traditional gearbox by:

- magnetic force amplification for high torque;
- structural redesign for low-weight, low-cost resistance to extreme forces;
- thermodynamic innovations for higher power density.

As a result, LiveDrive's torque is nearly three times the torque-to-weight of any direct-drive motor and it is 'nearly a hundred times' more precise than any gear-drive system. Industrial robotics is the first application that springs to mind. Genesis Robotics designed the LiveDrive to be 'plug & play'. "The control systems use the exact same motion control and drive systems that power today's actuators."

Because of its simple design – it has only one moving part – the cost of producing actuators can be reduced "as much as 50 percent or more". The LiveDrive is particularly suited for exoskeletons and 'assistive robots' in, e.g., healthcare and home environments, and Hilton also foresees potential in autonomous driving applications.

WWW.GENESIS-ROBOTICS.COM

WWW.ROBOVALLEY.COM

New laser scanning technology for portable measuring arm systems

The latest ROMER Absolute Arm from Hexagon Manufacturing Intelligence features a newly developed integrated high-speed laser scanner, the RS4. With completely new optics and electronics, the RS4 scans more than 60 percent faster than its predecessor, with performance particularly improved when measuring difficult object surfaces such as carbon fibre or machined steel. The RS4 has an ultra-wide laser line that is almost double the width of the previous model, as well as a better point resolution, giving users greater point cloud detail in significantly less time than before.

As with every ROMER Absolute Arm model, scanner warm-up and time-consuming scanner calibrations remain unnecessary. The longer stand-off of the RS4 allows users to scan more deeply into difficult to reach cavities than before, with no reduction in accuracy performance. The RS4 laser scanner will be available as a retro-fit product for existing ROMER Absolute Arm systems.

WWW.HEXAGON.COM

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Cleanrooms

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

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

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

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