DSPE MIKRONIEK

2020 (VOL. 60) ISSUE 6

PROFESSIONAL JOURNAL ON PRECISION ENGINEERING

- THEME: SYSTEMS ENGINEERING & DESIGN METHODOLOGY
- LARGE DYNAMIC RANGE ATOMIC FORCE MICROSCOPE
- BIO-INSPIRED SYSTEM DESIGN
- PREVENTING THE FREEZING OF VACCINES IN A COLD CHAIN

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

PUBLICATION INFORMATION

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

DSPE
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Publisher
DSPE
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High Tech Campus 1, 5656 AE Eindhoven
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Design and realisation
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+31 (0)40 – 251 99 29, info@snep.nl

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

Mikroniek appears six times a year.

ISSN 0026-3699

The cover image by Henri Werij (featuring the positioning stage of a large dynamic range AFM) is courtesy of TNO. Read the article on page 12 ff.

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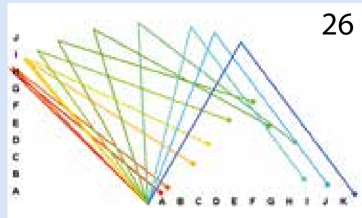

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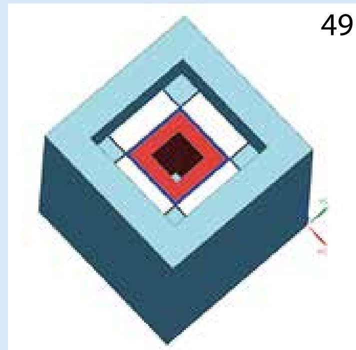

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FEATURES

A PRECISION PERSPECTIVE ON SYSTEMS ENGINEERING

Systems Engineering (SE) is hot in the Dutch high-tech community. Some years ago, there was a big boost in the application of SE processes in the civil sector, driven by government demanding the use of SE processes for contractors in infrastructure projects. Recently, we have seen increased focus on SE for the design and engineering of high-tech equipment. Driven by increasing complexity of systems and the accompanying increase in engineering team size, SE is being considered and adopted to better control the engineering processes.

Now, let's take the precision engineering perspective. When looking up a definition of precision engineering on Wikipedia, it highlights the multidisciplinary nature of the discipline to achieve its objective to design accurate, repeatable and stable equipment. One of the fundamental principles in precision engineering is that of determinism. There are many definitions for SE; one description is that of a multidisciplinary field of engineering and engineering management focusing on the development, realisation, etc., of complex systems. So, precision engineering and SE are both multidisciplinary and share a holistic approach, while precision engineering is more narrowly focused on design and manufacturing.

To address the increasing complexity of precision-engineered systems, adopting SE processes more broadly is a natural development. The principle of determinism will drive extensive use of models in the engineering process, for which model-based systems engineering is being developed in the international SE community. This innovation will bring traditional SE much closer to the way of working in the DSPE community, making it easier to adopt SE processes in our work. Precision engineering in the Netherlands will enter a new phase, building on the foundation of design principles as laid down by Wim van der Hoek and his collaborators and successors, and the subsequent extension to the field of precision mechatronics.

At Eindhoven University of Technology (TU/e), the High Tech Systems Center is promoting the use of SE in the research and development of high-tech equipment. This is not an isolated effort: at the University of Twente, SE has been part of the design engineering training for some time, while Delft University of Technology offers SE training with a strong connection to aerospace engineering. Work is required to create innovative interpretations of SE that have a good connection to high-tech equipment engineering and its foundations in design principles and mechatronics. These innovations in SE ideally will be rooted at the Dutch universities of technology and universities of applied sciences. A uniform framework will allow uniform training of new generations of engineers and allow for collaboration in improving and extending it. We don't need a fully independent SE, but we need to adopt a dialect that is sufficiently tailored to our specific world of precision engineering and its application in high-tech equipment.

Artificial intelligence (AI) is a popular topic these days. AI is expected to contribute significantly to the world as we know it. Dutch government has created incentives to promote research and development of AI technologies. The Eindhoven AI Systems Institute has developed a research programme for this field and defined a specific topical area for the intersection of AI and (systems) engineering technologies. One of the research directions is to develop thinking assistants that can support (systems) engineers in the development of systems. The capabilities of AI to manage large amounts of data may prove very useful in the exploration of large design spaces, keeping track of design data and supporting complicated trade-offs. It will be interesting to see how SE and systems engineers will be able to extend their capabilities in managing the complexity of even larger systems.

This edition of your favourite magazine will present these developments from a variety of angles and give you a good overview of where these developments may take us.

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LINEAR, LOW-MASS, LOW-COST

A systems engineering approach to the design of a wafer handler is presented, starting with an introduction to wafer handling, followed by the corresponding requirements and lastly common system architectures. Regarding wafer-handling robots, the conclusion is that the moving robot mass increases when contamination requirements become more stringent. Moreover, robotic concepts containing a linear stroke can improve stiffness and reduce mass at the cost of contamination-sealing complexity. To conclude, the design and realisation of a low-end, low-cost magnetic bearing for high-cleanliness robotic applications is discussed.

RICK BAADE

Introduction

The front-end-of-line semiconductor manufacturing process contains multiple sequential process steps; one simplified cycle is presented in Figure 1. This cycle is repeated up to 50 times for each wafer. The wafers are transported between manufacturing tools inside a standardised container, called a front-end opening pod (FOUP), which holds 25 wafers. Before each process step, a wafer-handling module is required as an interface between the automated material-handling system (AMHS) that transports the FOUPs and the actual manufacturing equipment. The main task of the wafer-handling module is to extract wafers from a FOUP and place the wafers onto a stage or a chuck, where the actual process takes place. Key functionalities of the wafer-handling module are to transport the wafers throughout the manufacturing tools and, depending on the application, perform position aligning and/or thermal conditioning steps.

Wafer-handling modules usually contain a carrier handler to accept FOUPs, one or two robots for wafer transfer, an alignment module, and wafer storage and conditioning tables. These modules can be designed and supplied by different suppliers, therefore clear requirements on performance and interfaces are important to assure that the fully assembled system, where all modules are combined, meets the system level requirements.

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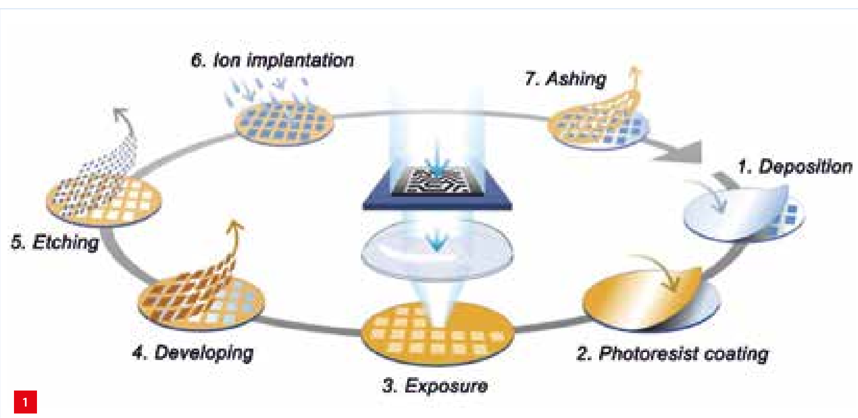

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Front-end-of-line process cycle (ASML).

Requirements

Requirements on wafer-handling modules vary for different applications. A distinction can be made between requirements that influence the performance of the actual manufacturing process and requirements that impact productivity or yield; see Figure 2. Examples of requirements that impact the manufacturing process are position accuracy, thermal uniformity and thermal stability of the wafer. The importance of these requirements and how stringently they are specified depends on the application.

Lithography and metrology steps pose stringent requirements for wafer positioning and alignment, typically in the order of a few micrometers. For chemical and physical processes such as etching or layer deposition tools, wafer-positioning specs are less relevant and in the order of 100-500 micrometers.

Similar to the positioning accuracy specs, requirements on thermal stability and thermal uniformity are challenging for lithography and metrology tools where milli-Kelvin stability and uniformity are demanded. Wafer temperature is less relevant for other process steps; some take place at elevated temperatures of a few hundred degrees Celsius.

Requirements that impact productivity are always important, independent of the application. The complexity of semiconductor manufacturing equipment keeps increasing, following Moore's law, resulting in a continuous

WH-requirements

Process performance:	Productivity:	General:
Positioning: repeatability, accuracy	Availability: failure rate, mean time to repair	Interfaces: volume claim, mechanical interfaces, electrical interfaces
Thermal uniformity	Yield: particulate contamination, molecular contamination	Cost: cost of goods, service life
Thermal stability	Throughput: motion parameters	...
...	...	

2

Overview of typical requirements for wafer-handling modules.

rise in equipment costs. Productivity has to increase to justify the high equipment cost. Defining productivity as a combination of throughput, availability and yield, throughput is mostly limited by the manufacturing process itself and not by the wafer-handling module, although the wafer handler is a significant productivity contributor in availability and yield. Contamination, both particulate and molecular, is believed to be a major source of yield loss. Therefore, key requirements for wafer-handling modules are defined on availability and contamination control.

Common system architectures

Three main wafer-handling architectures can be identified as corresponding to the requirements, as depicted in Figure 3. The first architecture is an equipment-front-end-module (EFEM), shown in the left of Figure 3. This type of wafer-handling module is used for most atmospheric wafer-handling applications. The EFEM acts as an interface with fabs (semicon fabrication plants) by accepting multiple FOUPs. Inside the EFEM is a wafer-handling robot provided with an extended vertical (z)-stroke to enable it to reach all FOUP positions. The robot is often placed on top of a linear axis so it can reach multiple FOUPs placed side by side. In some cases, a wafer aligner module is included for coarse alignment. Most requirements and interfaces are defined in industry standards (SEMI).

The second architecture, cluster tools, is mostly applied for in-vacuum processes and tools that apply parallel operations on multiple wafers. Examples are etching and layer-deposition tools. A cluster tool consists of a central transfer chamber that features a wafer-handling robot at the centre. The transfer chamber has a controlled environment, typically at vacuum pressure. Wafers are fed to the transfer chamber through a load lock that is often coupled to an EFEM. Multiple separate processing chambers are attached to the transfer chamber.

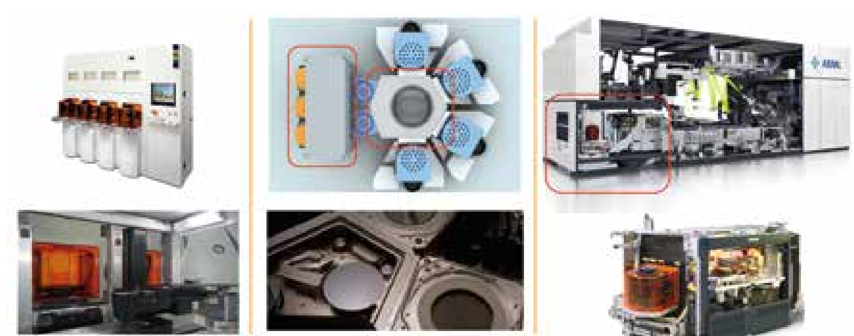
The final architecture is used in applications with the most stringent requirements and often provides additional functionalities, e.g. thermal conditioning. Here, the wafer-conditioning unit is integrated into the manufacturing tool. Integrated conditioning units are seen mostly in manufacturing equipment associated with the lithography step. Multiple tools that are often supplied by multiple OEMs are physically connected. For example, a wafer track that applies photoresist is coupled to the lithography tool. After the lithography step, the wafers return to the track for development. A metrology and inspection tool can also be included in this tool chain. In such a coupled system architecture, wafers are moved between manufacturing tools directly by robots without the involvement of an AMHS and FOUP.

Wafer-handling robots

Wafer-handling robots are one of the key elements of wafer-handling modules. The robots require three degrees of freedom (DoFs) for most applications, often expressed in spherical coordinates with respect to the robot base. Two in-plane DoFs are indicated by a radial distance R and an angular rotation θ. Additionally, an out-of-plane translation is required along the z-axis. The construction of most commercially available robots is based on either a selective compliance articulated robot arm (SCARA) or dual-SCARA kinematic concept, as shown in Figure 4.

The majority of the commercially available substrate-handling robots are relatively heavy compared to their payload, which is a silicon wafer with a mass of 125 g. A typical robotic arm weighs around 4.5 kg. This is due mainly to the limited height that is available to provide out-of-plane stiffness. Moreover, there is a trend towards the moving mass increasing significantly when contamination requirements become more stringent. This is due to the addition of contamination seals that significantly increase the mass, cost and complexity of the system.

The increase in moving mass negatively affects other performance requirements. High-accuracy and high-dynamic motion benefits from a high-stiffness and low-



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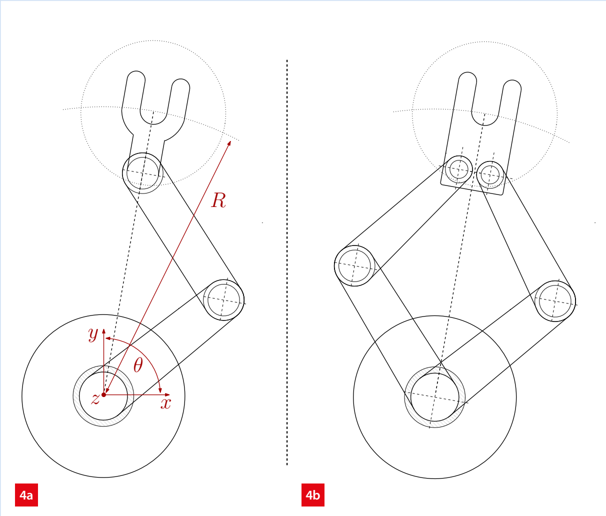
Three common wafer-handling system architectures, from left to right: Kensington Laboratories (top) and Brooks Automation (bottom); Applied Materials; ASML. See text for further explanation.



Robot architectures.
(a) SCARA.
(b) Dual-SCARA.

mass system. Minimising heat dissipation for a system with a reciprocating motion trajectory, containing a lot of acceleration and deceleration phases, favours a low moving mass. Considering the workspace and required DoFs, kinematic structures containing prismatic joints can potentially improve performance.

Magnetic bearing systems

In robotic systems, or motion systems in general, mechanical joints between moving bodies are often the main source of contamination. Typically the joints contain rolling-element bearings and contamination seals to prevent contamination from reaching the clean process environment. Examples of such contamination seals are ferrofluid, labyrinth and differentially pumped gas-purged seals. The seals contribute significantly to the mass, cost and complexity of the system. Sealing long-stroke linear joints is more difficult than sealing rotational joints, especially for in-vacuum applications. Commercially available linear contamination seals that meet semiconductor industry performance requirements have not been found.

Active magnetic linear bearings could provide an advantageous alternative to conventional rolling-element bearings [1]. As magnetic bearings are contactless, there is no mechanical friction and thus little particle generation. Moreover, there is no need for lubrication, which enables in-vacuum operation without significant outgassing. These aspects ensure that contamination seals can be omitted. The main challenges in applying magnetic bearings in high-tech in-vacuum systems lie in the minimisation of heat generation in the coils, the implementation of a stable position-feedback control loop and the linearisation of the typically nonlinear characteristics in the case of nonlinear actuators.

The remainder of this article describes the design of magnetic bearing modules intended for use in a linear guide that is part of substrate-handling robots (Figure 5).

State of the art

A significant amount of research has been done by a number of institutions on the design and control of linear motors, magnetic bearings and magnetic levitation systems for high-tech manufacturing equipment. Most of this research was driven by increasingly demanding requirements on positioning accuracy, stability and increasing velocities and accelerations (throughput).
One example is the work of Trumper [2] at MIT on a high-performance linear actuator and a long-stroke magnetically levitated stage. Another is from the University of British Columbia, where Lu and Usman [3] developed 6-DoF motion stage. In 2009, Laro [4] designed an electro-magnetically suspended slider for optical disk mastering. At Philips Applied Technologies, De Klerk et al. [5] developed a stage based on e-core reluctance actuators for e-beam inspection tools.

The research described here differs from the state of the art in the sense that the focus is on a cost-effective, high-reliability solution that minimises contamination. Position accuracy requirements are less stringent and more comparable to those for conventional rolling-element bearings, in the order of 1 μm reproducibility at the end of stroke. Three main cost drivers of magnetically levitated systems have been identified, namely the motor drives, position sensors and the actual hardware such a coils and mechanics. In the proposed design, cost of these components is minimised by the development of a new sensor type and the use of linear power amplifiers.

Example of a wafer-handling robot containing a linear guide (Asys Micro).

Additionally, the use of the reluctance actuation principle reduces mechanical tolerances on the coils.

Lorentz vs. reluctance

We can distinguish two types of linear electromagnetic actuators, namely the Lorentz and the reluctance types. Lorentz actuators generate a force by placing a current-carrying coil within a magnetic field. Reluctance actuators are based on the attraction force of ferromagnetic materials within a magnetic field. Table 1 shows a high-level comparison [6]. It can be concluded from this table that reluctance actuators are more efficient in terms of energy dissipation and use of volume, given the higher steepness and force density, but at the cost of increased control complexity due to the nonlinearity and negative stiffness.

Given the proposed operation of the electromagnetic actuators in a linear-bearing application with constant gap set point, the nonlinear dependence of the reluctance force on the air gap width can be linearised around the gap set point. The constant gap set point enables the short-actuation-stroke position stability requirements corresponding to conventional rolling-element bearings, in the order of 1 to 10 μm, which are believed to be feasible with reluctance-based actuators.

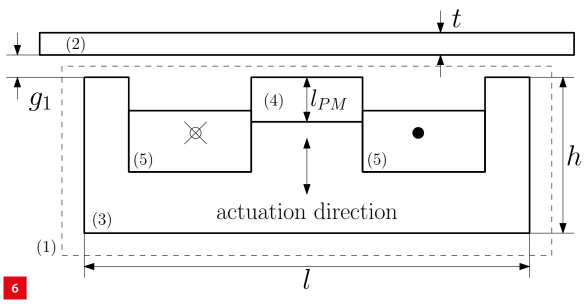
Proposed bearing modules

The reluctance bearing modules are based on the bearings proposed in [5] and [7]. A single magnetic bearing module is shown schematically in Figure 6 (detailed design depicted in Figure 7) and consists of a moving e-core assembly (1) and a static back iron (2). The e-core assembly consists of a laminated e-core (3), where a permanent magnet (4) is mounted on the central tooth and a coil (5) is wound around the central tooth. The static back iron is located at a distance g_1 from the e-core assembly.

This system defines a low-reluctance path where the resulting magnetic flux density in the air gap will yield a gap-dependent attraction force between the e-core and the back iron. The magnetic flux density in the air gap can either be magnified or reduced, based on the direction and

Table 1
High-level comparison between Lorentz- and reluctance-type actuators.

Parameter		Lorentz	Reluctance
Linearity	[N/A]	High	Nonlinear in current and air gap
Force density	[N/m³]	Low	High
Steepness	[N²/W]	Low	High
Negative stiffness	[N/m]	Low	High
Bi-directional actuation	[-]	Yes	No
Stroke	[mm]	Long	Short



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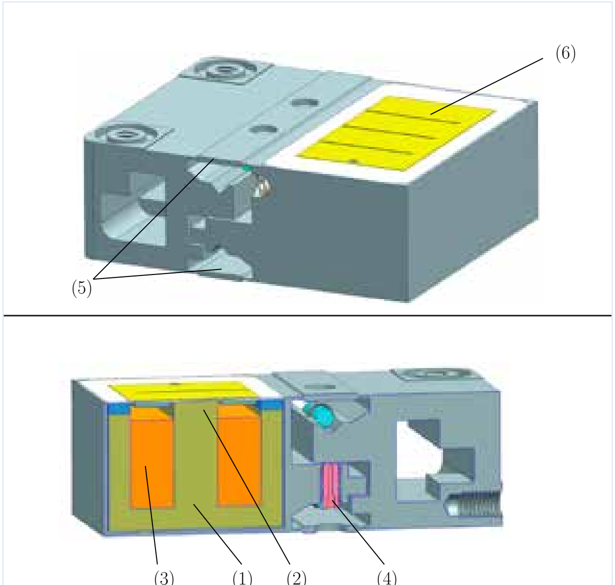
Schematic representation of a single reluctance-bearing module, comprising:
(1) bearing module;
(2) static back-iron;
(3) e-core;
(4) permanent magnet;
(5) coil.

magnitude of the current running through the coil, thereby controlling the magnitude of the attraction force. The actuation direction is perpendicular to the air gap (vertical direction in Figure 6). Note that this system can only generate an attraction force, thus no repelling force, between the e-core and back iron. Preloading opposite to the attraction force is required for bi-directional actuation.

Adjustment mechanism

Bearing modules that constrain out-of-plane DoFs can be preloaded by the weight of the payload. To minimise energy dissipation, i.e. heat generation, steady-state forces, which are required to counteract the weight of the payload, are generated by permanent magnets. Any mismatch between the static forces generated by the permanent magnets and the forces required to counteract the weight will require a



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A single bearing module, highlighting the e-core (1), permanent magnet (2) and coil (3) with an adjustment mechanism consisting of two leafsprings (5) and an adjustment screw (4), and an integrated gap sensor (6).

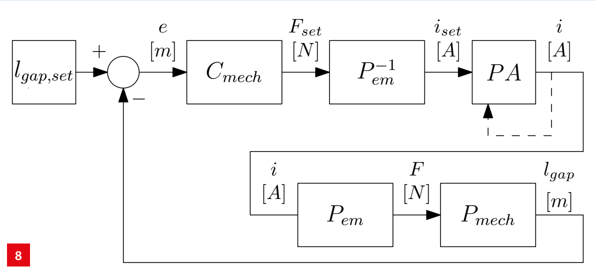
current through the coils to correct the force balance and maintain the position set point. This will in turn lead to additional heat generation. This mismatch, for example due to tolerances on permanent-magnet parameters, can be compensated for by adjusting the air gap set point such that steady-state currents approach zero. To level the system, each bearing module has a mechanical adjustment mechanism as depicted in Figure 7, comprising two parallel leafsprings (5) with a setscrew (4). The mechanism is designed to have a stroke of 0.2 mm and an expected sensitivity of 10 µm.

Gap sensing

Given the less demanding micrometer-level positioning requirement, feedback control is based only on position or air gap sensors without additional flux sensors [8]. The sensor requires a measurement range of approximately 1 mm with an accuracy of 0.5 µm. Capacitive displacement sensors are best suited for this application. Commercially available capacitive sensors are generally cylindrical or flat shaped, with a typical minimal thickness of 4 mm. These shapes make it difficult to integrate the sensor with the magnetic bearing module and measure in the centre of the e-core (Abbe criterion).

Moreover, each sensor requires one (often tri-axial) cable for shielding, measurement signals and guard signals. In many applications, these cables need to be fed through mechanisms and rotational joints. The diameter and bending stiffness of the cables can influence the design of these rotational joints and mechanisms significantly. Additionally, these commercially available sensors are a significant cost driver for the magnetic bearing system.

Given the relatively low accuracy and dynamic-range requirements, it was feasible to design dedicated capacitive sensors. The sensor probe is integrated in the cover of the magnetic bearing (yellow surface in Figure 7), enabling gap measurement directly in the air gap. The electronics architecture includes a local pre-processing PCB that only requires two coax cables to be fed through the mechanics for up to five sensor probes, thereby significantly reducing



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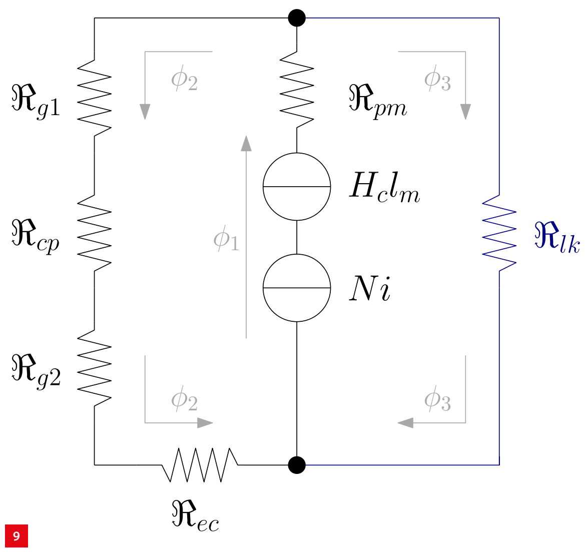
Feedback control loop showing the air gap set point, the feedback control (C_{mech}), an inverse electromagnetic model (P_{em}^{-1}), a power amplifier (PA) and the reluctance actuator itself (electromagnetic model P_{em} and mechanical model P_{mech}).



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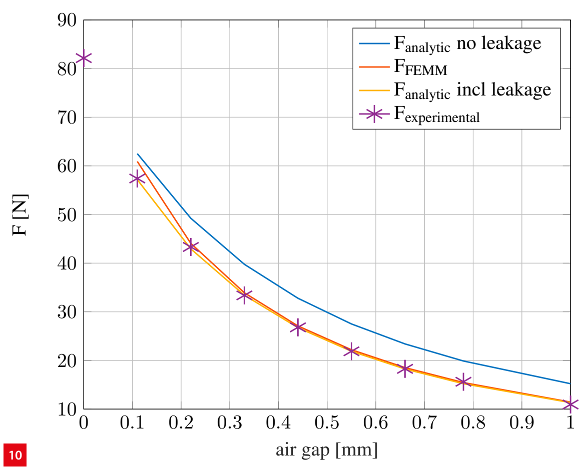
Equivalent electrical circuit containing two sources. The permanent-magnet contribution is given by the coercivity (H_c) and the magnet length (l_m), the coil contribution by the number of windings (N) and the current (i). Furthermore, several reluctance paths are shown, namely the air gap (R_g), the e-core (R_{ec}), the static counter plate (R_{cp}) and the leakage path (R_{lk})

the complexity and dimensions of the cable feedthroughs throughout the system. Ultimately, the cost of goods has been reduced by a factor 10 to 20 with respect to commercially available sensors. The accuracy was found to be within ±0.1 µm of the reference around the operating point of the magnetic bearings.

Electromagnetic system modelling

A typical feedback control scheme is shown in Figure 8. An inverse model of the electromagnetic system (P_{em}^{-1}) that maps the actuator force as a function of air gap width and current is needed to calculate the current set point. This inverse electromagnetic system is nonlinear in both current and air gap width. The actuators are used as a bearing functionality with a fixed gap set point, which allows for linearisation of the inverse model. Several analytical models



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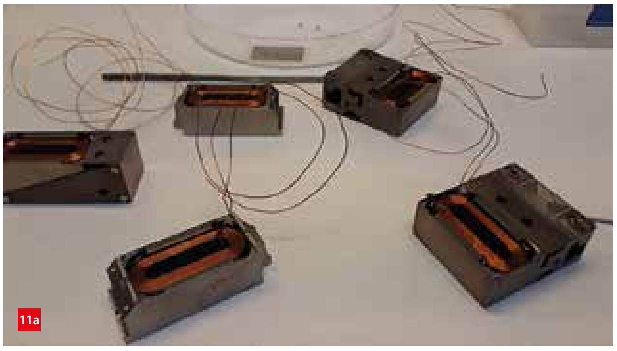
Force vs. air gap relation.



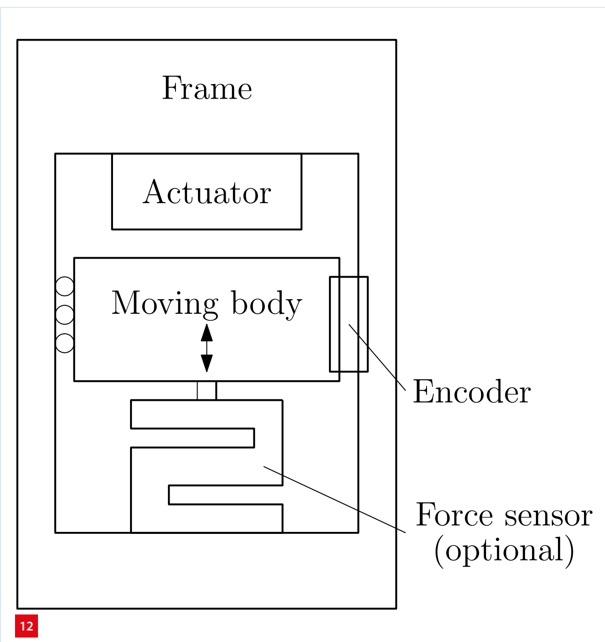
Magnetic bearing modules.
(a) Five modules during assembly.
(b) A single module with the sensor surface integrated in a glass cover. The white cable is a coaxial sensor cable and the copper wires are the coil leads.

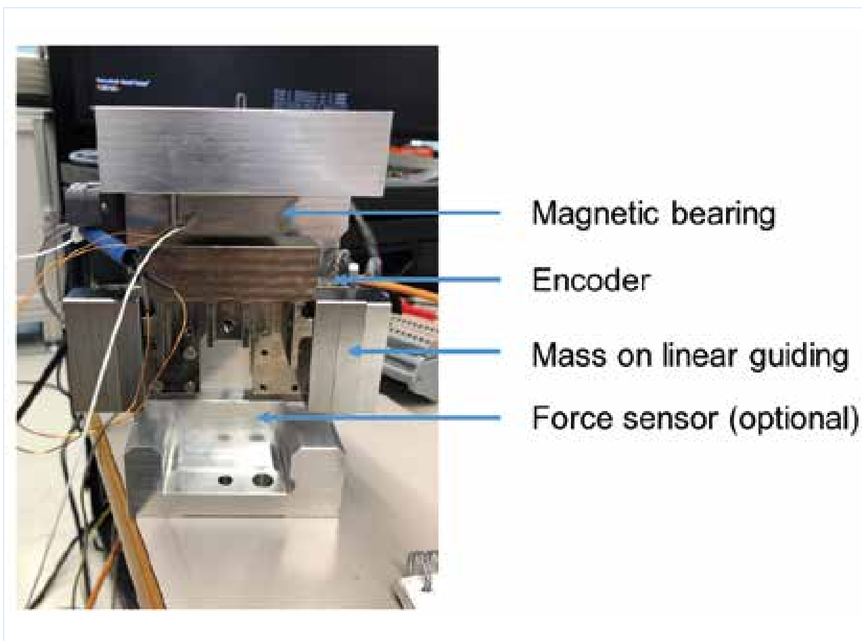
with different levels of complexity have been evaluated and compared to finite-element modelling simulations and actual measurements.

Figure 9 shows an example of an equivalent electrical circuit [9]. The left branch describes the most basic reluctance model of a bearing module. This model comprises the coil, permanent magnet, e-core, two air gaps and the metal counterpart. The reluctance values were calculated analytically. It was found that the most basic model deviates significantly from measurements and simulations. When flux leakage is included in the model (right-hand side of Figure 9), the differences between measurements and models are within 5 per cent (Figure 10). The reluctance value of the leakage path was extracted from finite-element model simulations, at the nominal air gap value without current flowing through the coils.

Experimental validation

A number of magnetic bearing modules have been realised, as shown in Figure 11. The bearing modules consist of a titanium grade-5 housing that contains the e-core with a permanent magnet and a coil. A capacitive gap sensor is integrated in the glass cover of the bearing module. A set-up available at VDL ETG was used for experimental validation of the force vs. gap relation as described above, depicted in Figure 12. The magnetic bearing module is mounted to the aluminium frame. A steel mass is mounted to a linear bearing and translates along the actuation direction of the magnetic bearing (perpendicular to the air gap). The position of the mass, and thus the air gap width, is measured using an optical encoder (Renishaw TONiC). Additionally, a force sensor (Burster 8512) can be included to measure steady-state forces. Control and data logging are done using a Speedgoat real-time target.





Reluctance actuator measurement set-up at VDL ETG.

Concluding remarks

The first part of this article provided an introduction to wafer-handling equipment and the corresponding requirements. The second section described the design and realisation of magnetic bearing modules, with the intended use as a linear guide as part of a novel wafer-handling robot. A demonstrator prototype of a linear guide containing seven bearing modules is currently under construction.

REFERENCES

[1] A. Peijnenburg, J. Vermeulen, and J. van Eijk, "Magnetic levitation systems compared to conventional bearing systems", *Micro-Electronic Engineering*, pp. 1372-1375, 2006.

[2] J.Y. Yoon, L. Zhou, and D.L. Trumper, "Linear stages for next generation precision motion systems", *Proceedings of the 2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 241-247, 2019.

[3] X. Lu, and I. Usman, "6d direct-drive technology for planar motion stages", *CIRP Annals -Manufacturing Technology*, vol. 61, pp. 359-362, 2012.

[4] D.A.H. Laro, "Mechatronic design of an electromagnetically levitated linear positioning system using novel multi-dof actuators", Ph.D. thesis, Delft University of Technology, 2009.

[5] G.Z.A. Angelo, C.P. de Klerk, and J. van Eijk, "Design of a next generation 6 dof stage for scanning application in vacuum with nanometer accuracy and mgauss magnetic stray field", *Proceedings of the 19th annual ASPE meeting*, 2004.

[6] Philips Innovation Services, "Comparative evaluation of Lorentz and reluctance actuators", technical report, 2016.

[7] R.T. Meindert, L. Norg, and J. van Eijk, "Active magnetic bearing controls strategy and calibrations", *Proceedings ASPE Spring Topical Meeting*, 2008.

[8] A. Katalenic, "Control of Reluctance Actuators for High-Precision Positioning", Ph.D. thesis, Eindhoven University of Technology, 2013.

[9] R. Hamelinck, "Adaptive deformable mirror based on electromagnetic actuators", Ph.D. thesis, Eindhoven University of Technology, 2010.

LARGE DYNAMIC RANGE ATOMIC FORCE MICROSCOPE

In semiconductor manufacturing, the shrink following Moore's law requires ever tighter overlay and registration between the different (material) layers. For accurately characterising this overlay and registration, TNO has developed a large dynamic range atomic force microscope demonstrator; the LDR-AFM can measure marker-to-feature distances over several millimeters with sub-nanometer reproducibility. It features a highly stable metrology concept and a 6-degrees-of-freedom positioning platform (hexapod) carrying an AFM scan head able to move the AFM probe tip. Repeatability measurements have demonstrated that both drift and reproducibility figures are well below the smallest feature size of the newest semiconductor processing nodes.

RODOLF HERFST, MAARTEN VAN ES, STEFAN KUIPER, GERT WITVOET, JOOST PETERS AND ROB WILLEKERS

Introduction

Scanning probe microscopy (SPM) is a form of microscopy that uses a probe to scan a surface in order to form high-resolution images far below the diffraction limit of light in the visible range. Various types and implementations have been developed over the year, but atomic force microscopy (AFM) in particular has revolutionised the imaging industry. It was invented in 1986 [1] and offers high-resolution (down to atomic scale [2]) imaging on relatively cheap and simple instruments.

Two significant drawbacks of the technique however are that it is relatively slow (a few minutes or more for a single high-resolution image), and capable of imaging on only relatively small length scales (typically 100 micron or less [3]). As a consequence, AFM has been mostly restricted to research and laboratory settings and its strengths have not been widely applied in production environments, although there are some examples where it has been used in semiconductor fabs for inspection and process control purposes [4-5].

Naturally, the unique strong points of AFM have led to efforts to mitigate its drawbacks for both general-purpose imaging as well as metrology purposes. Examples are the development of video-rate AFM [6], the high-throughput parallel AFM developed at the Netherlands Organisation for Applied Scientific Research (TNO), now being commercialised by Nearfield Instruments [7], and the large dynamic range AFM (LDR-AFM) [8-10]. This last one aims to drastically increase the length scale accessible by the technique and is the topic of this article. It combines an AFM measurement head optimised for sub-nm accuracy with a highly accurate long-stroke motion stage with six degrees of freedom (6-DoF). This is then mounted in a metrology frame large enough to accommodate 300-mm wafers. We will present an overview of the system's concept and implementation, as well as experimental results that showcase the high performance achieved.

The tool is aimed at providing sub-nm metrology over a distance of several millimeters (i.e., dynamic range > 10^6). This can be used to characterise both overlay (relative shift) and registration (absolute shift, with respect to a coordinate system) between the different (material) layers in chip fabrication. In established overlay metrology tools, alignment markers are used to assess how large the relative shift between two or more layers is. If the markers are then correctly printed with respect to each other, it is assumed that the device features printed in the same exposure steps as the alignment markers are also placed correctly with respect to each other. However, this is not necessarily the case, especially for the extremely small device features that are possible with the newest lithography techniques, such as EUV. For example, features with a very small pitch can be affected differently by lithography lens aberrations than the coarser marker shapes that are printed for alignment.

To accurately determine overlay of device features associated with, e.g., two different lithography steps, the LDR-AFM is used twice to very accurately measure the distance between a device feature and an overlay marker in each of the two layers. After this, a more traditional (optical) overlay metrology tool determines overlay between the two marker structures. This then gives enough information to infer the overlay between the device features, even if one of those features is not visible anymore in, e.g., a SEM (scanning electron microscope) or AFM image. Apart from aiding in overlay and registration, the LDR-AFM can

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be used to obtain detailed profile information of both device and marker features.
In the next sections, we will first discuss the LDR-AFM's hardware, followed by a brief explanation of how the hexapod positioner is controlled and deals with the inherent cross-couplings. Then, we will go into how the AFM control loop functions. Finally, we will show some results obtained with the system that highlights its potential for metrology applications

Hardware details

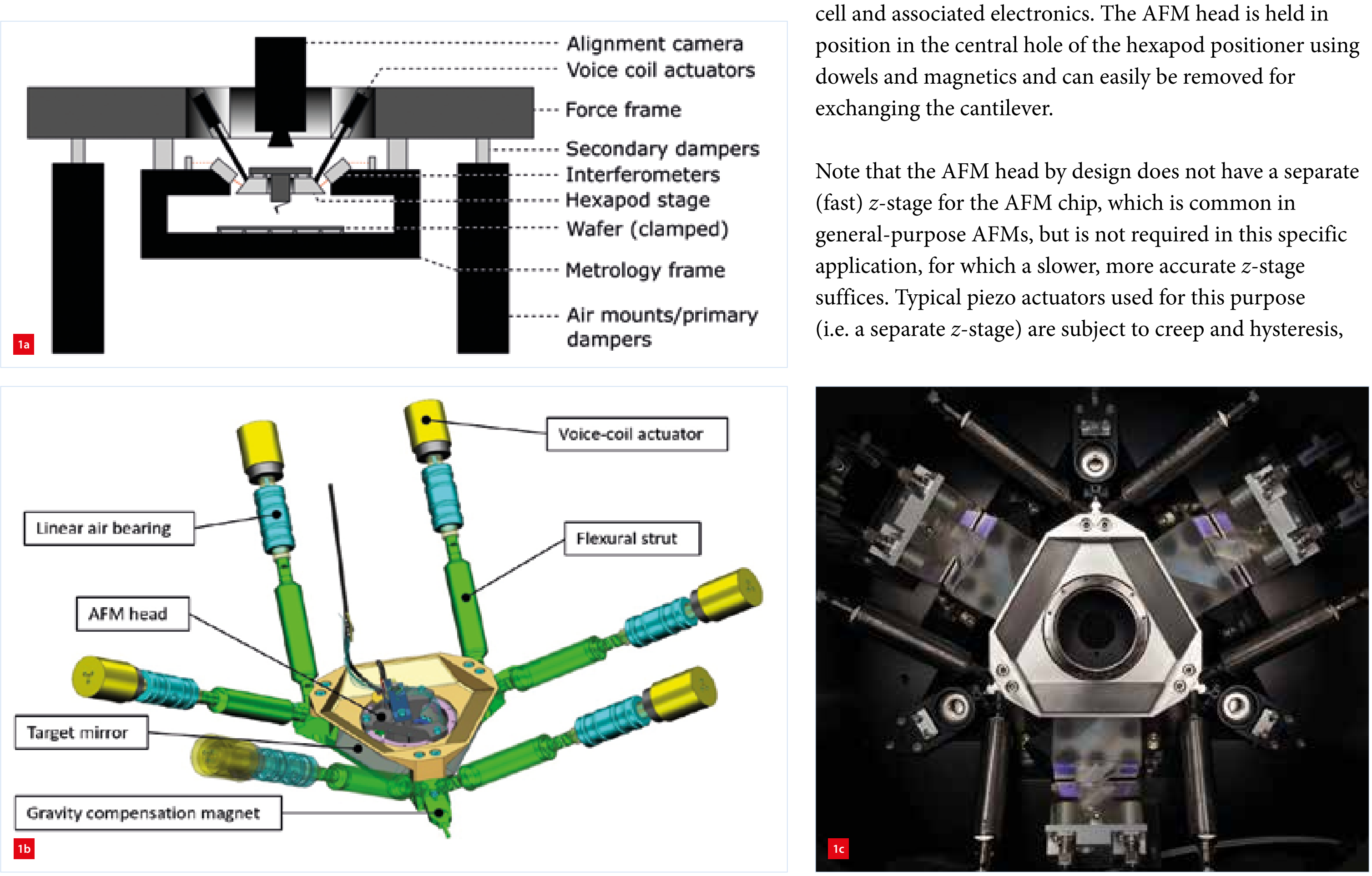
A schematic overview of the system is shown in Figure 1a. At the heart of it, the AFM head with a tilted probe is situated (Figures 1b and 1c). A 6-DoF hexapod positioner [11] can move the AFM head within a hexagon-shaped box (8 mm diameter and 4 mm height). The hexapod is attached to a metrology frame in which a 300-mm wafer can be mounted. The metrology frame is attached to a force frame through (secondary) dampers, which are connected to the ground through the primary dampers.

The 6-DoF hexapod positioner uses six voice-coil actuators via flexural hinges to realise translation and rotation. Of course, if no current is flowing through the coils, no (magnetic) forces are generated by them. Therefore, counteracting gravity forces using only voice coils would lead to a large power dissipation, which would in turn heat up the voice coils. In order to reduce this, gravity forces are compensated by magnets on each of the three corners of the stage (see Figure 1b). These magnets are positioned between sets of external magnets, resulting in an upward force on the stage.

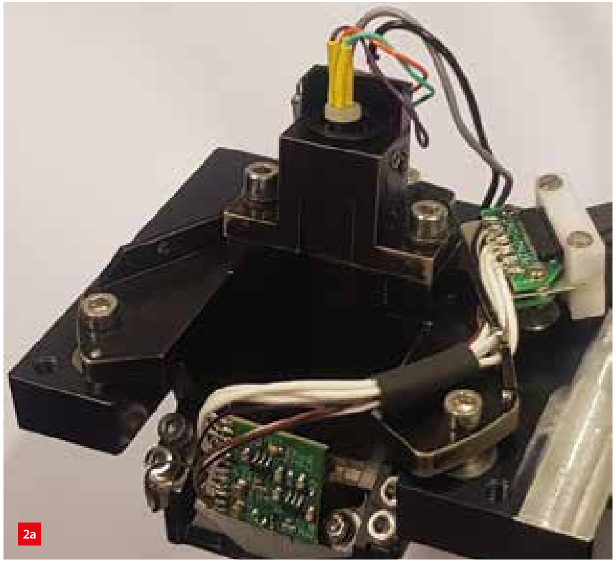
To determine the position and rotation of the hexapod, six laser interferometers are incorporated. The interferometer beams are pointed at target mirrors on each side of the stage. When the hexapod is controlled, the point of which the position should be most accurately known is the tip of the cantilever. In order to reduce Abbe errors at this point, the interferometers are in an orthogonal configuration and the normal of each mirror points toward the AFM probe.

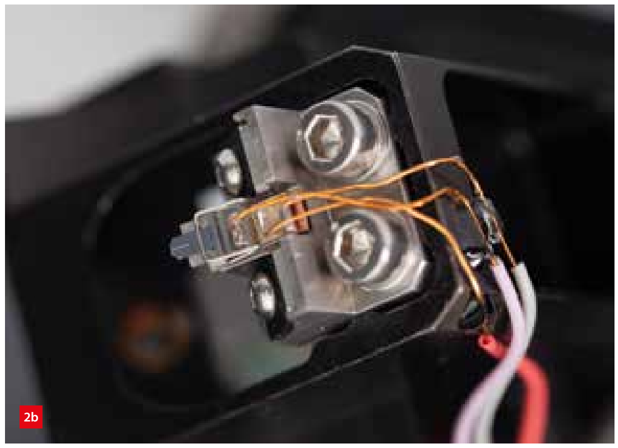
In the AFM head (Figure 2), the AFM chip is attached to the probe holder, underneath which a dither piezo is situated that excites the cantilever. Cantilever motion is measured using the optical beam deflection technique (OBD), featuring a laser diode, a focussing lens, a quadrant cell and associated electronics. The AFM head is held in position in the central hole of the hexapod positioner using dowels and magnetics and can easily be removed for exchanging the cantilever.

Note that the AFM head by design does not have a separate (fast) *z*-stage for the AFM chip, which is common in general-purpose AFMs, but is not required in this specific application, for which a slower, more accurate *z*-stage suffices. Typical piezo actuators used for this purpose (i.e. a separate *z*-stage) are subject to creep and hysteresis,



The large dynamic range AFM system.
(a) Concept.
(b) Design (CAD drawing)
(c) Realisation with the hexapod 6-DoF positioner and mounted AFM head.





Unmounted AFM head.
(a) Showing laser connection wires (top, white socket with yellow shrink tube) and quadrant cell electronics (bottom, green PCB).
(b) Close-up of the cantilever holder with the AFM chip mounted (obscured by the quadrant cell).

negatively affecting the accuracy of the AFM measurement as the extension of such a piezo actuator would not be captured adequately by the interferometers. This is due to the fact that they measure the position of the stage as a whole, i.e. not directly the location of the AFM cantilever.

Hexapod control

While the described hexapod positioner concept has a number of advantages over alternatives such as a spindle-based approach, including very low hysteresis, no slip-stick effects and fast actuation, it does need active feedback control to be operated. Although the six actuators and six interferometers are sufficient to actuate and measure all three displacement axes and three rotation axes, the actuation and sensing axes are (by design) obviously not orthogonal. Hence, to control this cross-coupled platform, the multiple-in-multiple-out (MIMO) control scheme as shown in Figure 3 has been implemented. This approach decouples the problem into six independent single-in-single-out (SISO) control loops. Matrices transform the signals in the control loop between three different coordinate systems:

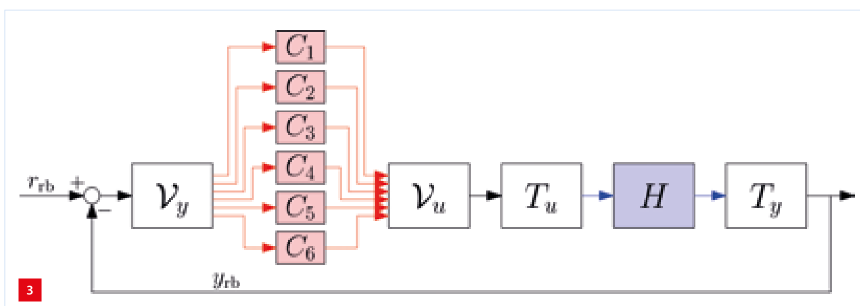
1. Rigid-body motion space (orthogonal, indicated in black, origin of coordinates at cantilever).
2. Actuator sensor space (indicated in blue).
3. Controller space (indicated in red, origin of coordinates at centre of gravity).

Matrices T_u and T_y transform the system's transfer function $H(s)$ into rigid-body coordinates, allowing the user to define setpoints in terms of translations and rotations of the AFM cantilever. Moreover, V_u and V_y further optimise the decoupling for controller design (by shifting the coordinate system origin to the hexapod's centre of gravity), so as to minimise the remaining interaction around the targeted bandwidth and to allow for the usage of six SISO controllers.

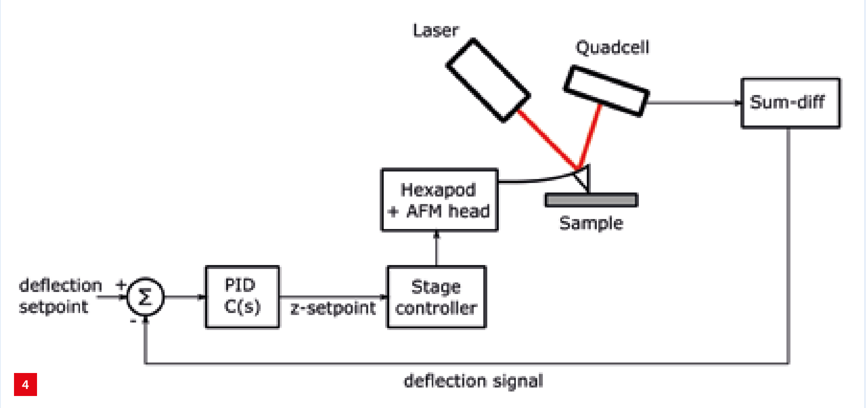
The initial design of the decoupling matrices and the SISO controllers was fully based on predictive models [3]. Because we use a static magnetic gravity-compensation scheme, the hexapod stage is open-loop unstable. In order to be able to stabilise the stage on first use, a decently fast initial controller was required. This was constructed using a finite-element model (FEM) of the stage, which resulted in an initial open-loop bandwidth of about 100 Hz. Having this as a starting point, the six controllers were further optimised, yielding a bandwidth of 210 Hz in *x*- and *y*-direction, and 270 Hz in *z*-direction [12]. Although this latter bandwidth is rather low for topography tracking in a regular AFM, it is sufficiently high for the distance measurements that this tool is designed for: a measurement cycle of about one minute is enough for sub-nm reproducibility. In the experimental results section, we will show measurement data corroborating this claim.

AFM control

In addition to the controller required to operate the positioning stage, another loop is necessary to perform actual AFM measurements with it. A (simplified) schematic



Implemented 6-DoF control scheme with decoupling matrices; the matrices T_u and T_y transform the system H into rigid-body coordinates, whereas V_u and V_y further decouple the system to allow for the usage of six SISO controllers.



4

Control loop for contact-mode AFM. PID adjusts the z-setpoint of the positioning stage controller executing the control loop of Figure 3.

of this is shown in Figure 4. This shows a cantilever in contact with a sample, which causes the cantilever to bend. The laser, quadrant detector, and sum-difference amplifier together perform the OBD sensing and generate a signal proportional to the bending of the cantilever (deflection signal). The AFM control loop keeps the deflection equal to the deflection setpoint by continuously adjusting the z-setpoint of the positioning stage.

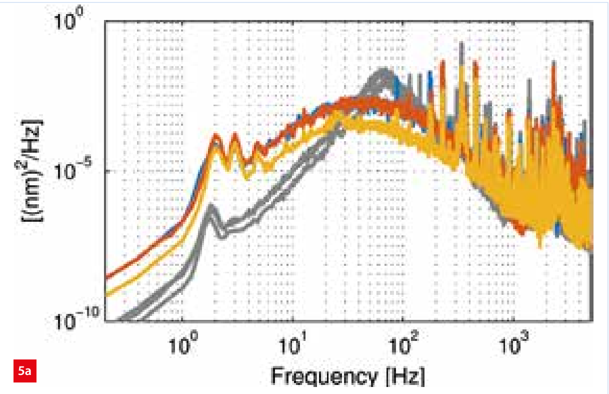
Apart from the contact-mode AFM shown here, tapping-mode AFM has been implemented as well. For this, the cantilever is excited at its resonance, and instead of acting on the deflection, the control loop adjusts its height to keep the resulting cantilever vibration amplitude constant. This mode can greatly reduce both tip- and sample-wear compared to the contact mode.

Experimental results

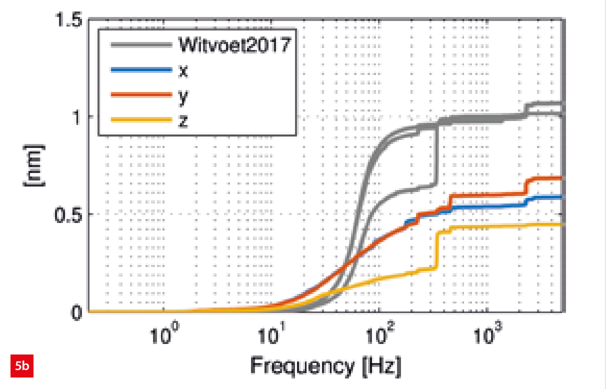
After the LDR-AFM was built and control was implemented and optimised, we performed a series of tests to characterise the performance of the full system. Since the system is a metrology tool, two very important performance metrics are the system's noise and reproducibility. To assess the positioning noise of the stage, the closed-loop interferometer signals have been traced for two minutes and converted to rigid-body motion of the stage. From this data, the power spectral density graph as shown in Figure 5a was determined. The cumulative amplitude spectrum in Figure 5b shows the overall rms noise is below 0.7 nm and 0.4 nm in *xy* and *z*, respectively (note that the true stage noise will be slightly lower, as high-frequent sensor noise will not propagate into stage motion). This is low enough to accurately resolve nm-scale structures, and allows for distance measurements with sub-nm resolution.

The problem with Figure 5 is that it does not necessarily say anything about the actual stage motion, it is simply how the feedback sensor measures it; hence one still needs to validate this metrology by some absolute validation sensor or measurement.

While the above results show that the contribution of the tracking error to overall measurement reproducibility is low, this does not necessarily mean we can conclude that likewise the actual stage motion reproducibility is good; the graphs are simply based on what the sensors report as stage motion. Hence, for real certainty one still needs to validate this metrology by some absolute validation sensor or measurement. To get such an absolute validation, an end-to-end drift measurement was performed. A cantilever was loaded on the AFM head, and the contact-mode AFM control loop was activated while the *xy*-position was kept stationary. The AFM control loop then kept the stage in close proximity to a flat sample by making sure the cantilever deflection remains constant. While in this state, the interferometer-derived *z*-signal was measured for more than 5 hours, the result of which is shown in Figure 6. As can be seen, the system exhibited less than 20 nm drift over the full duration of the measurement, i.e. under 50 pm/minute.

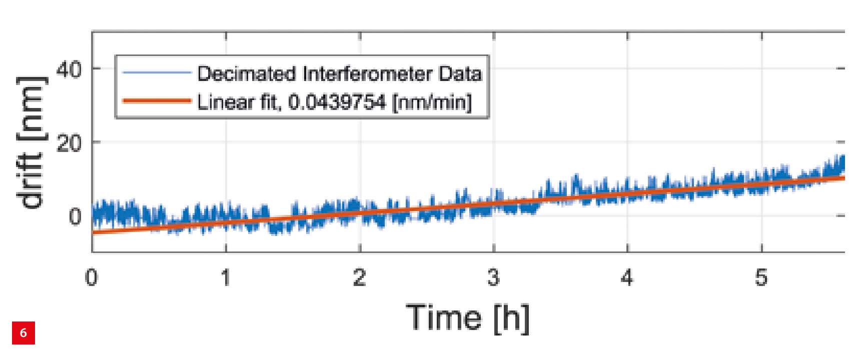


5a



5b

Closed-loop error in translational directions at a certain stand-still position.
Grey lines: preliminary controller.
Coloured lines: optimised controller.
(a) Power spectral density.
(b) Cumulative amplitude spectrum (Witvoet2017 = [10]).



6

Drift measurement of the stage z-position, while controlling both its x- and y-position and the cantilever direction to constant values. Over several hours an average z-motion of less than 50 pm/min is observed, while the 1-minute moving average varies only a few nm. Data is shown decimated by a factor 100 with respect to the real-time control system's sampling rate.

To determine the stability in lateral (*xy*) direction, a more complicated kind of test is required, which resembles real-world overlay and registration tests more closely, as schematically illustrated in Figure 7. A sample with SRAM (static random-access memory) cells is loaded into the system, and the AFM control loop is configured and activated. Two SRAM cells that are nominally 1.3 mm apart are measured, and the position of the left sidewall of each of the two SRAM cells is identified. Then, a distance measurement loop is set up that repeatedly performs the following steps:

1. Measure sidewall on SRAM cell 1.
2. Retract stage.
3. Move to SRAM cell 2.
4. Approach sample.
5. Measure sidewall on SRAM cell 2.
6. Retract stage.
7. Move back to SRAM cell 1.

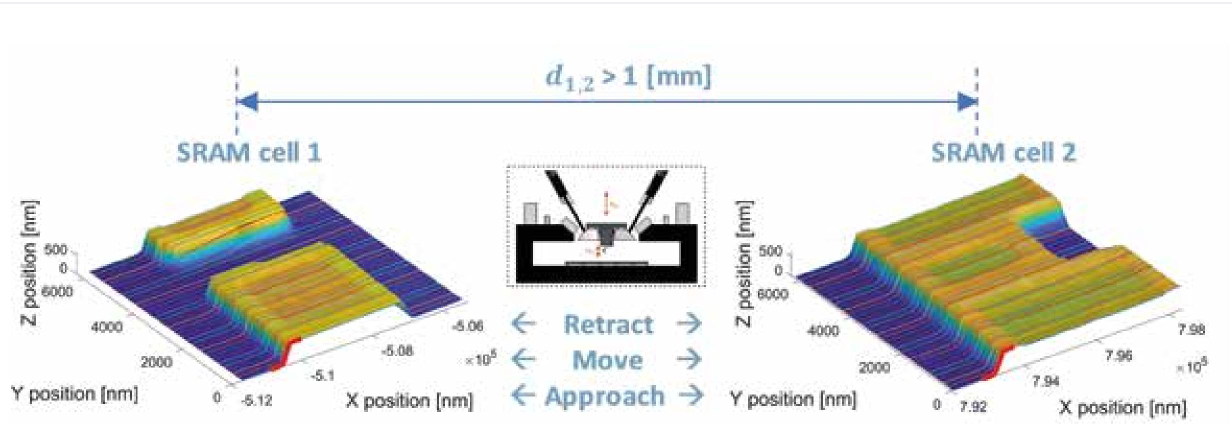
Each distance measurement cycle took approximately one minute. In post-processing, for each sidewall measurement the lateral position of the sidewall was extracted. From this we calculated the distance in two slightly different ways:

- Feature 2 measured after feature 1; $D_1(n) = x_2(n) - x_1(n)$.
- Feature 2 measured before feature 1; $D_2(n) = x_2(n) - x_1(n+1)$.

This way, if the positions of the features have a common lateral drift component, its effect will show up as a difference between $D_1(n)$ and $D_2(n)$. To further improve the distance measurement, a moving average using four consecutive cycles is applied to the data set; $D'_1(n) = ¼\, \Sigma_{i=0..3}\, D_1(n-i)$. This effectively makes the test time for a single point four minutes.
As can be seen in the result (Figure 8), no significant effect of common lateral shifting is visible; the red and blue markers follow the same trends and do not significantly separate. As for the reproducibility, during the first 4-5 hours of the test, there was about 1.5 nm change in the 1.3 mm distance measurement (< 20 pm/minute). After 5 hours the trend became flat (we expect the system was thermally stabilised), and the obtained length values exhibited < 0.25 nm rms variation. A summary of the test results in shown in Table 1.

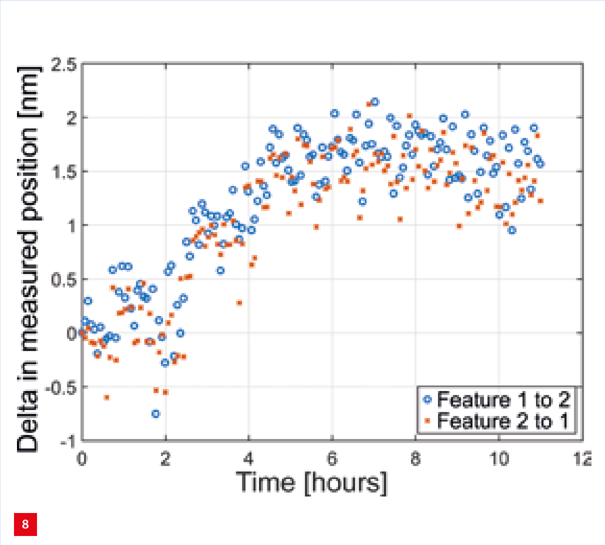
Table 1
Summary of the LDR-AFM system performance. Value for $\sigma(d_{1,2})$ (i.e., the rms variation in the length measurements) obtained from data points in the flat section in Figure 8 (i.e., after 5 hours).

Performance variable	Value	Unit
Stage bandwidth, *x*, *y*	210	Hz
Stage bandwidth, *z*	270	Hz
x, *y* stand-still servo error	< 0.7	nm rms
z stand-still servo error	< 0.4	nm rms
ϕ, θ, ψ stand-still servo error	< 15	nrad rms
Stand-still drift in *z*	< 50	pm/min
Distance drift in *x*, > 1 mm stroke	< 20	pm/min
$\sigma(d_{1,2})$ over > 1 mm stroke, 12 hr	< 0.25	nm



7

Schematic illustration of a distance measurement cycle: 3D images of actual data obtained with the LDR-AFM; in red the portion of the edge that is remeasured in each distance measurement cycle.



Change in measured feature distance as function of time. Each data point represents the average of four distance measurement cycles.

Summary and conclusion

In this article, the design and first results of the LDR-AFM developed by TNO have been presented. A high-performance instrument was realised using a unique combination of a large-range positioning stage (Figure 9)

Close-up of the LDR-AFM's positioning stage. Right of centre is the hexapod positioning stage with a hole for accommodating the AFM head. Also visible are the laser interferometers consisting of fibres with collimation optics (top-left, top-right), beam-splitters (large glass blocks with blue-coloured rectangles due to a reflective dielectric coating on two of the mirrors), and mirrors attached to the positioning stage. (Photo: Henri Werij)

with full 6-DoF control, accurate metrology, separation of force and metrology frames, and a very sensitive AFM sensing head. The results show the predictability and reproducibility of the LDR-AFM and demonstrate its potential for sub-nm metrology over several millimeters distance. Future work includes further optimising the metrology tool's environmental conditions, investigating metrology applications for the tool, and addressing metrology-specific challenges and measurement recipe development.

Acknowledgments

The authors would like to thank the other project members at TNO for their vital contributions to the realisation of the LDR-AFM, and ASML for their valuable inputs. Furthermore, we would like to thank prof.dr. H.G.C. Werij for his photo (Figure 9) of the LDR-AFM's positioning stage, featured on the cover of this Mikroniek issue.

REFERENCES

[1] C. Werner, P.C.J.N. Rosielle, and M. Steinbuch, "Design of a long stroke translation stage for AFM", *Int. J. Mach. Tools Manuf.*, 50(2), pp. 183-190, 2010.
[2] F. Ohnesorge, "True atomic resolution by atomic force microscopy through repulsive and attractive forces", *Science*, 260 (5113), pp. 1451-1456, 1993.
[3] P. Eaton, and P. West, *Atomic Force Microscopy*, Oxford University Press, New York, NY, USA, 2010.
[4] H.U. Danzebrink, et al., "Advances in scanning force microscopy for dimensional metrology", *CIRP Annals - Manufacturing Technology*, 55(2), pp. 841-878, 2006.
[5] J. Foucher, R. Thérèse, Y. Lee, S.-I. Park, and S.-J. Cho, "Introduction of next-generation 3D AFM for advanced process control", *Proc. SPIE*, vol. 8681, p. 868106, 2013.
[6] G. Schitter, and M.J. Rost, "Scanning probe microscopy at video-rate", *Materials Today*, 11 (special issue), pp. 40-48, 2008.
[7] H. Sadeghian, et al., "High-throughput atomic force microscopes operating in parallel", *Review of Scientific Instruments*, 88, p. 033703, 2017.
[8] S. Kuiper, E. Fritz, and W. Crowcombe, et al., "Large dynamic range atomic force microscope for overlay improvements", *Proc. SPIE*, vol. 9778, p. 97781B, 2016.
[9] G. Witvoet, et al., "First results from the Large Dynamic Range Atomic Force Microscope for overlay metrology", *Proc. SPIE*, vol. 10959, *doi: 10.1117/12.2514044*, 2019.
[10] G. Witvoet, et al., "Predictive-model-based MIMO motion control of an unstable 6-DoF hexapod stage for overlay measurements", *Proc. Conf. Control Technol. Appl.*, pp. 726-731, 2017.
[11] D. Stewart, "A platform with six degrees of freedom", *Proc. Inst. Mech. Eng.*, 180 (1), pp. 371-386, 1965.
[12] G. Witvoet, et al., "Line-to-line repetitive control of a 6-DoF hexapod stage for overlay measurements using Atomic Force Microscopy", *Proc. American Control Conference 2019*, pp. 2464-2469, 2019.

EINDHOVEN ENGINE FUELS FRESH STARTS IN INNOVATION

At just over a year old, Eindhoven Engine has already produced a large number of appealing projects. The driving motivation behind this initiative in innovation stimulation is to create an inspiring atmosphere comparable to that of the famous Philips NatLab (Philips Research). Here, clever scientists were more or less free to investigate innovative ideas in close cooperation with colleagues and product designers.

FRANS ZUURVEEN

In 1914, Gilles Holst started work in Eindhoven (NL) as a physics researcher. His tasks were the development of new Philips products, like radio valves, and the improvement of existing ones, mainly incandescent lamps. Holst had recently left Leiden (NL), where he had been collaborating with Heike Kamerlingh Onnes, who had just succeeded in producing liquid helium, reaching a temperature of nearly 0 K.

The work Holst supervised in Eindhoven as director of NatLab ('Physical Laboratory') included gas discharge, radio and X-ray tubes, magnetic ferrites and television. He had good intuition for which phenomena to investigate in the continuously expanding NatLab. Before the Second World War, however, he made a 'misjudgement' in his decision to favour film and cheap consumer cameras instead of predicting a future for the new medium of television. Nonetheless, this misconception led Philips to the successful production of film projectors and even the much less successful recording of a feature film.

1

The former NatLab lecture theatre at the Eindhoven Kastanjelaan. (Photo by Johan Bakker [1], 2017)

The NatLab atmosphere

Before, during and after the Second World War, the NatLab was housed in premises at the Kastanjelaan in Eindhoven. Prominently visible from outside is the lecture theatre (see Figure 1), where every Thursday young scientists, after having been at Philips for a year, used to give an insight into their research ambitions. In the sixties, the NatLab moved to premises on Philips grounds south of the city of Eindhoven, where the High Tech Campus is now located. Characteristic for an atmosphere facilitating the easy exchange of ideas and opinions between people were the large restaurant and the goose pond. After lunch, NatLab workers used to make a short walk around the water, often explaining problems concerning their work and providing colleagues with the opportunity to suggest solutions.

The other end of the terrain housed the Philips Patent Office. Scientists discovering a new invention presented their findings to the NatLab directional board with a so-called white card. After permission was given by the appropriate member of the board of directors, the card was transferred to the Patent Office to formulate a patent application. Of course, only a small fraction of ideas led finally to a commercially available Philips product, but in an annual assembly of the CEOs of Philips and American Bell Labs, the Philips patents did help the company to acquire the formal right to exploit relevant American discoveries.

Eindhoven Engine

Fast forward to 2020 and the directors of Eindhoven Engine, Maarten Steinbuch and Katja Pahnke, who are responsible respectively for the technical and operational aspects. They have this to say about the initiative: "Co-creation and co-location are the basic ingredients for unleashing the collective intelligence in order to boost innovation." Their

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2

The TU/e MultiMedia pavilion, housing Eindhoven Engine.

aim is to recreate the NatLab atmosphere described above by supplying the means for opportunities to innovate to scientists, companies and engineers, and now also students from both Eindhoven University of Technology (TU/e) and Fontys University of Applied Sciences.

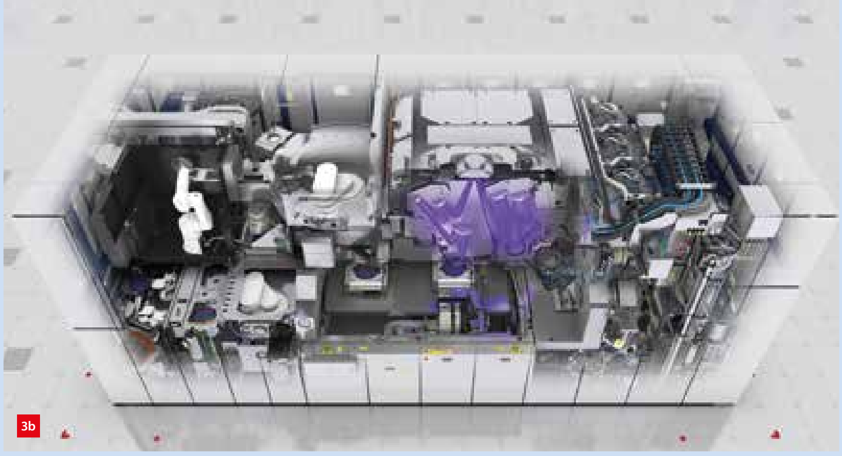
The basic location for Eindhoven Engine is the MultiMedia pavilion on the TU/e campus (see Figure 2). The building has undergone intense and rigorous modification to suit the demands of an interactive exchange of ideas in and around the various Eindhoven Engine projects. The opening and inauguration of the renewed building was planned for 10 December, 2020, the current state of the Covid-19 pandemic permitting.
The people working in Eindhoven Engine originate from various companies and knowledge institutes in Eindhoven Brainport, the ecosystem based in the region's high-tech systems industry. They generally spend at least one day a week in the Eindhoven Engine building. The interaction of ideas and results is stimulated by, among other things, the organisation of regular meetings comparable with the Thursday morning meetings at the former NatLab, and also cross-project team meetings. Many projects have a larger quarterly meeting, giving them the opportunity to release progress reports. Naturally, interactions between projects through workshops, etc. are of vital importance. The general

Piezo-electric wafer stage

ASML is greatly interested in innovative ideas for the precision movement and positioning of wafers in their advanced wafer scanners, which work with ultrashort-wavelength EUV illumination (see Figure 3). Moving and positioning a 12-inch wafer, with a positioning reproducibility in the nanometer region, has up until now been achieved in two stacked stages: one for a 'rough' long-stroke movement and one for a highest-precision short-stroke movement. Originally, the long-stroke stage consisted of an H-form configuration: two Y-guides for the movement of one X-guide that bears the short-stroke wafer carrier. This century, this H-configuration has been replaced by a planar actuator stage, designed as a big electromagnetically levitated box. The Eindhoven Engine project aims at a new concept for the short-stroke stage. The present design has the disadvantages of high mass, disturbing magnetic fields and high actuation forces in a mechanical system structure with limited stiffness. The idea is to investigate how piezo technology could help to achieve mass reduction (5 kg instead of 20 kg, for example) in compact and stiffer short-stroke actuators. A successful design also might be applied in future ASML wafer inspection machines.

Partners: ASML, TU/e High Tech Systems Center, with the later involvement of NTS, VDL ETG and TNO.

3a



3b

An ASML EUV wafer scanner. (Images courtesy of ASML)
(a) Opened front view with EUV beams in yellow.
(b) Opened top view with EUV beams in purple.

exchange of knowledge is also facilitated via the physical set-up of the building: there are no closed private rooms. Instead the space consists only of open connections to stimulate the consultation of colleagues.

More than 16 projects have already been approved by a team of experts. New OpenCall projects will be launched in the coming years. The blue boxes highlight three current projects with precision engineering interfaces.

To conclude

Time will tell whether the recreation of the NatLab atmosphere has helped to stimulate innovation in the Eindhoven Brainport region. We will continue to scrutinise what happens there in the world of precision engineering.

REFERENCE

[1] *nl.wikipedia.org/wiki/Philips_Natuurkundig_Laboratorium*

INFORMATION
WWW.EINDHOVENENGINE.NL

Efficient air quality

The aim of this project is to improve the efficiency of clean-air production, because air installations are responsible for around 35 per cent of all energy consumption in buildings. Ultimately, this should benefit schools, because inferior environmental conditions within classrooms have both short- and long-term health effects due to tiny particles in the air.

A spin-off of this schools-directed project may target cleanroom design. Many precision-engineering products can only be manufactured under cleanroom conditions (see Figure 4). Every cubic meter of untreated outdoor air typically contains 35,000,000 particles of 0.5 µm and larger. In contrast, ISO 1 cleanrooms should have no particles of that size at all. The investigation of sensors, filters, ventilators and air control systems in this project may help to reduce energy consumption in the assembly of high-tech equipment.

Partners: Building G100, Camfil, ISSO, Kropman, Lucas Onderwijs, NedAir and TU/e.

4

An ASML technician working on a wafer scanner in a high-grade cleanroom. (Photo courtesy of ASML)

SmartMan

Smart manufacturing, SmartMan for short, is a rather well-known activity within the high-tech systems industry that involves the optimisation of factory efficiency by improving production processes. However, SMEs generally lack capacity to create innovation in this area. By offering student resources and experience from comparable previous cases, Fontys University of Applied Sciences is able to help SMEs to innovate, with TNO filling in the strategic directions of smart manufacturing. This includes aspects such as robot-assisted manufacturing, data sharing, industrial artificial intelligence, virtual reality and autonomous transport. One important objective of the project is to stimulate Fontys students and graduates to become active in this project by integrating quality control, automation and flexibility on existing shop floors. The ultimate goal is to create a community of SMEs that support each other on innovation issues.

An interesting SmartMan activity is the collaboration of Fontys, Siemens Nederland and Bozhon Precision Industry Technology. This involved the creation of a virtual digital twin of a machine with robot arms for the industrial connection of the front and back sides of smartphones (see Figure 5). A saving of 30 per cent in development time was achieved by simulating the specified machine using this virtual 3D model, including an interface with the open, cloud-based operating system MindSphere. During the real manufacturing of the machine in China, functional tests could be executed at the virtual twin machine in the Netherlands.

Partners: Fontys, TNO and Smart Industry fieldlab partners VDL, VBTI and several SMEs.

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A Bozhon precision mounting machine for the connection of smartphone parts. The development time for this machine was reduced with the aid of a digital twin. (Image courtesy of Siemens Nederland)

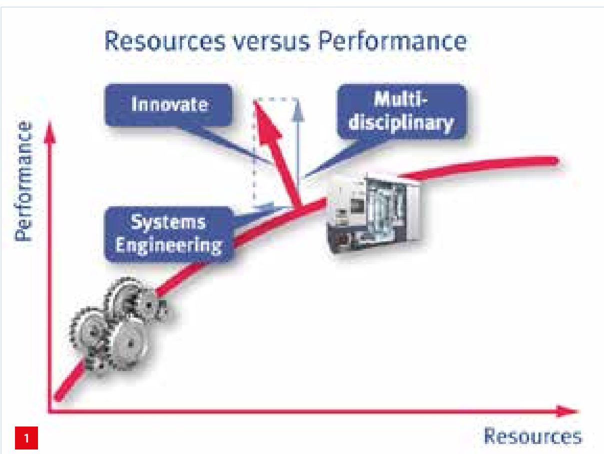
MERGING SYSTEMS ARCHITECTURE AND PROJECT MANAGEMENT

In recent years, systems engineering (SE) is becoming more important in the Dutch high-tech equipment industry. Increasing system complexity and increasing team sizes put more emphasis on the explicit coordination of design activities. SE connects two worlds: the technical world with system models managed by the systems architect and the management world with process models managed by the project manager. In the Dutch high-tech equipment industry, we are already used to these worlds closely collaborating.

ANTON VAN DIJSSELDONK, MARC HAMILTON AND TON PEIJNENBURG

SE is defined in many ways. According to the International Council on Systems Engineering (INCOSE), "Systems Engineering is a trans-disciplinary and integrative approach to enable the successful realisation, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods" [1]. SE can be applied to technical systems, but more general to other kinds of systems as well, such as organisational systems, societal systems, etc., as a means of dealing with complexity (see Figure 1). SE relies strongly on systems thinking, which itself has many definitions. A practical one is "Systems thinking is the ability or skill to perform problem solving in complex systems" [2].

In general, Dutch high-tech companies use model-based development methodologies. Design teams are always multidisciplinary, mechatronics is one of the terms that is used to express this multidisciplinary character. The design teams use a design methodology that is based on models of which the detail increases as the design evolves. Starting out with simple, lumped parameter models to capture the most important performance-limiting interactions in the system under development, details are added when the design progresses. Many models are being developed, and not always do these models evolve over the full design cycle. Typically, a variety of models rooted in various technical disciplines are used, oftentimes including multi-physics models.
Never we use all-encompassing, all-physics models that can capture all relevant details for all phases of the design cycle. It is hard to conceive that such all-in-one models will ever become available for developing a system; however, visualising a full system will be possible.



1 *Dealing with increasing complexity. (Source: TU/e HTSC)*

So, while our system design efforts critically depend on truthful models using correct parameters to efficiently develop effective and reliable engineering solutions, they must deal with many of these, often multi-physical models that each evolve over time in their own rhythm. The management of all these models becomes a severe challenge, especially for large and complex high-tech systems. Noting that the union of all the models captures all relevant aspects of the system we are developing, a single-source-of-truth (at a given moment in time in the design process) for all models becomes an important requirement.

Since the design of the whole system will require regular rebalancing of requirements and their allocation to the various subsystems, management of the models is a system-level responsibility. It is here that SE should have its key responsibility: SE should provide processes and a methodology to structure and coordinate model-based engineering. Novel developments in the world of SE

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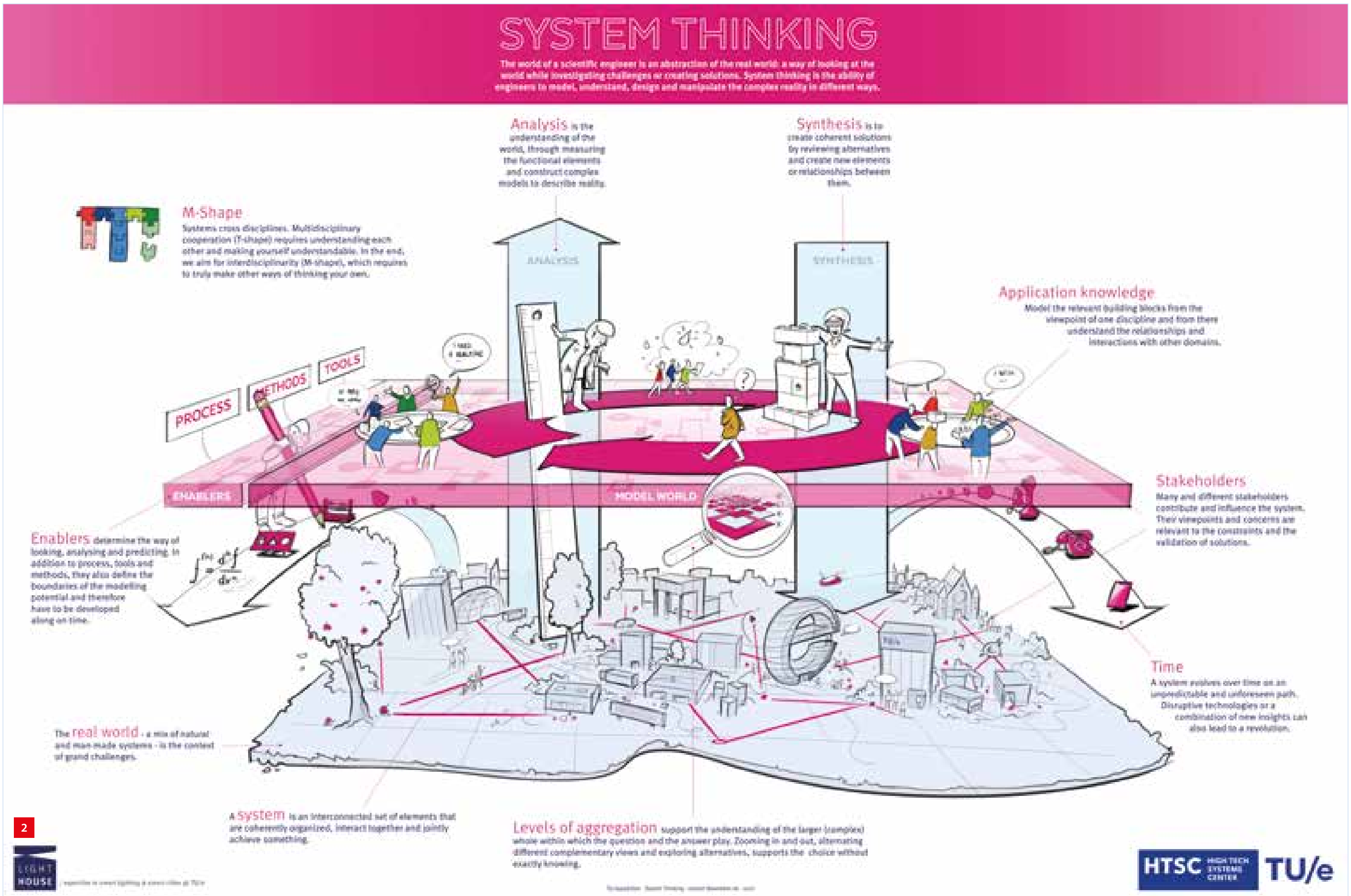

2

Systems thinking and systems engineering. (Source: TU/e HTSC)

organisations such as INCOSE are addressing this development under the term model-based systems engineering (MBSE).

Systems engineers and systems architects are working in close cooperation: in our definition a systems architect organises the design of a solution, especially at the sub-system and module level, such that a system can be built while a systems engineer is responsible for defining the constraints for the development such as properly articulating the requirements and coordinating the interfaces between the various sub-systems and modules.

Systems thinking

In a study group at Eindhoven University of Technology, the integration of systems thinking in education was discussed. As a result, the picture of Figure 2 was made. It shows the real world, in grey and at the bottom. In pink, a model representation of this world is drawn. In the centre is a magnifying glass that shows how this model world is a hierarchy of increasingly detailed models. In the model world, multidisciplinary teams of differently coloured engineers develop solutions for real-world problems, iterating between analysis and synthesis. In the analysis phase, the real world is measured and understood, as is the way in which real-world problems may be addressed. In the synthesis phase, solutions are engineered and deployed.

Ideally, the engineers have T- or M-shaped profiles, whereby in-depth understanding of one or two aspects (the vertical lines of a T- or M-shape, respectively) is combined with the ability to work with and understand engineers from other disciplines (the vertical lines of the shape). Aspects of application knowledge, stakeholders, enablers and levels of aggregation are also highlighted.

The Dutch 'secret sauce' to SE

Systems thinking in Dutch high-tech equipment design has evolved out of systematic analysis of mechanical design principles, as initiated by Wim van der Hoek, and the use of feedback control as an extension to those design principles. Feedback control was required to further improve accuracy and speed of equipment, and the control engineering discipline grew central to system performance and to its design. By putting relevant technical disciplines together in teams, a way-of-working was developed that was both effective and efficient. An informal domain-specific language was created describing high-tech equipment; this language was transferred to new generations of design engineers by means of post-academic in-company training. This training was first available within Philips, and later became available at the universities and outside of Philips as well.

Although SE methodologies are being used, traditional SE as promoted by INCOSE (and as adopted in aerospace and automotive industries) has never been used in a formalised manner by Dutch high-tech companies. As an example, design process information, such as system requirements, has mostly been kept in office document and spreadsheet formats, not in formalised data systems. Formal reviews are conducted based on such documents, leading to quite some administrative overhead. Design decisions can be captured in presentation slides or just some email messages.

The sole source of truth as mentioned before is in fact a source distributed over many documents, of many distinct kinds, part of which are kept in document-based repositories. While these document-based repositories typically allow for some form of version control, other essential information management concepts such as traceability are often not supported. The system models on the other hand are kept in a variety of formats, specific to the model tooling being used. These models are sometimes maintained in the same version-controlled repository, but typically lack a managed co-evolution of the various models during the design of a system. There is no hard coupling of engineering information to the engineering process.

Dutch high-tech equipment design has been highly successful; our ability to design equipment that is among the most complex in the world is widely recognised. Still, we believe that we must evolve our SE methodologies to maintain our competitive edge and be able to design systems that are even more complex than the current ones. Our future SE must be tightly integrated with all engineering disciplines. Engineering design tools will become more interconnected. System requirements will not only be traced, but further formalised so they can be better analysed and serve as a basis to support automated synthesis of solutions. These developments can be captured under the term of model-driven (systems) engineering. Data science techniques (as well as AI techniques for design automation) will become important, not just to interpret the data generated in the equipment or to generate data to drive the equipment, but also to support the designer in the design of the equipment. In this case, the term digital engineering is being used.

Structuring the SE approach is becoming a more fundamental requirement for the engineering process. SE models should be organised (or in some cases developed) such that their dependencies and model relations are (semantically) meaningful; consider, for example, linking optical models to thermal or dynamic models. Defects in SE models will manifest as defects in the system being produced. This change will require a different approach and to achieve this, education of future systems engineers will have to adjust.

SE education

At universities of technology and universities of applied sciences, future engineers, including systems engineers, are trained. It is widely recognised in industry that SE roles require senior engineers with extensive domain and application knowledge, as well as experience in system design. We cannot expect engineers to pick up such roles fresh from university, so that leaves the interesting question on which aspects universities should focus their training for SE and systems thinking. In addition, we know that the receptivity for SE-related knowledge and know-how is not optimal for young students not having any industry experience. SE training in US and Canada is typically given as graduate training, after students have gained industrial experience as design engineers and after their bachelor training.

Where experience cannot be learned, we believe that the role of universities should be sought in laying a foundation on which future SE is based. By way of illustration, we mention some aspects that we think need attention in engineering programmes.

A more fundamental understanding of design processes and their fundamental aspects must be included in the programme. The coupling between ‘intention’ and ‘realisation’ is important to understand. Students must be able to deal with abstractions such as conceptual, functional, logical and physical reasoning in the context of a design objective. The difference between engineering models and scientific models is important for understanding the different objectives of modelling and design.

An important aspect that should be addressed in university is the understanding of connections and relations between various disciplines – technical disciplines such as software engineering and mechanical engineering, but also other disciplines that are relevant for design such as marketing and service engineering. The ability for productive multi-disciplinary collaboration critically depends on understanding of and respect for each other’s disciplines. Understanding the refinement processes and the corresponding languages of other disciplines is important as is the understanding of other design cultures that become relevant when working for external and/or international customers.

Proper identification and formalisation of requirements is an important skill for system engineers. These skills can be trained in university and will help the new engineers to become more effective in their job. Taking a systems perspective to derive requirements, determine their relative importance and their allocation in the requirements tree for the overarching system forces engineers to consider the objective of their task and stimulate them to start negotiations with other parts of the system their design will be part of more thoroughly.

Formalised optimisation of systems will become important given the increase in system complexity. For small parts of a system, an informal, qualified trade-off may be sufficient. For large and complex high-tech systems, these are too vulnerable to influences such as cognitive bias or incompleteness. Premature convergence to a single solution is sometimes difficult to avoid, the need for quantification may help prevent this. Currently, our system developments are typically based on budgeting for key parameters, and quantification trade-offs are easier when based on clear budgets.

Conclusions

Systems engineering for high-tech equipment is evolving into a critical engineering discipline due to the integration of ever more complexity, disciplines, dependencies and specialisations into the design process. There is a need for more comprehensive system overviews in the presence of high complexity, faster responses to changing requirements and boundary conditions, more formalised trade-offs considering many factors and more generally also a faster feedback cycle between all engineering disciplines and the SE coordination.

The role of universities needs to be adapted and intensified to establish a future-proof SE culture for high-tech systems. Unification of fundamental SE principles throughout the various educational programmes of the university will lay the foundation for consistency. A backbone of system design courses will provide a clear path towards required SE and design skills. Future systems engineers should be prepared for widening their view/scope of solutions and their impact (holistic applications, artificial intelligence, systems thinking). An active interaction with industry experience is a prerequisite to continuously tune the educational programme.

REFERENCES
[1] *www.incose.org/about-systems-engineering*
[2] *en.wikiversity.org/wiki/Systems_Thinking*

UPCOMING **EVENTS**

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

2 February 2021, Veldhoven (NL)
CLEAN Event
This theme day, organised by Mikrocentrum, provides an expert's view on cleanliness, focusing on design, production, assembly and packaging.

WWW.MIKROCENTRUM.NL

Virtual event

10-11 March 2021
Lamdamap 2021
Fourteenth edition of this event, focused on laser metrology, coordinate measuring machine and machine tool performance.

WWW.EUSPEN.EU

29 March 2021, Düsseldorf (GE)
Gas Bearing Workshop 2021
Fourth edition of the initiative of VDE/VDI GMM, DSPE and the Dutch Consulate-General in Düsseldorf (Germany), focused on gas bearings as important components or integral technology of most advanced precision instruments and machines.

WWW.GAS-BEARING-WORKSHOP.COM

26-27 May 2021, Veldhoven (NL)
Materials+Eurofinish+Surface
At this event, a combination of three trade fairs, product developers, product designers, engineers, R&D professionals, production staff, material specialists and researchers can meet the entire materials value chain.

WWW.MATERIALS-EUROFINISH-SURFACE.COM

2-3 June 2021, Veldhoven (NL)
Vision, Robotics & Motion
This trade fair & congress presents the future of human-robot collaboration within the manufacturing industry.

WWW.VISION-ROBOTICS.NL

7-11 June 2021, Copenhagen (DK)
Euspen's 21th International Conference & Exhibition
The event features 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.

DTU, the Technical University of Denmark, will provide the venue for euspen's 21th International Conference & Exhibition.

WWW.EUSPEN.EU

9-10 June 2021
RapidPro 2021
The annual event showcasing solutions for prototyping, product development, customisation and rapid, low-volume & on-demand production.

WWW.RAPIDPRO.NL

16-17 June 2021, Den Bosch (NL)
Food Technology 2021
Knowledge and network event about high-tech innovations in the food industry.

WWW.FOOD-TECHNOLOGY.NL

14-15 September 2021, Eindhoven (NL)
DSPE Conference on Precision Mechatronics 2021
The fifth DSPE conference on precision mechatronics, organised by DSPE, will be a special edition, in view of the uncertain pandemic situation. It will combine two elements: (1) inspirational presentations by several invited international speakers from adjacent application areas, such as bio-inspired mechatronics, robot-assisted surgery, virtual reality, artificial intelligence, and more; (2) the opportunity for the community to meet/network and exchange ideas in a pleasant atmosphere, including a BBQ. For more information, see page 60.

WWW.DSPE-CONFERENCE.NL

BIO-INSPIRED INTELLIGENT SYSTEM DESIGN

Natural environments pose great challenges to designers of intelligent systems. So how can data analytics (DA) and artificial intelligence (AI) help? Also, what can biology teach us about realising AI with a minimal footprint (costs, effort)? To answer these questions, we investigate both the relationship between DA and AI, and concepts that can mimic biology (animals, humans) to engineer better-balanced systems, in terms of cost price as well as engineering effort. Then, we zoom in on a particular artificial neural network architecture that fits these concepts. Finally, we present the application of DA and AI in a robot-arm trajectory planning case.

JAN JACOBS

Introduction

This article addresses the engineering of AI systems that operate in a natural environment. For example, robots picking apples in an orchard where their fingers have to feel the normal and slip forces of the fruit, or a truck with a double trailer reverse parking autonomously into a bay. In the near future, we can expect robots will be able to learn to compensate for faulty parts themselves, or even discover automatically as yet unknown/unintended operation modes. In the context of intelligent system design, questions such as "What properties does a natural environment have?" and "How should we best engineer AI systems?" arise.

As they are key concepts for intelligent system design, here we will elucidate data analytics (DA) and artificial intelligence (AI), and answer two main questions:

1. How do DA and AI participate in intelligent system design?
2. What can biology teach us about engineering an AI system with a minimal footprint (costs, effort)?

Firstly, we will clarify the concepts of DA and AI, and how they relate to each other. Next, we will scout some of the concepts that can mimic biology (animals, humans) and explain how we can use these to engineer better-balanced systems, in terms of cost price and engineering effort. Then, we will zoom in on a particular artificial neural network architecture that fits these concepts. Finally, we will describe a concrete case in which DA and AI are put to work in robot-arm trajectory planning.

Data analytics and artificial intelligence

In short, DA places the data in a central role and is used to derive meaning from it. So, it is about building models, often created by an interactive explorative DA activity, which provide insights to decision makers. It uses a mixture of statistics, mathematics and programming to derive such models. Once a model has been set up and validated, it can be used in practice by allowing the decision maker to make predictions, i.e. evaluating the impact of new data on their business. DA is often exchanged by data science, but this is incorrect, as will be explained later.
AI, on the other hand, aims at enabling machines to act like human beings. It is modelled after the natural intelligence that animals and humans possess, and it makes use of algorithms to perform autonomous actions. Thus, it is about performing actions in the world that are indistinguishable from actions performed by a real animal or human [1].

In Figure 1, the DA activity takes place in the left part (yellow block); sensors connected to the real world deliver all kinds of data that is then processed, involving a kind of information compression resulting in a compact, semantic-like description of what happens in the real world. This description is used by a decision maker acting as a control entity (orange block).

AI, however, is concerned with performing actions in the world where they can be observed and tested. It is for this reason that AI emerges as an observable result of performed cyclic actions in the world. As these actions ought to be indistinguishable from animal or human behaviour (i.e. from an operational definition of AI, one that enables machines to act as human beings, there should be no discernible difference between the two), often lots of actuation is needed to mimic the required nuances.
This processing involves a kind of information expansion, resulting in a potentially wide vector of steering information for actuation; quite the inverse of the DA part. In this way, we close the cycle by preparing the desired compound actuation by using a data-intensive activity called data

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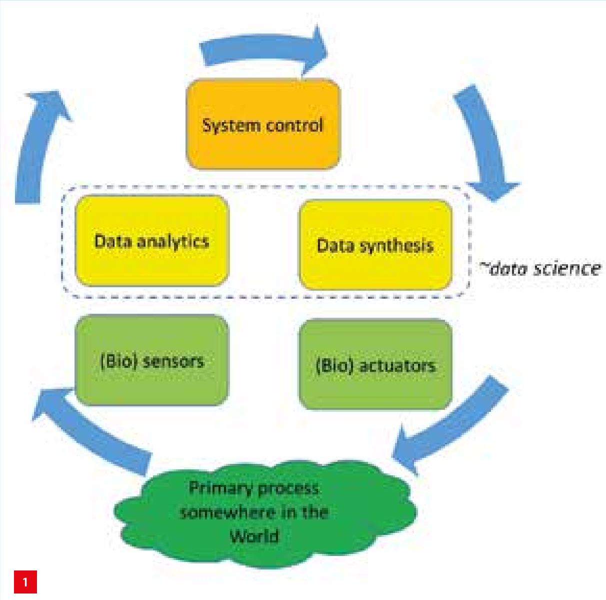

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Intelligence emerges as the end result of cyclic control, rather than programmed data science.

synthesis (right yellow box in Figure 1). As both analytics and synthesis activities involve data extensively, we unify them in the term data science.

A next question is how to measure intelligence? A popular test is the Turing test [2], in which an interrogator tries to distinguish between a – for them hidden – real human and an AI system by typing questions into a terminal and checking the answers from both for essential differences. There is some criticism of this way of testing [3], in particular concerning the use of language and the fact that the interrogator is part of the test set-up. Just using language as a way of expressing intelligence is too limited and excludes intelligently behaving animals and robots that do not have linguistic capabilities. When language does not, however, monopolise the test, other ways that do not use an interrogator could be used. For example, an observer monitoring only the behaviour of the robot versus that of an animal or human, and judging purely on performed actions in the world, would render this a more broadly applicable test and provide a fairer 'competition'.

Then, one could wonder if AI is only AI if its behaviour is similar to that of a human or animal. Is this AI's end goal or will it develop to a higher level with even better behaviour as a consequence? The latter has already become true, as demonstrated by games like chess and Go and the quiz Jeopardy!, for example, that have already been 'conquered' by AI. Other categories of behaviour will follow in the future. We will need other definitions of AI, and new ways of measuring it, because intelligence will transcend to a new field of science (and as a result, new forms of engineering) where human beings will play a lesser part.

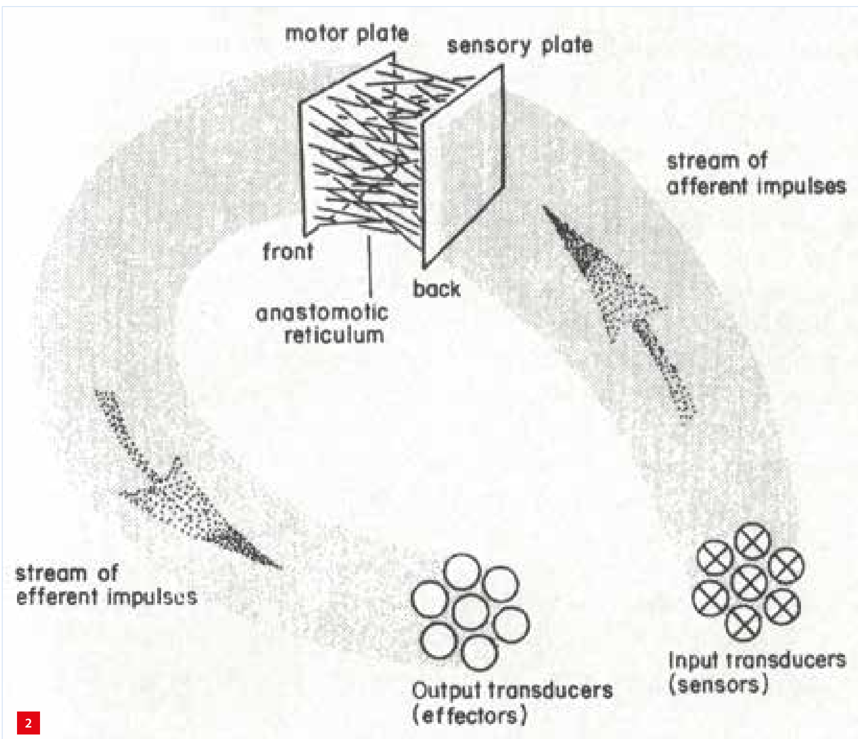
Finally, a more controversial question associated with the Turing test is whether observations alone can prove that an AI system really understands or can at least explain the flow of reasoning in the interaction. Yet does this matter in a system that functions well enough?

How biology can inspire AI

The real world is the arena in which AI systems are deployed. The real world is, however, less conditioned and less predictable. This is called indeterminism [4], denoting a situation in which events are not caused, or not caused deterministically. This contrasts strongly with pure software systems, which are 100 per cent deterministic (informatic systems).

For systems embedded in a natural environment, we need therefore a regulatory system to deal with this indeterminism, which leads to a form of control. Inspired by biology, Stafford Beer's Viable System Model [5] reckons with the complexity of its environment and as a consequence has to have sufficient internal variability to counter this complexity in order to reach a form of homeostasis/equilibrium.

This process is very much like control; for a biological example see Figure 2 (Beer named this cybernetics in contrast to informatics: the science of the unknowable). The anastomotic reticulum stands for a highly interconnected bunch of neurons from a sensory plate to a motor plate, and acts as a decision-making entity. These plates consist



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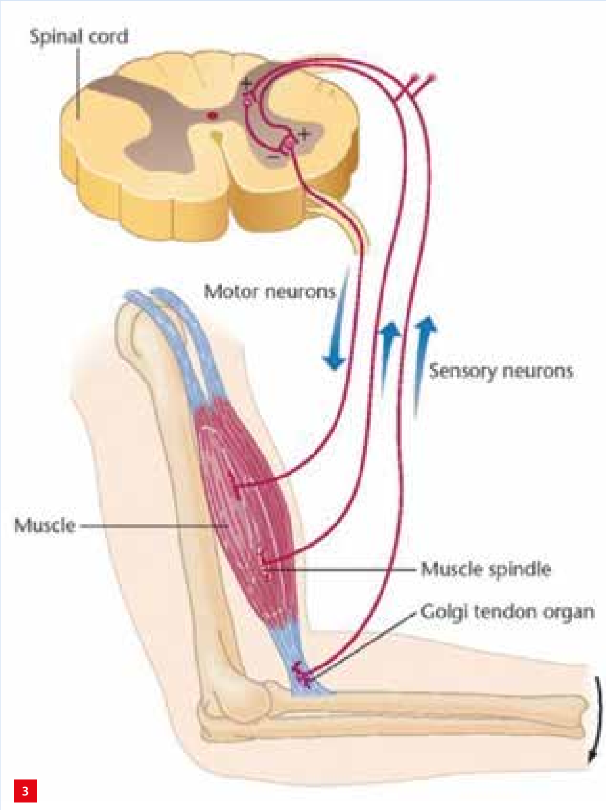
Intelligent behaviour of a very basic system controlling its environment [5].



Proprioception by monitoring the activation of muscles [6].

of a limited set of prototypical sensor, respectively motor representations that realise sufficiently generic models. Both plates, as well as the interconnecting neurons, are being trained by input as well as output impulses caused by interactions with the environment.

Note: Prototypical sensor and motor representations are generic representations learned from instances that actually were sensed or actuated during training. Together with the reticulum, they offer, after training, a direct path from unseen but similar sensed instances to the right motor neuron for actuation. In this way, living organisms can make the right decisions for survival in nature.

A nice example of such a control loop is the hand-eye coordination, where visual information as well as the position information of all involved arm muscles guide the hand to a specific target. This is called proprioception: the sense of self-movement and body position. It is developed in childhood during (un)conscious movements of parts of the body. For example, when an arm is moved, nerve fibres (tiny sensors in the muscles) detect the amount of stretch and direct this information to the spine and brain (see Figure 3). Joints have fibres too, which detect the relative position of each bone. Moreover, touch-sensitive nerve endings in fingertips, fingers, the hand and the arm contribute by relating this body position to external objects. When using the arm to make specific conscious movements, we simply use the hand-eye control loop, supplemented with hand-touch control.

This all allows one, after having been trained by one's brain, to determine the position of every part of one's body. This self-learning process is called motor babbling or, referring to the relevant stage of life, baby babbling. This form of adaptivity is another advantage that can be deployed in engineered systems: it allows the system to train its basic actuation repertory or map itself and reduce programming to a minimum.

Yet how can we translate these concepts into engineering guidelines for use in real-world systems/robotics? A bio-inspired system architecture (subsumption) for AI robotics is given in [7], with a set of associated design principles. One of these principles is 'ecological balance' and it describes the balance between the complexity of sensory, motor and neural systems, as well as the balance of task distribution between morphology, materials and neural control.
The essence of this principle is that we should balance all involved chain links in the closed-loop AI architecture; the strength of the cycle is determined by its weakest link. This does not involve only concepts such as sensors, motors and neural processing, but also the form of the body of the robot (morphology), as well as the material it is made from. A good illustration of this is the simplicity of design shown when a housefly executes a flight plan: it uses only a few neurons and yet it is in perfect balance with the form of the body (facet eyes) and the lightweight material it consists of [8].

Optimality of design depends, of course, on the ecological niche in which a (robotic) system is situated. An optimal but specific robot gripper for strawberries will look different from one for apples. But what is optimal? Optimal can also be related to the universal hand that can pick strawberries as well as apples. Over time, the development of the human hand has been steered by all the different behaviours a human being had to exhibit to survive in this world. The human hand is therefore very versatile and proven to be optimal for its task. When robotic hands and fingers are constructed for a single task, they will surely deviate from the human hand. Economic arguments will then pick a sweet spot in the trade-off between context specificity and generality.

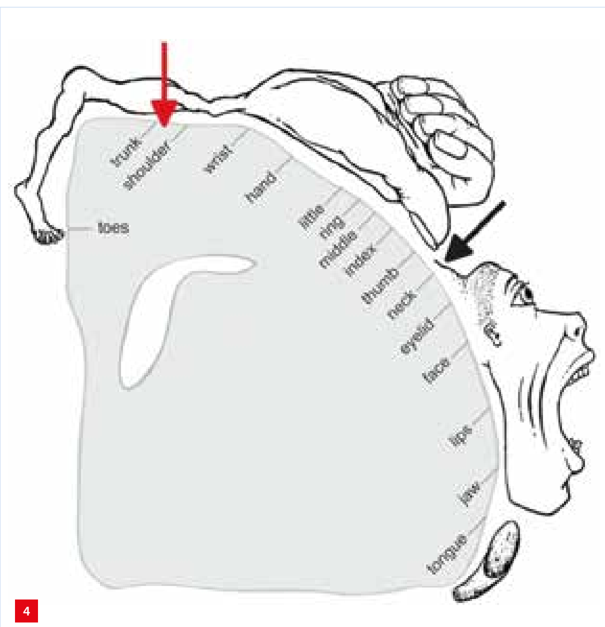
Several factors prevent systems engineering nowadays from being applied optimally. First of all, the dominance of data-intensive engineering tempts the designer to follow a more informatics-driven workflow, where the focus is more on understanding data input than on the direct improvement of the primary process itself.

Next, engineers apply control theory only in small contexts and not on wider system levels (cybernetics) where it could directly steer the primary process in multiple ways, as well as in continuing iterations. By utilising cyclic information from the primary process as well as the (robotic) system that is acting upon it, one can ensure that the systems are not made too complex.

Finally, neural processing can adaptively compensate for non-uniformities or spontaneous deviations in the specs of system parts, thereby avoiding costly redesign and maintenance cycles. So, systems engineering for natural environment applications overlooks the fact that indeterminate systems, in the end, need a kind of regulatory (cybernetics) solution. This solution allows for dealing with indeterminate responses of the external environment as well as for online adaptation to potentially changing conditions of the system itself. In this regulatory approach, these self-learning systems do not have to be overdimensioned, and therefore are cheaper and require less effort than a data-intensive solution.

To summarise, the advantages of copying the above biological processes to engineered systems, e.g. robots, are:

- lower cost, because the cybernetic control loops (e.g. hand-eye and hand-touch for a robot arm) can use less expensive parts;
- lower effort, because neural building blocks are partially self-learning, so very little programming is needed;
- large adaptivity to changes in the context or conditions of the system itself (e.g., the robot arm joints can deteriorate, have 'rheumatism').



Topological ordering of parts of the somatosensory map.

The next section will briefly introduce a neural network architecture that allows for the necessary self-learning adaptivity and will position it in a closed-loop AI architecture.

Self-organising map

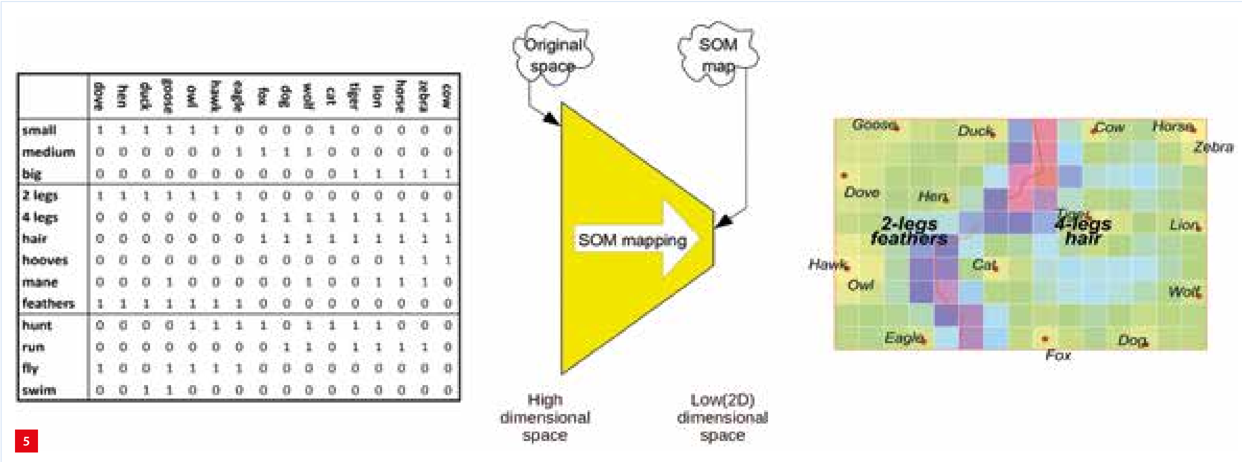
Figure 2 shows that biology uses compressed and prototypical representations of the most important sensor and motor information (sensor and motor plates or maps). Several recent deep-learning neural network architectures do possess these prototypical representations, like auto-encoder architectures and recurrent neural networks [9]. As inspired by the way our human brain is set up, we can further improve deep-learning architectures by allowing for other types of artificial neural networks (ANNs) than the standard multi-level perceptron (MLP) model.

Furthermore, unsupervised ANNs should be incorporated to allow for a kind of self-learning in order to bootstrap intelligence. Such a heterogeneous deep-learning architecture is expected to have a smaller neuron budget and would take less effort to train, as well as, because of its self-learning capabilities, being adaptive to changes in the outside world.

One such different, unsupervised neural architecture is the self-organising map [10] [11]. We will use this ANN, as this network follows the neural structures of mammal brains closely, but first we will introduce an essential concept called a topographic map.

Although the human brain consists of billions of more-or-less freely deployable neurons, it does exhibit a preference for specific locations for hosting specific functionalities. An interesting phenomenon related to this is the so-called topological ordering of neural functionality. For example, the somatosensory map (the projection of the skin's surface onto the brain), partly shown in Figure 4, shows that skin areas located close to each other are mapped near each other in the brain.
Notice the ordering of the arm parts in this figure, between the red and the black arrow. Such a topological ordering in our brain is called a topographic map. In general, such a map is the ordered projection of a sensory surface, like the retina or the skin, or an effector system, like the musculature, to one or more brain structures. Topographic mapping can be found in all sensory systems and in many motor systems [12].

At the end of the 1980s, the SOM was modelled after this topological ordering of brain parts. This unsupervised artificial neural network organises itself without any external help and is very useful in bootstrapping intelligence, as will be explained later. In short, a SOM



	dove	hen	duck	goose	owl	hawk	eagle	fox	dog	wolf	cat	tiger	lion	horse	zebra	cow
small	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0
medium	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
big	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
2 legs	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
4 legs	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
hair	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
hooves	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
mane	0	0	0	1	0	0	0	0	0	1	0	0	1	1	1	0
feathers	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
hunt	0	0	0	0	1	1	1	1	0	1	1	1	1	0	0	0
run	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1	0
fly	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
swim	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0

SOM map example of encoding a 13-dimensional toy animal data set into a 2-dimensional representation.

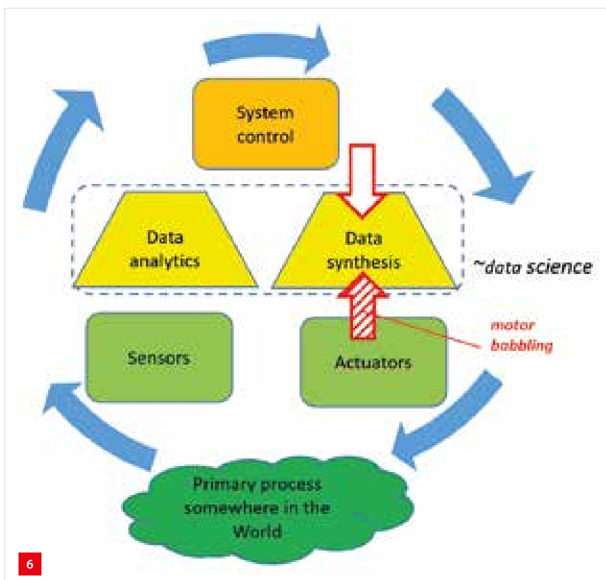
creates a small set of prototype vectors that can replace all the training vectors. (Note: A prototype vector is a single vector that can replace a set of similar vectors.) These prototype vectors also offer topological ordering: nearby neurons are similar to each other, in a manner very similar to a mammal brain (see Figure 5 for an example).

The left side of Figure 5 shows 13-dimensional training vectors (column wise), the right side the resulting map containing 10x15 = 150 neurons, each containing a 13-dimensional prototype vector (vector components not shown). Despite these 13-dimensional proto-type vectors, the map can be condensed to a convenient two-dimensional (2D) representation with annotations (such as 2 legs, hair, cow, hawk, ...) that are helpful in interpreting the original data space. The two axes in Figure 5 correspond to the two largest eigenvalues of the data set. Although there is no a-priori meaning associated with the two axes of a trained SOM map, a meaning can be derived based on eigenvectors [14]. The two axes of a map (e.g. in Figure 5) more or less correspond to the two largest eigenvalues.

In this example we consider a very a small artificial zoo of 16 animals (columns), each of which has 13 features or properties (rows); see the left side in Figure 5. In real engineering cases, these properties would typically be measured, but for this toy example we have used stereotypical values. The purpose of this example is to show the emerging topological ordering in the map. A dove, for instance, is small, has two legs and feathers, and can fly. A duck, however, cannot fly as well as a dove, but it shares enough similar features to be positioned close to the dove. Obviously, the table contains only rounded numbers 0 and 1, but despite this the resulting map in the right part exhibits interesting details. One can clearly see the following topological orderings:

- the birds (left) and mammals (right) are separated properly by a clear colour-coded border;
- examples of animals that are quite similar, as derived from the table, are placed close to each other in the map, check e.g. goose and dove, or wolf and dog;
- predators in the left bird cluster as well as in the right mammal cluster are both positioned at the bottom of the map.

The colour-coded border, also called a 'fold', indicates a relatively high level of disorder among neighbouring neurons. Colours like blue, purple and red indicate large differences between these neurons, while colours like green and yellow on the contrary indicate a high level of ordering. As a result, this fold then correctly conveys the higher distance between duck and cow as compared to the distance between duck and goose, although in the map the respective 2D distances seem to be similar.



Motor babbling builds up an actuation map by making random arm movements (shaded arrow), thus preparing for conscious movements later (blank arrow).

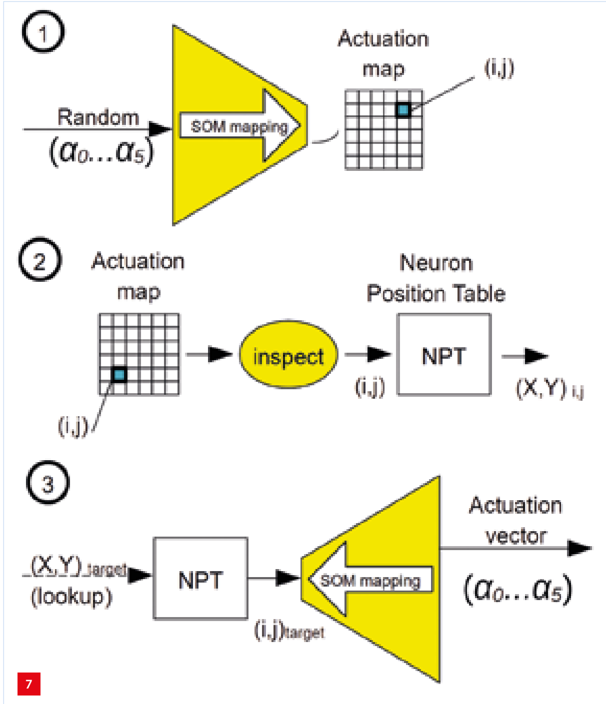
The SOM is one of the simplest model-based machine learning algorithms. It is unsupervised, so it does not need much human involvement. It is an iterated procedure of comparing and adapting the set of prototype vectors to all training samples until some quality variables reach desired levels. These variables involve the quantisation error (how well does the training set fit the set of prototypes?), topology error (are the 2D distances in the map proportional to the high-dimensional distances?) and generalisation errors (how well do not-trained samples fit the map?).

The SOM architecture is generic enough to cope with animals that are not trained. For example, a giraffe, when expressed in the same 13 features, would be positioned in the neighbourhood of cow and horse. This is very much like learning the concept of 'car', when one is confronted with lots of examples of cars such as Peugeots, Mercedes-Benzes and Mazdas, and is still able to identify a not-trained Fiat as a car. It is this generalisation property that is the essence of the aforementioned bootstrapping of intelligence. Now, new but similar sensed events trigger desired responses thanks to the topological ordering of neurons.

The middle part of Figure 5, the yellow trapezoid, symbolises the compression or mapping of a high-dimensional data set to a low-dimensional (2D) representation. This mapping, in general, preserves the high-dimensional distance relations in the 2D map.

Due to this dimension reduction, the SOM can also fit in the compression and expansion blocks in Figure 1. Compression in the sensory/left part (see Figure 6) is evident: the SOM's high-dimensional input vector connects to the various sensors obtained from the primary process in the world. But how does the SOM fit the expansion in the right part? In particular, the high-dimensional actuation vector is meant to be output; how can it then serve as input for the SOM training?

The answer is simple and – as one would probably expect – inspired by the mammal/human world: in our infancy stage random movements (baby babbling) are induced that trigger the fibre nerves to fire. This forms the input for a SOM-like training in our brain (shaded red arrow). When we are in our toddler stage, where we can make conscious movements, we use the trained actuation map as a starting point. By this the trajectory planning is eased for realising an orchestrated movement of the arm by all involved muscles. Also in the infancy stage, well-known senses such as seeing, hearing, tasting and smelling are being mapped by SOM-like training and form their own specific maps. In the next section, we will illustrate the usefulness of the concepts, in particular motor babbling, with the case of trajectory planning of a robot arm.



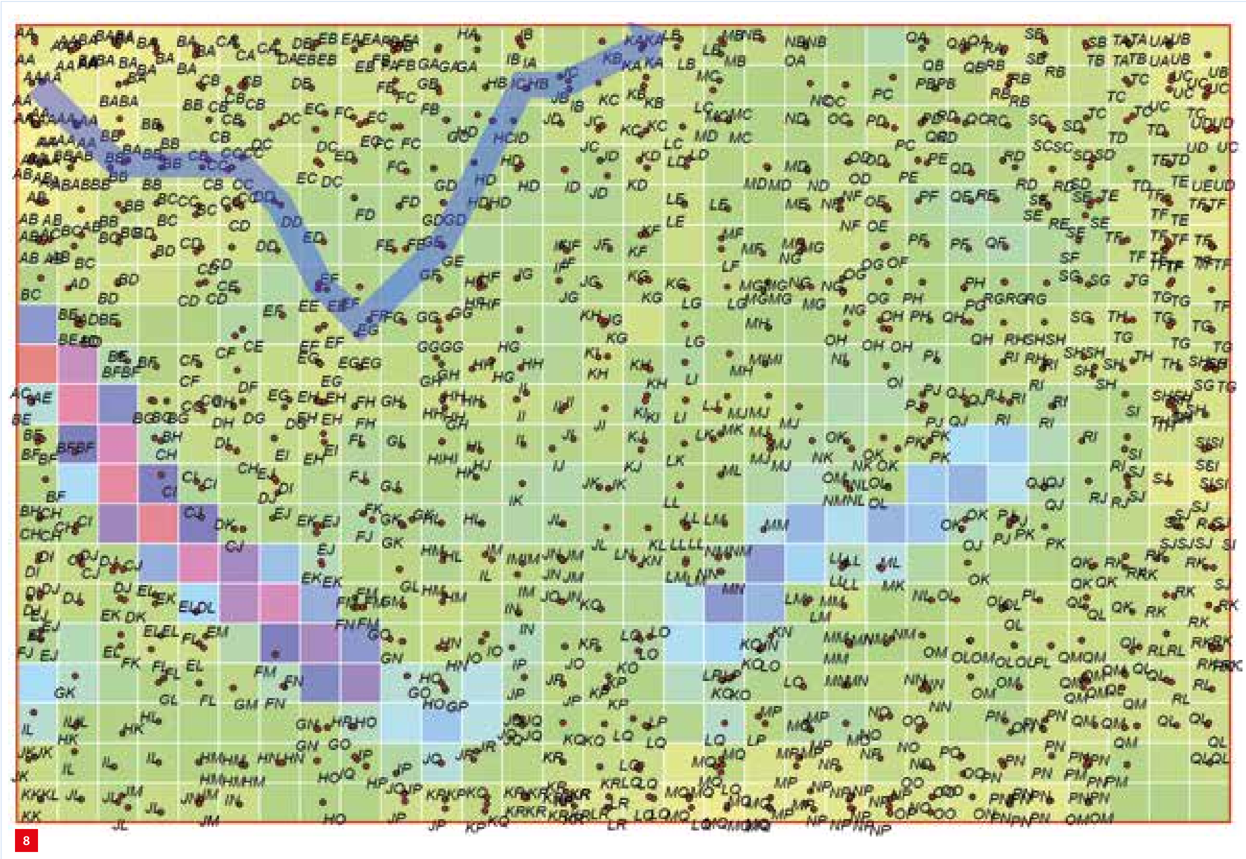
Stylised rendering of the three-step learning process:
1) baby babbling phase (unconscious state);
2) association of 2D positions to the actuation map (conscious state);
3) conscious actuation by target coordinates.

Example: motor babbling of a robot arm

The purpose of this case is not to use it in a concrete comparison with a more classical solution, but to point out other ways for designing complex (AI) systems. Firstly, we will show how intelligence in general is being bootstrapped and used in three discrete steps. Then, we will demonstrate a simple case of path planning.

We use a 6-degrees-of-freedom robot arm modelled by human proportions: upper arm, forearm, wrist, palm, and three phalanges operating in a 2D plane. In this example, the 2D constraint is for simplicity reasons, but this can easily be extended to 3D volumes. For the purpose of illustration we have taken a 6x6 SOM, but it could be of any other shape. The three steps involved are illustrated in Figure 7 and listed below.

1. Randomly actuating all motor joints and building an actuation map using the SOM (motor babbling during the unconscious infancy stage). At the end of this phase, the 6x6 SOM (actuation map) will contain 36 distinct 6D prototypical actuation vectors ($a_0 \ldots a_5$), which provide for a sufficiently large repertoire of simple movements. This step is inspired by the way babies unconsciously build up their actuation maps. A brainstem reflex, the so-called Moro reflex [13], stimulates muscles to perform random movements and the baby's actuation map is trained via proprioceptive sensors/muscle spindles (see Figure 2). This mapping (Figure 7) is actually performed



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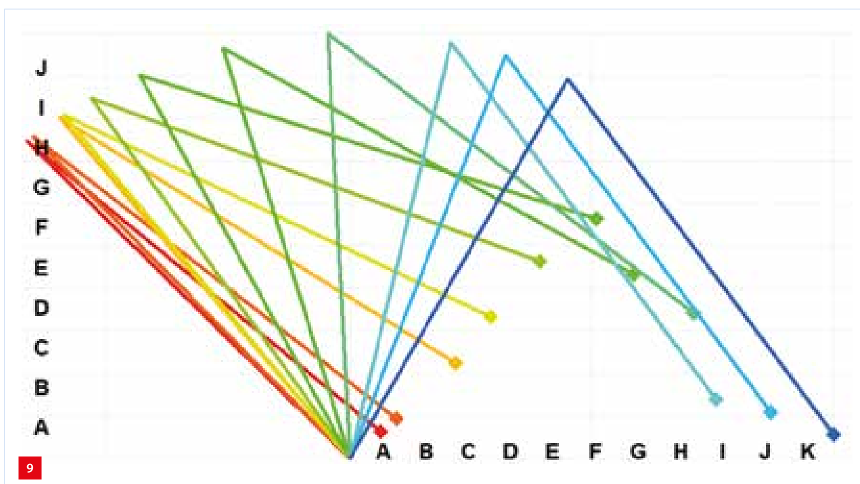
SOM map containing 20x30 prototype angles, each prototype consisting of a shoulder and an elbow angle. The purple polyline describes the target trajectory AA → BB → CC → DD → EE → FF → GE → HD → IC → JB → KA.

in 'inverse' direction when looking at the normal flow of the closed-loop AI cycle, starting from: real world → sensed data → data analytics → control/brain → data synthesis → actuation → real world, as depicted by Figure 6. In this stage of development, the map is of little use; it only contains a set of prototype vectors that code for the most popular arm, hand and finger postures.

2. Associating each of the 36 prototypes with a real world 2D (X, Y) position (during the conscious toddler stage). This can be done by performing a standard forward kinematics procedure, measurements etc. Results are stored in a table (neuron position table, see Figure 7) for later reference. As babies grow more conscious, they can associate muscle spindle sensations with a 2D/3D coordinate of the location of body parts as arms, hands and fingers. In this stage, the most popular arm postures in the map are associated with position information stored elsewhere.

3. Exercising the conscious movements by first looking up the nearest actuation vector, by its real world (X, Y) coordinate, and using the 6D 'winning' neuron vector for actuation. In this step the normal direction of the closed loop is followed, see unshaded red arrow in Figure 6. By the time babies deliberately reach out for a cup, for example, they associate the targeted (X, Y) with the best fitting 6D muscle/arm posture.

The last step will be demonstrated by simple path planning in a simpler robot arm. We assume absence of obstacles and will only consider two joints (shoulder and elbow) and two arm segments (upper and lower arm). We will use a coarse-grain coordinate system ranging from A → K in the



9

Target trajectory AA → ... → KA in the 2D plane. The 11 steps that are taken over time are represented by different colours, starting from red to blue. Directly left of coordinate AA is the shoulder joint at a fixed position. The elbow joint moves from top left to right; the end of the arm is depicted by a diamond marker.

horizontal as well as in the vertical direction. To avoid cluttering the SOM map with endpoint coordinates, we trained the map with 1,000 randomly chosen angle constellations. For the shoulder joint we assume rotations between 0 and 180° and elbow joint rotations between –180° and 180°.

First, we show a SOM map as result of the unconscious training (see Figure 8). Here we have chosen a larger map (20x30 neurons, little coloured squares with white perimeter) to show the topological ordering. For example, the (A, A) coordinates are all concentrated in the upper left corner and (B, A) as well as (B, B) are in a nearby neighbourhood. Also, a fold as dicussed above can be seen in the left of the map, starting from the mid-left (neurons coloured red, purple or blue) to indicate that neighbourhood relations between above and beneath the fold are not nearby. Care should be taken not to set up a trajectory that crosses this fold. A last remarkable point is that multiple different arm constellations can map to the same end-coordinate: check (A, C) in upper left – just two neurons above the fold – as well as in the neuron just below the fold.

A sample trajectory is expressed in this coarse grain coordinate system and consists of 11 positions and hence 10 movements; AA → BB → CC → DD → EE → FF → GE → HD → IC → JB → KA, which obviously follow a triangular shape. This path is visualised in the SOM map by a purple polyline, see Figure 8.

Yet how is the endpoint of the two-armed robot moving in the 2D plane? This is depicted in Figure 9. Note that the shoulder position is fixed (but the upper arm can rotate), just left of coordinate AA while the elbow is moving from top left to right. The end of the lower arm is indicated by a diamond. The first six coordinates (AA → ... → FF), with increasing values of the y-coordinate, are visualised by the first six arm constellations and coloured from red to green. The last five, now with decreasing values of the *y*-coordinate, cover the remaining movements that end in KA (colours green to blue). The moving robot arm is completely controlled by the 11 corresponding angles that are retrieved from the SOM map.

Conclusions and recommendations

This article addressed two main questions. Regarding the first, how DA and AI participate in intelligent system design, we argued that DA is about the understanding of data, and AI is about mimicking animal or human behaviour. The difference can best be expressed by the fact that AI systems can exist without understanding how they work (cybernetics). The relationship between the two is that if we – for some reason – want to understand an AI system, we have to include DA (informatics). Furthermore, it is necessary for AI systems to include a data expansion (data synthesis) building block to control the primary process optimally.

Regarding the second question, what biology can teach us to realise AI with a minimal footprint (costs, effort), we have shown that studying biology can give rise to new ways of engineering that could lead to lower-cost and low-effort intelligent system design. Two concrete ways addressed in this paper are: the use of control/cybernetic mechanisms; and bootstrapping intelligence by learning on the job (motor babbling). Essential to this is an ecological balance between all involved parts in the closed-loop AI architecture.

It is recommended that the applicability of bio-inspired technology and architectures in various intelligent system/(co)bot settings be investigated and the minimum footprint claims are tested. Furthermore, it is advised that bio-inspired research be extended to even more advanced concepts, such as consciousness and emotions for systems/robotics.

REFERENCES

[1] DATAFLAIR team, *data-flair.training/blogs/data-science-vs-artificial-intelligence*
[2] *en.wikipedia.org/wiki/Turing_test*
[3] Katrina LaCurts, "Criticisms of the Turing Test and Why You Should Ignore (Most of) Them", MIT CSAIL, 6.893, 2011.
[4] *en.wikipedia.org/wiki/Indeterminism*
[5] Beer, S., *Brain of the firm: A Development in Management Cybernetics*, Herder and Herder, New York, NY, USA, 1972.
[6] Prof. D. Abbink, *cs.lr.tudelft.nl/cybernetics/research*
[7] R. Pfeiffer, and C. Scheier, *Understanding Intelligence*, MIT Press, Cambridge, MA, USA, 1999.
[8] V.C. Müller, and M. Hoffmann, "What Is Morphological Computation? On How the Body Contributes to Cognition and Control", *Artificial Life*, 23 (1), pp. 1-24, 2017.
[9] A. Géron, *Hands-On Machine Learning with Scikit-Learn and TensorFlow*, O'Reilly Media, 217.
[10] T. Kohonen, *MATLAB Implementations and Applications of the Self-Organizing Map*, *docs.unigrafia.fi/publications/kohonen_teuvo*
[11] D. Miljković, "Brief Review of Self-Organizing Maps", *40th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*, 2017.
[12] *en.wikipedia.org/wiki/Topographic_map_(neuroanatomy)*
[13] *www.neurorestart.co.uk/primitive-reflexes*
[14] *en.wikipedia.org/wiki/Eigenvalues_and_eigenvectors*

Van de Rijdt Innovatie – the power of 'hand' calculations

In the professional equipment industry the complexity of mechatronics design is continually increasing. Fewer and fewer people are able to create an overview of how a complete machine works and how the performance of each element is achieved. Creating an evolutionary successor or a revolutionary new version is even more complex, when no line has yet been drawn for the new design and analysis and design are playing a 'chicken-and-egg game'. Van de Rijdt Innovatie advocates the use of simple analytical tools, even 'hand' calculations, in the early design stages.

Because of the mechatronic complexity, many critical analyses have to be made of different aspects, such as metrology, actuation, dynamics, control, thermal behaviour, manufacturability, etc. Such (detailed) analyses take weeks or even months and involve contributions from many persons. The drawback of analysis is that it can only be performed on the basis of a design, posing a kind of 'chicken-and-egg problem'. Knowing that the design, and not the analysis, determines the performance, the question is how to produce the (first/right) design.

Let's start by defining two types of analysis:

1. Analysis to support the iterative process of the design:
   - Exploratory, to understand the sensitivity of the design with respect to the different aspects.
   - Easy/fast, to be able to perform multiple 'design' iterations per day:
     - by head;
     - hand calculations;
     - Excel, MatLab, MathCad;
     - simple FEM (finite-element model).
2. Analysis to evaluate the performance of the design:
   - Detailed, taking into account all the boundaries of different aspects.
   - Complex/comprehensive, involving experts for the different aspects:
     - complex FEM;
     - complex MatLab;
     - with specific tooling per discipline.

The project architect or lead designer (in Dutch, *hoofdconstructeur*) should be able to make all the 'simple' calculations on his own, supported by multiple disciplines. Balanced design decisions can only be made when all aspects are understood.

Let's take the design of a moving stage. It starts with understanding the application in order to define the right specifications for the stage, to start with. Understanding the application of the system is also critical when design choices need to be balanced, because not all specifications have the same 'weight'. In translating the specifications to an initial design, analysis must be performed on (multiple) basically delineated concepts/designs.

Examples of analysis for a moving stage:

- Metrology (budgeting, errors, sensitivity).
- Actuation:
  - setpoints (balancing velocity, accelerations, jerk and settle time);
  - mass budget;
  - motor (duty cycle, peak force, current, voltage, dissipation):
    + off-the-shelf motor or a specific motor;
  - amplifier.
- Thermal behaviour:
  - dissipation;
  - 'cross-talk' to performance;
  - cooling (flow).
- Dynamics/control:
  - disturbances;
  - bandwidth required;
  - mechanical eigenfrequencies.
- Lifetime:
  - fatigue.
- Manufacturability:
  - technologies required;
  - cost.

For all the above analyses one can start with simple modelling in a spreadsheet (Excel).

Over the years, Van de Rijdt Innovatie has created basic calculation sheets for the individual aspects. It is important to create the sheets oneself and not to copy (complex, detailed) sheets of others, in order to obtain the best feeling of how it works and what the sensitivities are. Analyses of, for example, mechanical eigenfrequencies or fatigue require FEM calculations; simple models will suffice to guide the design direction.

With the analysis approach described here, one person can perform multiple design iterations per day. In this way, the design can grow to a maturity level in which all the aspects have been taken into account and a larger team can start working on the different elements with more detail.

In a project that Van de Rijdt Innovatie carried out for the development of a high-performance stage successor, it was found during the first analysis iterations that the optimal design direction to achieve the best integral performance was not 'lightweight and high-frequent', but 'as heavy as possible for throughput, at maximum stiffness'. This resulted in a significant improvement in all the performance aspects with a simpler, more cost-effective design.

Resume: from graduation to career-arching award

Hans van de Rijdt studied mechanical engineering at the HTS Eindhoven, now Fontys Engineering University of Applied Sciences in Eindhoven (NL). After graduation in 1989, he started working at Philips CFT (*Philips Centrum voor Fabricage Technologie*, Philips Centre of Manufacturing Technology) in Eindhoven. There, he devoted himself, among other things, to the designs of a feeder for a placement machine for electrical components, a laser tracking mechanism for CD players, various medical diagnostics systems, and the mechanisation of the production of video recorders and audio cassette tapes. In 2005, he became Assembléon's mechatronics development manager, and three years later he started his own company, Van de Rijdt Innovatie, helping companies such as ASML, VDL ETG and Nexperia with technical solutions for mostly multidisciplinary issues.

In 2019, Hans van de Rijdt received the Rien Koster Award, which every two to four years – at the initiative of DSPE – is presented to a mechatronics engineer/designer who has made a significant contribution to the field of mechatronics and precision engineering. The jury honoured him for his merits as a developer of multidisciplinary and straightforward concepts for high-tech systems that score well on manufacturability and cost. His work is a superb example of the Dutch design principles school founded by Wim van der Hoek and extended by Rien Koster and his successors.

At the Precision Fair 2019, Hans van de Rijdt (right) received the Rien Koster Award from the hands of the namesake. (Photo: Mikrocentrum)

THE ESSENCE OF SYSTEMS ENGINEERING...?

Although systems engineering (SE) is in the veins of Dutch mechatronics and precision engineers, the SE methodology as for instance propagated by INCOSE (International Council on Systems Engineering), is not always well-known. To take advantage of the benefits, one needs to find the essence of SE, and leverage best practices as appropriate for the specific application domain and business. This article presents an example for the Philips Innovation Services - Mechatronics organisation that is working in both the high-precision (semiconductor) and the medical device domain.

GERT VAN SCHOTHORST

Introduction

With the digital transformation ongoing, the role of systems engineering (SE) is getting ever more important. We have moved from 'complex systems in a simple world' to 'simple systems in a complex world' [1], and the next move is towards 'systems of systems' [2]. Whereas this will heavily impact the application of SE methodology, we already face some challenges in applying SE nowadays. The SE landscape is wide and comprehensive, and shows a lot of different faces.

Although we have handbooks full of SE theory, e.g. from INCOSE [3] [4], and SE practices are being more widely adopted in industry, the term SE is a sort of 'catch all'. To take advantage of the benefits, one needs to find the essence of SE, and leverage best practices as appropriate for the specific application domain and business. This article presents an example for the Philips Innovation Services - Mechatronics organisation that is working in both the high-precision (semiconductor) and the medical device domain.

The essence of SE

Philips has a long track record in systems architecting and implicitly in SE. The relevance of SE in Philips has been made explicit by establishing a Systems Engineering Center of Excellence in Philips in 2018. In the years before, a company-wide harmonised development process had been defined and deployed, in which a dedicated V-model [5] has been introduced to anchor good SE practices.

With many V-models publicly available, like the one shown in Figure 1, Philips has added a number of thought-through nuances to the V-model approach:

- An explicit distinction is made between user requirements (also known as user needs) and business requirements.
- An explicit distinction is made between requirements and design decisions (captured by, for example, design specifications) on all levels of the product hierarchy; requirements form the design input and design specifications are considered design output.
- Risk management is woven into the V-model by including 'check and optimise' activities explicitly in between the two branches of the V-model; this will typically include (mandatory) FMEA (Failure Modes and Effects Analysis) activities.
- Distinction between product, element (possibly multi-level) and part levels allows for an adequate development process on each hierarchical level.

What's in a name?

In a global setting, the use of the terms systems architect and systems engineer may be confusing, especially where in the Eindhoven area the systems architect is often seen as the person with overall technical leadership and responsibility. In the US, this responsibility is typically allocated to the systems engineer.

For the sake of this article, there is no need to really make the distinction. Yet, with the systems architecture being one of the deliverables of the SE process, one might consider that the systems architect has more focus on the solution that addresses the user and business needs, whereas the systems engineer pays more attention to the overall development process, including for example requirements engineering, formal verification and documentation [1].

In a global company, it appears to be helpful to harmonise job titles and job descriptions, taking these nuances into account, in order to facilitate capability building and talent management.

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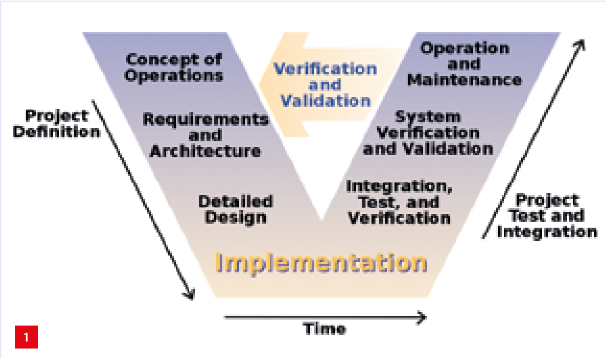
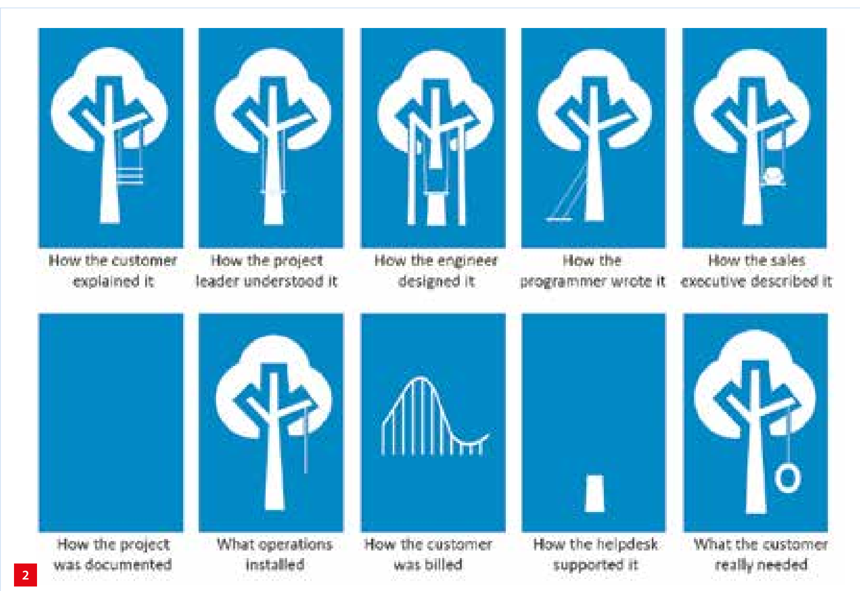


SE approach reflected in a V-model. (Image by L. Osborne, et al. [2])

As the scope of SE, covered by the activities related to the V-model, is very comprehensive and some focus is required for leveraging best practices, we have condensed the essential benefits of SE in three key objectives.

1. Meeting end-user needs:
   With an adapted version of a well-known graphic in Figure 2, it is needless to say that adequate requirements engineering is a basic element of good SE practice. Company-wide training and deployment can be used to make sure that products, services, systems or solutions meet the end-user needs. But also stress testing designs (test-to-fail, rather than test-to-pass) as well as adequate verification and validation practices are essential.
2. Managing complexity of systems:
   Especially for big systems, managing complexity by proper system decomposition, utilising different architectural views, and good interface control are indispensable for successful system development. It is believed that model-based systems engineering (MBSE, see later section) will be an enabler for managing the increased complexity of systems in the future.



Requirements engineering worst practices.

3. Quantitative underpinning of design decisions:
   Though quite basic, the use of modelling and simulation and other quantitative/statistical analysis tools is seen as the third key element in good SE practice. Designing for performance, quality and reliability will be frontloading the development process, but leads to significant cost reductions later on [4].

Note: the selection of focus points may depend on, for example, company size and application domain. Yet, there is a clear correspondence with the three key SE topics for engineering of high-tech systems as presented at the 2019 ESI Symposium [6]: requirements engineering, model-based, and quantified trade-off.

Leveraging SE best practices

When uncovering the essence of SE, while working in different domains like high-precision engineering and medical device development, it has become clear that the different domains can learn from each other, and may team up in future challenges. First, we give an example of best-practice sharing within the medical device domain.

Within the medical device domain

At the start of the Systems Engineering Center of Excellence in Philips, a company-wide assessment revealed that one of the Philips businesses used to have up to 11.000 system-level requirements defined. Partly that was a legacy from past decades, where the good practice of distinguishing between requirements and specifications had not been properly applied. In the same assessment, the Image Guided Therapy Systems (IGT-S) business showed for their complex systems (see Figure 3) to be able to keep the number of requirements on system level restricted to < 500.
By adequate system decomposition and a corresponding proper requirements flowdown (allocating and distributing requirements to lower levels of the product hierarchy), and moreover a strict separation between requirements and (design) specifications, IGT-S managed to keep the number of system-level requirements limited. As a result, the formal verification and corresponding evidence to be generated for regulatory approval could also be limited to the minimum required amount, leading to improved development efficiency.

The best practice of IGT-S is now being leveraged to another Philips business in an SE improvement activity, in which the requirements as well as the corresponding documentation are fully restructured. So far, having processed half of the requirements, a reduction of 90 per cent has been achieved on the number of system-level requirements.

From high-precision to medical

In the high-precision domain, it is common practice to have a sound quantitative underpinning of design decisions, for

Image-guided therapy system – an example of a highly complex system.

example by means of extensive modelling and simulation. The thorough understanding of the physics of the product or system in general enables design for (robust) performance and reliability, even in case of complex systems. In the medical device domain with its strong focus on clinical performance and safety aspects, it is sometimes observed that the use of quantitative methods to underpin design quality is underemphasised. In some cases, where medical device businesses originate from small start-ups, aspects of physical engineering are overlooked because of a lack of hardware engineering capabilities, as the focus is on clinical and software functionality. In such cases, leveraging of basic SE capabilities from the high-precision domain is very valuable.

The IPL case may serve as an example of applying a best practice from the high-precision domain to the medical device domain. Mechatronic engineers have supported the development of IPL hair removal devices (see Figure 4), by creating a so-called technical budget for the SmartSkin-sensor that needs to robustly classify the skin tone of the user. To further deploy this approach, which obviously stems from the 'error-budgeting' approach in the semiconductor industry, the IPL case is now used in an internal training on technical budgeting that is delivered across the company.
Note here that, although current IPL devices are consumer products, in the future they will have to be considered as medical devices under the EU MDR (Medical Device Regulations) regime.

From medical to high-precision
In the medical domain, it is common practice to deal with quality & regulatory requirements. Best practices developed there range from adequate usage of available design standards, through statistical approaches of design for quality, to risk-based methods for quality engineering and applying strict traceability throughout the V-model.

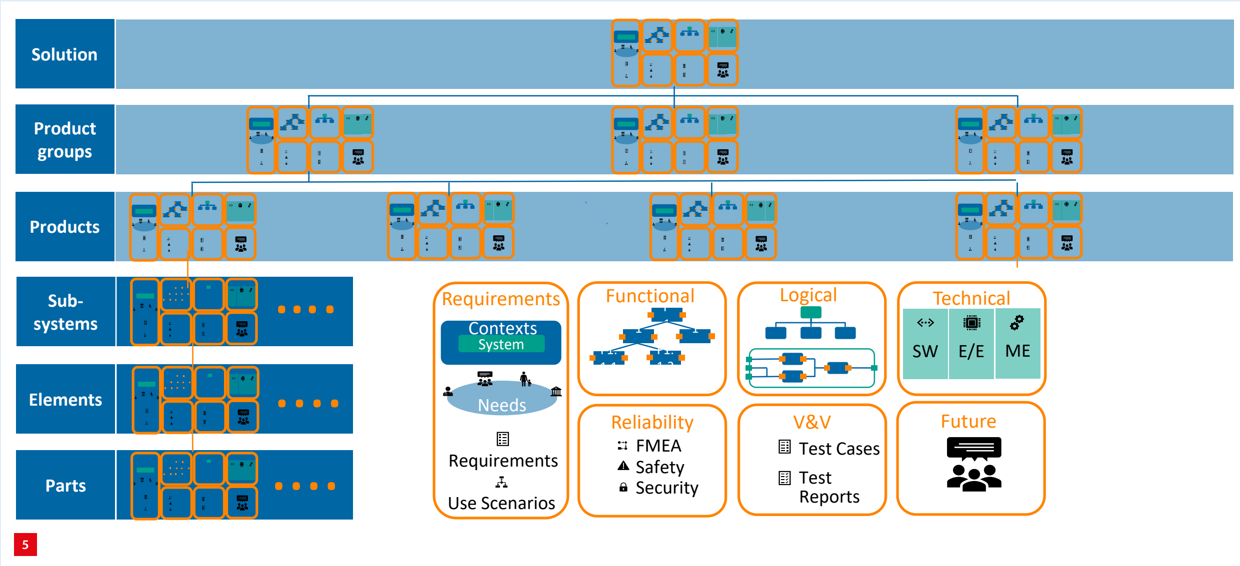
The high-precision domain may benefit from this experience by, for instance:
- arranging sufficient (external) regulatory knowledge in the development projects, to adequately deal with applicable standards;
- applying statistical methods to deal with variation, for example using tools from Design for Six Sigma methodology; high-precision engineers sometimes tend to think in $N = 1$ testing;
- finding a pragmatic quality engineering approach to balance affordability of development effort with regulatory compliance, based on risk evaluation and control;
- implementing full traceability from verification evidence to requirements, for instance by use of adequate tooling for managing requirements, test protocols/records and verification reports.

An example of leveraging this type of SE capabilities in a high-precision project was the extensive reliability analysis of a moving-cable-assembly subsystem. Apart from applying usual dFMEA (design-FMEA) techniques, Design of Experiments and further statistical analysis helped finding a trade-off between risk of failure and too lengthy/costly testing programs.

Advancing SE practices in both domains

Besides the cross-fertilisation between the domains, the ongoing digital transformation will pose challenges in SE, in which both domains will benefit from common approaches. A number of these challenges are being addressed by the High Tech Systems Center [7], as reflected in the recent online meet [8], and more specifically in [9]. Because of the

The development of the IPL hair removal product served as a case for the technical budgeting approach.



Recursive engineering methodology applied in the MBSE pilot project [12].

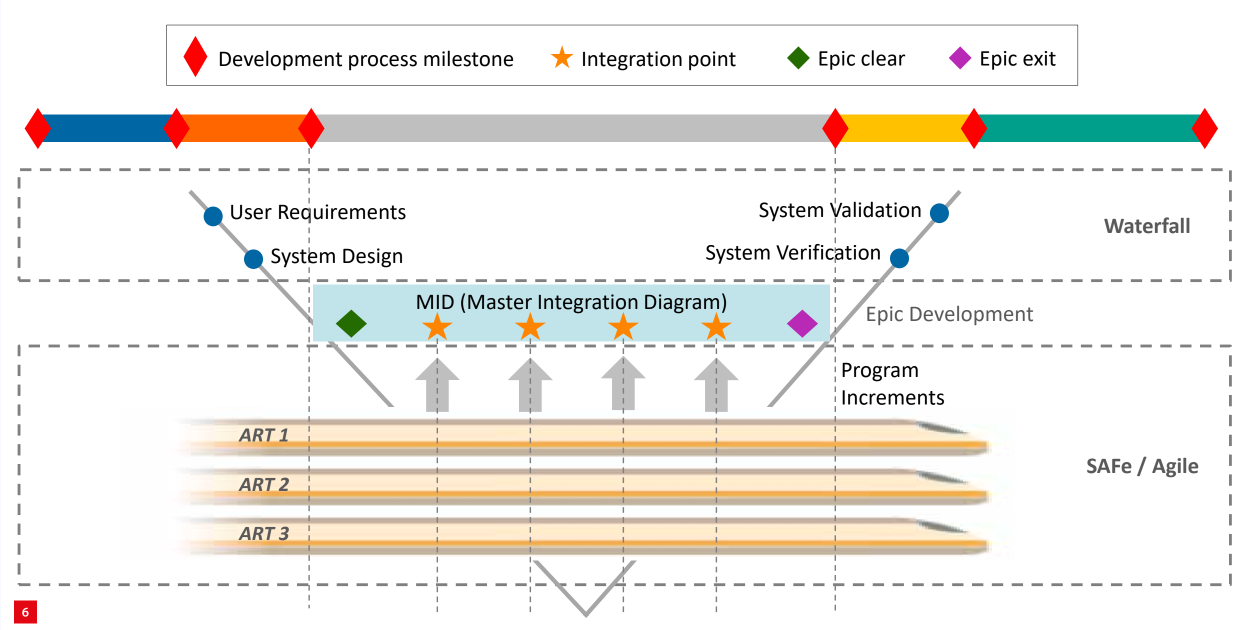
relevance for Philips, being active in both the high-precision and the medical device domain, two aspects will be highlighted here: MBSE and hybrid agile-waterfall approaches.

Model-based SE (MBSE)
Like envisioned by INCOSE in their Vision 2025 [10], MBSE is one of the grand challenges for SE in 2025: "Model-based systems engineering is a standard practice and is integrated with other modelling and simulation as well as digital enterprise functions." Although there are many more (potential) benefits of applying MBSE, from a practical engineering perspective, there are two challenges that drive the introduction of MBSE in Philips:

- Complexity of products, systems and solutions is increasing due to the digital transformation. In order to manage this complexity, where a document-based SE approach is reaching its limits, MBSE enables dealing with SE for complex systems, because the system models capture all relevant information in a structured and consistent way.
- Especially in the context of a healthcare business with medical regulations applicable, adequate documentation of evidence of the development activities is essential. This puts a high demand on SE resources, and often is demotivating for systems engineers that want to do engineering. Introduction of MBSE is promising here, as the systems engineer captures the relevant information (requirements, use cases, system decomposition, test cases, etc.) in the context of the system model, and the required documentation can be generated automatically.

To introduce MBSE in Philips, a number of pilot projects have been started, using SysML as the mainstream systems modelling language. In view of managing the complexity of system development, a so-called recursive engineering methodology is applied (see Figure 5). Although not fully implemented yet, on all hierarchical levels, the system artifacts will be captured in the SysML models, allowing for a consistent set of, for example, requirements, use cases, etc. Note that also aspects of reliability and safety risk management (including FMEA) are incorporated in the (data) models. First results of this pilot are promising, especially showing the benefits of automated document generation in compliance with the quality management system.
Other pilot activities focus on the implementation of parametric modelling in an MBSE setting, i.e., combining detailed physical models with system-level (SysML) models using tools like the Phoenix ModelCenter [11].

Hybrid agile - waterfall
Traditionally, SE practices, including the V-model approach, are often associated with a waterfall-type of project management. However, with software engineering being much more dominant in current development activities, agile approaches, including the Scaled Agile Framework (SAFe), are widely adopted. Interestingly, the SAFe community also embraces SE methodology [13] and MBSE [14]. Yet, for big innovation projects, especially in the medical device domain where regulatory compliance requires a hard sequence of development activities [15], the overall development plan will have a waterfall character. As a result, agile and waterfall approaches need to be combined, leading to a so-called hybrid model. An example of such a hybrid model, as currently being implemented in Philips IGT-S, is shown in Figure 6. Developing 'epics' ('work packages' in the agile approach) forms the interface between the agile and the waterfall world, and allows for a flexible scoping in a time-boxed setting, rather than having a flexible project timing given a fixed scope. Thanks to the flexible allocation of epics to fixed sub-teams, the overall output of the project team increases.



6

Hybrid model to combine agile and waterfall approaches in SE and project management.

Apart from project management challenges related to this hybrid model, the SE way of working is also impacted. To mention just two aspects:

- The proper flowdown and allocation of system-level requirements to lower-level requirements, and especially software requirements, needs to be adapted to the defined epics. Given an adequate choice of requirements management tools, requirements flowdown as well as traceability can be managed across the borders of the agile/waterfall worlds.
- The transparent definition of epics for both hardware and software development activities explicitly reveals the challenge of having different time scales. Software has shorter cycles with typical sprints of 2-3 weeks, whereas hardware development can also work with short sprints, but will not deliver hardware updates physically in the same pace. Although automated testing and CICD (continuous integration and continuous deployment) approaches work well for software development, systems engineers will need to develop adequate overall test and integration strategies, to synchronise the hardware and software development activities in the project.

Conclusion

Although SE is in the veins of Dutch mechatronics and precision engineers, the SE methodology as for instance propagated by INCOSE, is not always well-known. Especially when working in two different domains, such as high-precision and medical devices, it is nice to see the key benefits of SE. In essence, deploying the V-model methodology, SE enables:

1. Meeting end-user needs.
2. Managing complexity of systems.
3. Quantitatively underpinning design decisions.

Leveraging best practices, such as limiting the number of system-level requirements, applying technical budgeting, and adopting adequate risk management approaches, leads to a healthy cross-fertilisation between the domains. With the ongoing digital transformation, all domains have interesting challenges ahead, such as the introduction of MBSE throughout and implementing hybrid models to combine agile and waterfall approaches.

References

[1] B. Pronk, "System Architecture in high-tech systems – is there any time left for system engineering?", keynote lecture at *System Architecting Conference 2020*, Eindhoven, *www.sysarch.nl*
[2] E. Honour, "Systems of Systems International Trends", *INCOSE Space Coast Chapter meeting*, 2 March 2017.
[3] *www.incose.org*
[4] INCOSE, *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, version 4.0. John Wiley and Sons, New York, ISBN 978-1-118-99940-0, 2015.
[5] *en.wikipedia.org/wiki/V-Model*
[6] T. Peijnenburg, "Systems Engineering in an evolving context", *ESI Symposium 2019*, *www.esi.nl*
[7] *www.tue.nl/htsc*
[8] HTSC Research Meet (online), "Systems Engineering and beyond", 2 July 2020, *www.tue.nl*
[9] M. Hamilton in A. Pil, "No systems engineering without digital engineering", *Bits&Chips*, 29 September 2020, *www.bits-chips.nl*
[10] INCOSE, "SE Vision 2025", 2014, *www.incose.org/products-and-publications/se-vision-2025*
[11] *www.phoenix-int.com/product/modelcenter-integrate*
[12] F. Kühn, Philips Monitoring & Analytics, Böblingen.
[13] SAFe, "System and Solution Architect/Engineering", 30 December 2019, *www.scaledagileframework.com*
[14] SAFe, "Model-Based Systems Engineering", 24 February 2020, *www.scaledagileframework.com*
[15] FDA, "Design Control Guidance for Medical Device Manufacturers", 11 March 1997, *www.fda.gov*

LEARNING BY DOING

Systems engineers often grow into their role gradually within the context of one company, with their role evolving due to the increasing complexity of the systems they develop. Once in a while, the question arises as to whether the correct systems engineering methodology has been chosen for a particular project. Where does the innovation in engineering methodology come from? Saxion University of Applied Sciences and the TValley robotics and mechatronics innovation cluster have developed a method in which education, training, knowledge sharing and learning are connected in a practical feedback loop that ensures continuous innovation in systems engineering.

DIRK BEKKE, VICTOR SLUITER AND FLOOR CAMPFENS

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Introduction

Systems engineering (SE) is often 'learned on the job' within the context of a certain company. As such, it is hard for systems engineers to get practical experience regarding other methodologies. Different companies have different ways of applying SE. High-tech OEMs have several defined SE roles and often put high demands on their suppliers. Production SMEs sometimes follow a more pragmatic approach and even combine the role of systems engineer with that of project leader. There is no single best SE methodology, only a good (or bad) fit between the chosen methodology and the (business model of the) company.

The variety of companies, business models, systems complexity levels and application fields therefore leads to the need for different SE methodologies. This imposes high demands on any SE training or educational programme. In addition, the field is developing quite rapidly and new methodologies such as model-based SE are becoming popular. Within their projects, the Mechatronics research group at Saxion is experimenting with different SE methods in order to obtain and expand experience in this field.

1

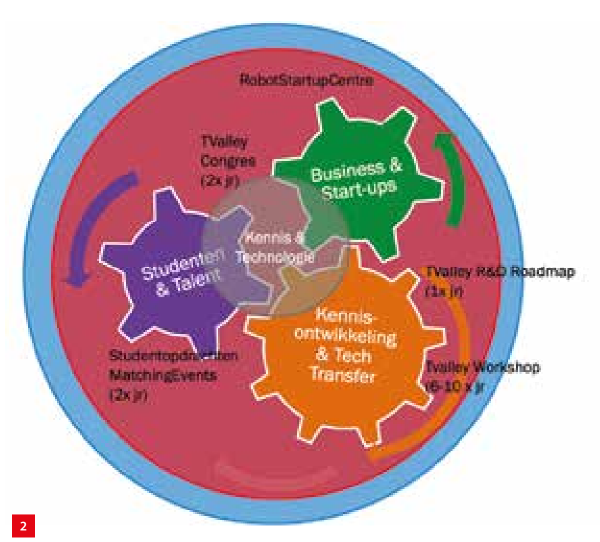
Examples of A3 Systems Overviews papers.

Experimenting with SE

At the beginning, the research group adopted the well-known V-model [1]. However, practice learned that the V-model did not fit the applied research process very well. Therefore, we started experimenting with new methods. The holy grail has not yet been found, but the research has led to interesting findings that have impacted our work.

It was found that the use of A3 Architecture Overviews [2] helped enormously in communicating effectively with our project partners. These documents were used in several projects, most successfully while gathering the requirements. Even after having finished lengthy discussions about what the project partners would like to have in a project, the moment we put the A3 Architecture Overviews paper on the table a lot of new comments on the system of interest were made (Figure 1). By making some (preliminary) design considerations explicit throughout this A3 procedure, we learned a lot about the limitations in design space, for example due to legislation in the application area concerned.

For writing down the requirements, two methods that were tested deserve attention, because our approach to requirements definition appeared to leave a lot of room for interpretation, as was also seen in the work of our students. Research into formal requirements syntax has resulted in these two methods: Easy Approach to Requirements Syntax (EARS) and Planguage. EARS [3] was developed at Rolls-



2

TValley's working model consisting of three pillars: Talent (Students & Talent), Technology (Knowledge development & Technology transfer) and Business (Business & Start-ups).

Royce and is now widely used in industry, with proven merits such as being less wordy and having better testability and less complexity within each requirement.

The EARS syntax is very simple but requires good thinking on system functionality while writing the requirements down. The syntax was 'augmented' in Saxion's own documentation with a 'rationale' per requirement. Students were also involved in building systems based upon EARS documents and writing their requirements in EARS. EARS appeared to really enhance the system understanding.

The other requirements technique experimented with was Planguage [4]. A course by Gilb/ValueFirst was followed to obtain a good understanding of this method, which can be used to describe quantified higher-level requirements such as 'reliability' or 'security'. At Saxion, Planguage was used for the case of a fire-extinguishing robot in the Firebot project. Describing such high-level requirements was new, but provided very good insights into what was really important for each stakeholder. The methodology, on the other hand, appeared too advanced for bachelor students. The project management method Evo [5], usually combined with Planguage, is very interesting, but has not been tested yet.

TValley Competence Group

The importance of SE has been recognised by the TValley robotics and mechatronics innovation cluster [6]. Its working model consists of three pillars: Talent, Technology and Business (Figure 2). The need for sharing SE experiences is acknowledged by industrial CEOs. A competence group was created this autumn, comprising systems engineers with around 10 years' experience. In a safe technical intervision setting they can share best practices and analyse challenges. In this manner, all the engineers involved get feedback on their questions regarding the methods used in a professional and efficient manner. Saxion, as a partner within TValley, also shares its experiences and uses the experiences and knowledge from the competence group for developing the Robotic Systems Engineer master.

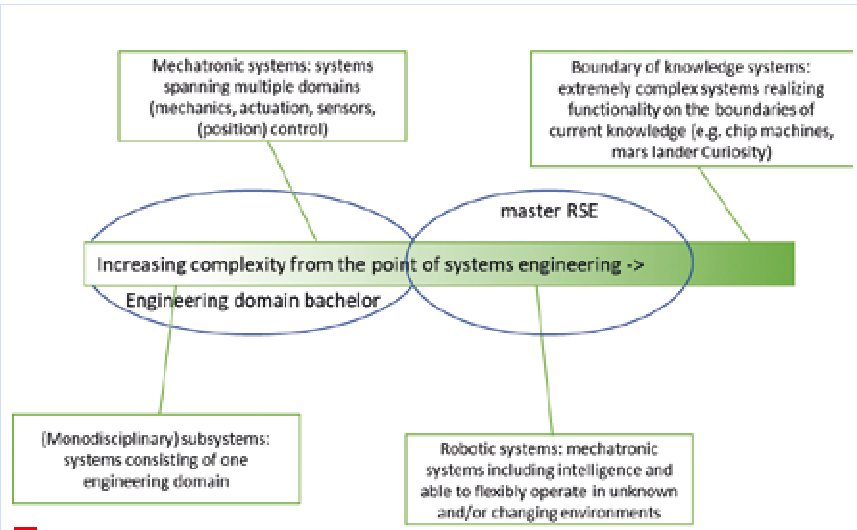
Robotic Systems Engineer master

The Robotic Systems Engineer master's degree programme is currently being developed, with the request for accreditation being recently submitted to NVAO, the Accreditation Organisation of the Netherlands and Flanders. Upon graduation, students are entitled to use the M.Sc. degree. Saxion aims to start the programme in September 2021.

As a professional master's degree, the programme will focus on training students in SE by developing – together with industrial partners – systems that can be brought to market. This is opposed to the focus of an academic master's degree, which trains students in scientific knowledge and technology itself. The scope of the programme (Figure 3) is robotic systems viewed as mechatronic systems incorporating intelligence and the ability to flexibly operate in unknown and/or challenging environments.

Students holding a bachelor's degree in engineering (e.g. mechanical engineering, electrical engineering, computer science or mechatronics) are entitled to enroll. They will be provided with a solid foundation of knowledge in robotics, but the focus is on equipping them with real-life, hands-on experience in SE tools and methodologies. The curriculum is shown in Figure 4.

In the 1.5-year master's degree programme, the first year consists of a combination of courses and projects (light



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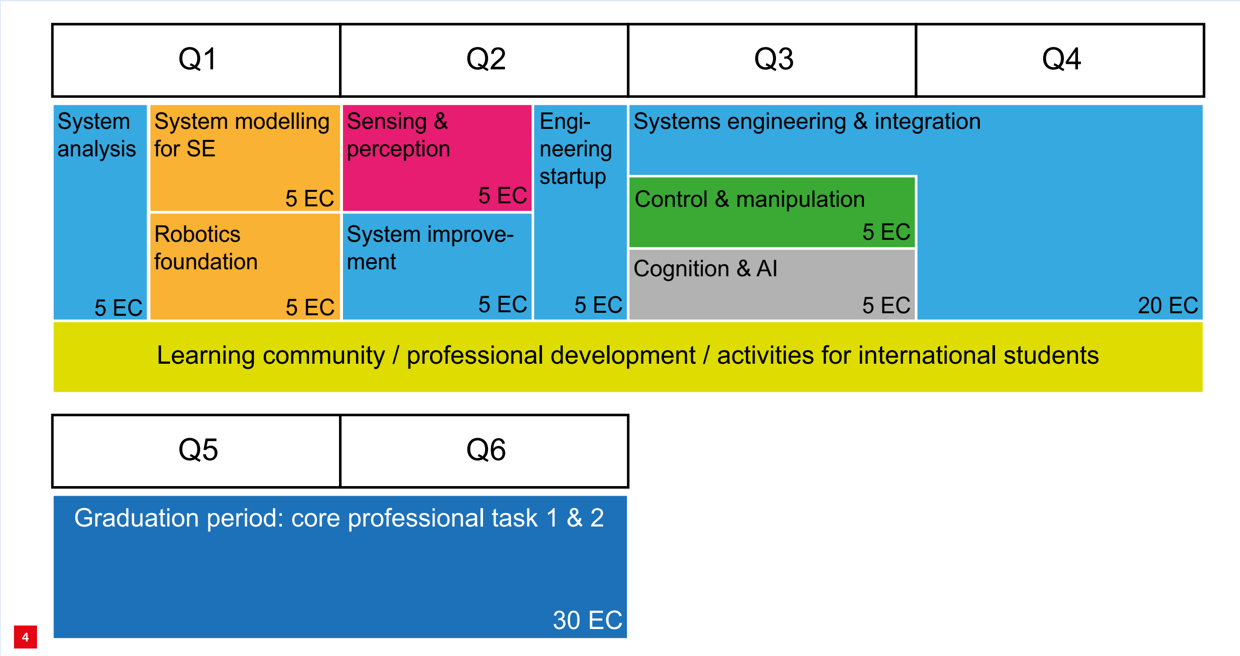
The scope of Saxion's Robotic Systems Engineer master.



Saxion's Robotic Systems Engineer master curriculum.

blue). The last six months is dedicated to the graduation assignment (dark blue). Similar to the current practice of learning 'on the job', learning within the projects is an essential part of the curriculum. The projects providing SE training make up 55 per cent of the first year's syllabus. Students will work on cases coming from projects in the Saxion Mechatronics research group's collaboration with its industrial partners.

The first project comprises analysis, verification and validation of the requirements for an already existing system. During the first year, the projects increase in complexity towards performing a complete design cycle. Via masterclasses, students will become familiar with various SE tools and methodologies. As students work on relevant cases and assignments, they can work with and learn under the supervision of experienced systems engineers from industry as well as the research group.

The outcomes will be presented within the TValley Competence Group, closing the important learning feedback loop. It couples the SE competence group directly with the master's degree programme and allows engineers to start low-cost experiments by setting up student assignments using other SE methods. The students' reflections on the applied SE methodology in projects will provide valuable input for the SE competence group. Students can learn from the advice of experienced systems engineers in the field, and at the same time they can provide a fresh look on the way SE is implemented in different companies.

Conclusion

Systems engineering can be studied in an academic way, but just like with cycling, in the end it requires 'learning by doing'. The art of SE is best taught in a master-apprentice setting. We hope we can completely roll out this training programme once the final approval of NVAO has been received in spring 2021. Meanwhile, we will keep on experimenting, sharing best practices and learning from them.

REFERENCES

[1] Zwikker, R., and Gunsing, J., "Merging process structure and design freedom", *Mikroniek*, 55 (2), pp. 5-13, 2015.
[2] Borches Juzgado, P., "A3 Architecture Overviews. A tool for effective communication in product evolution", Ph.D. thesis, University of Twente, 2010.
[3] Mavin, A., Wilkinson, P., Harwood, A. R., and Novak, M., "Easy approach to requirements syntax (EARS)", *17th international Requirements Engineering Conference*, pp. 317-322, 2009.
[4] Gilb, T., "The Use of Planguage to Improve Requirement Specifications", *INCOSE International Symposium*, 14 (1), pp. 1604-1614, Wiley, 2004.
[5] *www.gilb.com*
[6] *www.tvalley.nl*

CONFORMAL WAFER LOADING

In current photolithography machines, wafers are loaded onto passive tables. During the wafer loading process, residual stress is introduced into the wafer due to non-reproducible friction forces between wafer and wafer table, leading to significant overlay error contributions. This article presents a design for an actuated deformable wafer table, which has the potential to significantly reduce the overlay errors associated with wafer loading. By using a stack of six piezoceramic PZT layers, with embedded interdigitated electrodes, both the in-plane strain and curvature degrees of freedom can be controlled, conformal to the shape of the wafer.

SANDER HERMANUSSEN, HANS VERMEULEN, MARCEL HEERTJES AND MICHEL HABETS

Introduction

The semiconductor industry is known for constantly pushing the boundaries of technological advancements, following Moore's law. Newly emerging technologies such as extreme ultraviolet (EUV) lithography (which enables fabricating smaller features by using a shorter light wavelength), and applications, such as 3D-NAND (which increases memory density by vertically stacking more layers), require a rethinking of the heart of the production process: the photolithography machine.

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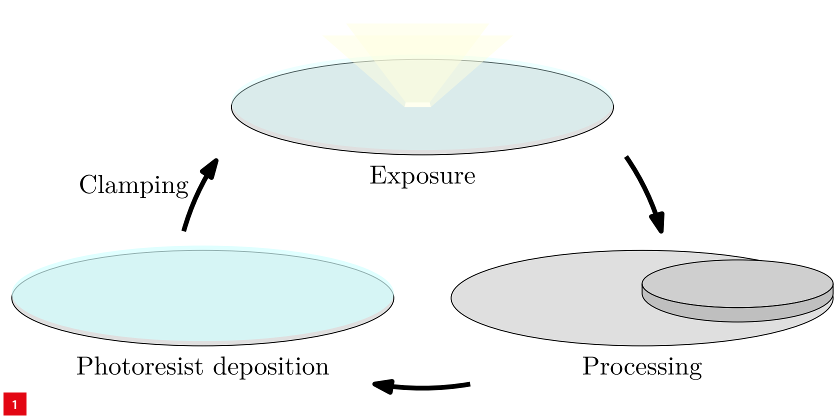
Integrated circuits (ICs) are fabricated in a cyclic process, see Figure 1. Before the exposure step, the wafer is tightly clamped electrostatically or by a vacuum on a nm-level flat wafer table, comprising tens of thousands of protrusions (burls). Next, a photoresist on top of the wafer is exposed in a repetitive scanning motion through a mask containing the lay-out of the chip. The exposed area of the wafer must be positioned within a few nm of the focal plane of the optical column during scanning.



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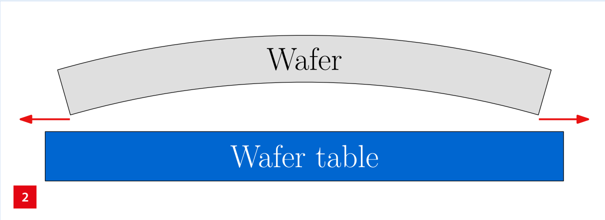
Simplified image of the fabrication cycle for creating ICs – the focus of this article is on the 'clamping' step. The exposure step occurs within wafer scanner machines and requires a high positioning accuracy. The various processing steps lead to increased wafer warpage.

Due to the cyclic nature of the process, in addition to the focus requirements, it is imperative that each exposure step is aligned to the already processed layers underneath within a fraction of a nm. This so-called overlay requirement, together with the aforementioned focus requirement, must be met across the entire wafer surface. If adequately measured, low-order deviations, such as tip, tilt and magnification errors, can be corrected relatively straightforward by repositioning the wafer stage and optical elements. However, higher-order deviations cannot always be corrected in this way, resulting in a decreased yield on each wafer.

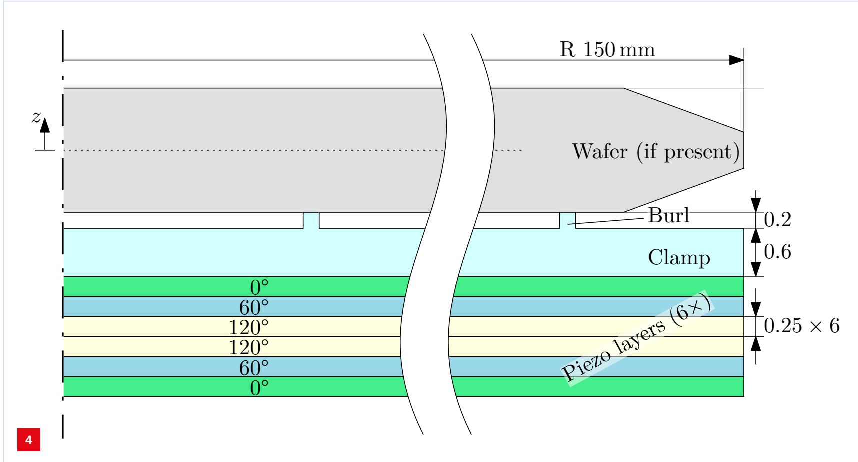
During the processing steps, such as film deposition, thermal processing and chemical-mechanical planarisation, residual stresses are introduced in the wafer top surface [1]. This stress causes the wafer to warp or bow before clamping. Because of this, an important source of both focus and overlay errors occurs already when loading the wafer onto the wafer table. Due to the unflatness of the wafer, initially it will contact the wafer table only at a few discrete areas. Subsequently, the wafer will slide across the wafer table as it is clamped down, until the local frictional forces are balanced by the internal stresses due to stiffness of the wafer.

This process is governed by the interaction between the local friction coefficient μ (which may vary due to, e.g., contamination or wafer backside processing) and the normal clamping force, and results in non-reproducible local variations of the overlay error. Furthermore, the resulting wear of the wafer table and wafer can lead to a further change in the local friction coefficient, impacting subsequent exposures. As the number of layers is expected to continue to grow, especially in 3D-NAND memory applications where typically 150-300 layers are exposed, the wafer warpage is also expected to increase, already reaching values of 0.5 mm peak-to-valley.



For this warped wafer (exaggerated), the initial points of contact will displace outwards, mostly due to the apparent rotation of the wafer edge.

In an earlier paper [2], a new procedure called conformal wafer loading was introduced. The current article presents an improved design for a piezo-electrically actuated wafer table required for this procedure. A mathematical model for optimising (critical dimensions of) the design is introduced.



Actuator cross-section (for confidentiality reasons, the thickness has been made dimensionless; the actual dimensions are known to the editor). The thickness is in the order of millimeters.

Conformal wafer loading

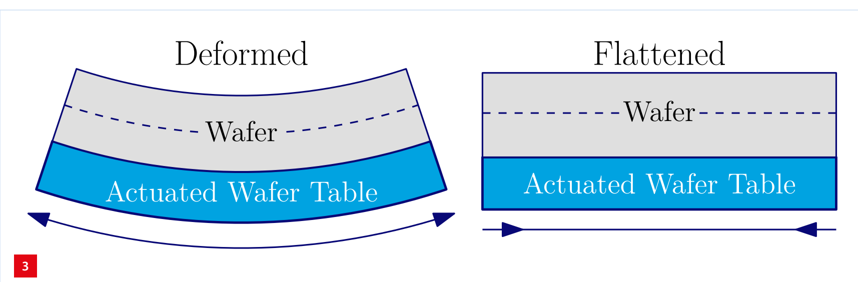
The underlying problem appears to be trying to force a warped wafer onto a flat wafer table as depicted in Figure 2. A solution might be to place a warped wafer onto an identically warped deformable wafer table. This so-called conformal wafer loading (CWL) procedure consists of four key steps:

1. Determining an actuation setpoint from the height map of the wafer, measured beforehand.
2. Actuating the wafer table conformal to the measured shape; the out-of-plane deformation must match the wafer as closely as possible.
3. Lowering the wafer onto the wafer table, and activating the (vacuum or electrostatic) clamp.
4. Actuating the assembly towards the focal plane of the lithography machine. During this step, in-plane actuation of the wafer table is required to prevent sliding between the wafer and wafer table, as demonstrated in Figure 3.

To unclamp, the process is repeated in reverse order to minimise wear.

Actuator design

To enable the CWL procedure, an actuator assembly was designed that can both deform out-of-plane and in-plane. The design goal was remarkably similar to that of deformable mirrors as found in adaptive optics (AO), commonly used in astronomy: how to deform a – typically round – surface to a desired shape with high precision? In AO, this goal stems from the need to correct for a non-flat wavefront from an incoming light source; in our case, it originates from the need to adapt to a non-flat wafer. In AO, a common approach is to put a thin face-sheet on a grid of axial actuators [3]; however, this does not allow to actuate the in-plane degrees of freedom. Instead, a bimorph-type actuator seemed suitable for this application: a stack of actuated layers is placed underneath the wafer table, introducing a curvature similar to a bimetallic strip, in addition to in-plane elongation or compression.



To flatten this warped wafer without relative sliding motion between wafer table and wafer, the wafer table must slightly contract in-plane, so that the neutral plane (dashed line) does not change in length.

By using piezo-electric actuators, a high-force density actuator can be made with low mass and high stiffness. Furthermore, virtually no power is dissipated after the wafer is loaded. Lead zirconate titanate (PZT), a piezo-ceramic material, was selected for its high piezo-electric strain.

Figure 4 shows a schematic cross-section of the design. Six layers of PZT are bonded to a wafer clamp. By using continuous layers, deformations are smoothly introduced into the wafer table. The poling direction of the different piezoceramic layers (and thus the direction of the piezo-electric strain, see the box on piezo-electric actuators) is rotated in-plane in increments of 60°, so that curvature $\boldsymbol{K}$ and mid-plane strain $\boldsymbol{\varepsilon}^0$ can be introduced in all directions.

A key difference between the deformable wafer table and a classical bimorph mirror is the way in which piezo-electric strain is introduced in each layer. On a typical mirror, an electric field is applied perpendicular to the mirror surface by printed-on electrodes at the back of the mirror. For piezoceramic materials however, the resulting d_{31} strain (see the box on piezo-electric actuators) is isotropic in the in-plane directions and it can only control the magnitude of the curvature vector $\boldsymbol{K}$ (see below), not the individual

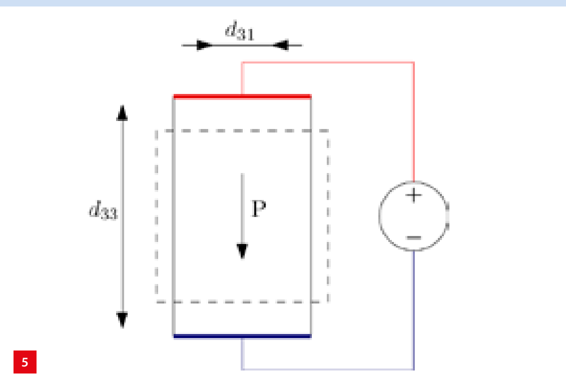
Piezo-electric actuators

The backbone of the design in this article is a piezo-ceramic actuator. To understand how it works, it is important to learn the basic principles of piezo-electric, specifically piezo-ceramic, actuation. For further reading, see [4].

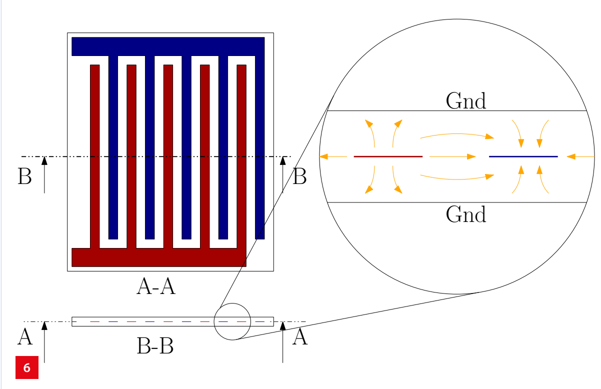
A piezo-ceramic actuator makes use of the indirect piezo-electric effect. This refers to the phenomenon of a piezo-electric material that is subjected to an electric field exhibiting mechanical strain due to a slight asymmetry in the crystal lattice. In principle, this strain is directly proportional to the electric field, although in practice, many materials exhibit hysteretic and creep effects.

Piezo-electric materials can be either monocrystalline or ceramic. In the actuator design, a piezo-ceramic material, namely lead zirconate titanate, was chosen for its high strain capability. A piezo-ceramic actuator is manufactured in a similar fashion as a ceramic capacitor: a slurry containing a finely ground powder is tape-cast into thin layers, onto which electrodes are deposited. These layers are then stacked and sintered. After sintering, the individual grains have a random orientation. By applying a very high electric field on the internal electrodes, the orientation (polarisation) inside the microscopic crystal lattice can be aligned to the electric field. This process is called poling, and is typically performed in an oil bath to prevent arcing, and at elevated temperature to speed up the process.

After poling, the actuator will display the indirect piezo-electric effect if a new electric field is applied, using the same internal electrodes. In the direction of the electric field (called the 3-direction), the strain is related to the electric field through the equation $\varepsilon_3 = d_{33}E_3$. Perpendicular to this direction, the strain is defined as $\varepsilon_1 = \varepsilon_2 = d_{31}E_3$, with $d_{31} \approx -0.45d_{33}$. This is shown in Figure 5. One can compare this to a Poisson contraction.



Operation of a piezo-ceramic actuator when subjected to an electric field. In dashed lines: undeformed actuator. P indicates the poling direction.



Interdigitated electrodes demonstrated as a thin square actuator (left), and the resulting electric field in orange (right).

components. The solution is to apply an in-plane electric field through interdigitated electrodes (IDE) for both actuation and poling, as depicted in Figure 6. The resulting field has a significant in-plane component between the electrodes, and a vertical (out-of-plane) component above and below the electrodes. The piezo-electric strain produced in this way has different components in the different planar directions, with a large contribution of the d_{31} strain parallel to the fingers. To shield the different layers from each other, a ground-plane electrode is added between each layer.
To explain why a number of six layers are required, we can look at the definitions of strain and curvature. The in-plane strain $\boldsymbol{\varepsilon}^0$ at a plane $z = 0$, and the local curvature $\boldsymbol{K}$ are defined as:

$$\boldsymbol{\varepsilon}^0 := \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix} := \begin{bmatrix} \frac{\partial w_x}{\partial x} & \frac{\partial w_y}{\partial y} & \frac{\partial_{w_x}}{\partial y} + \frac{\partial w_y}{\partial x} \end{bmatrix}^T$$

$$\boldsymbol{\kappa} := \begin{bmatrix} \kappa_{xx} \\ \kappa_{yy} \\ \kappa_{xy} \end{bmatrix} := \begin{bmatrix} \frac{\partial^2 w_z}{\partial x^2} & \frac{\partial^2 w_z}{\partial y^2} & 2\frac{\partial^2 w_z}{\partial x \partial y} \end{bmatrix}^T$$

Here, w_x, w_y and w_z are the displacements in x, y and z, respectively, due to deformation. Both the strain and curvature have three components, bringing the total number of controlled degrees of freedom to six. By applying a different voltage and thus a different piezo-electric strain to each piezo-electric layer, all six components can be controlled independently.

Actuator modelling

The actuator stack is described as a thin-plate laminate, comparable to a carbon-fibre composite panel. A global Cartesian coordinate system is used, with x and y the in-plane directions and z the out-of-plane direction. The coordinate $z = 0$ is placed exactly at the mid-plane of the wafer (see Figure 4). This corresponds to the neutral plane of the wafer, which by definition remains undeformed if the wafer only experiences bending moments, as explained in Figure 3. For a thin plate, the plane stress assumption holds:

all stresses in z-direction are assumed zero. In general, the in-plane strain varies as a function of z by the relation:

$$\boldsymbol{\varepsilon}(z) = \boldsymbol{\varepsilon}^0 - z\boldsymbol{\kappa}$$

From this equation, we can conclude that the strain at different z coordinates varies linearly with curvature and, consequently, the stiffness and piezo-electric strain of various layers of the actuator stack with a different z coordinate influence the curvature to a different degree. The main system of constitutive equations describing the actuator stack is given as:

$$\begin{bmatrix} \boldsymbol{P} & \boldsymbol{Q} \\ \boldsymbol{Q} & \boldsymbol{R} \end{bmatrix} \begin{bmatrix} \boldsymbol{\varepsilon}^0 \\ \boldsymbol{\kappa} \end{bmatrix} = \boldsymbol{F}\boldsymbol{v} + \begin{bmatrix} \boldsymbol{n} \\ \boldsymbol{m} \end{bmatrix}$$

This system is derived from Equations (3.108) and (3.109) in [5], by substituting thermal strain in a classical composite material with piezo-electric strain. On the left-hand side, the matrices $\boldsymbol{P}$ and $\boldsymbol{R}$ are the in-plane stiffness and bending stiffness, respectively, whereas matrix $\boldsymbol{Q}$ represents the bending-stretching interaction. On the right-hand side, we find the actuation matrix $\boldsymbol{F}$ and any external forces and moments $\boldsymbol{n}$ [N/m] and $\boldsymbol{m}$ [Nm/m], respectively. The actuation matrix is multiplied by a vector $\boldsymbol{v}$, containing the electric field (in V/m) in each of the six layers of the design.

As there are in principle no external forces or moments, the equation can be rewritten for optimising the actuator:

$$\boldsymbol{v} = \boldsymbol{F}^{-1} \begin{bmatrix} \boldsymbol{P} & \boldsymbol{Q} \\ \boldsymbol{Q} & \boldsymbol{R} \end{bmatrix} \begin{bmatrix} \boldsymbol{\varepsilon}^0 \\ \boldsymbol{\kappa} \end{bmatrix}$$

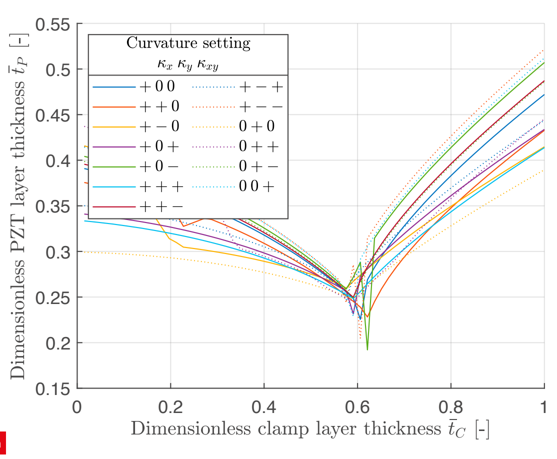
The matrix $\boldsymbol{F}$ must thus be invertible. In practice, this can only be achieved by using six piezo-electric layers in at least three different orientations, as per the design.

Design optimisation

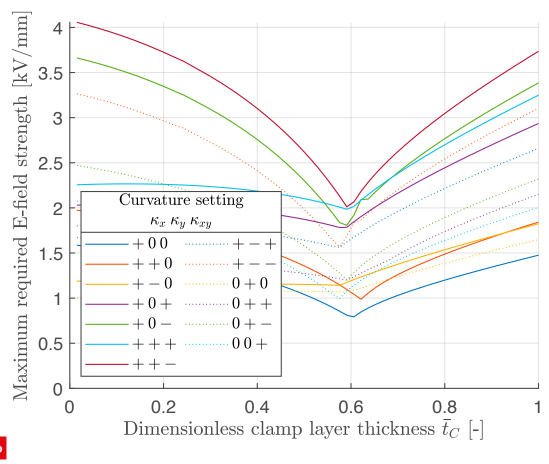
Based on the mathematical description from the previous section, the design can be optimised for maximum performance. As wafer curvature is expected to increase further, 'performance' is here defined as the largest possible curvature the actuated wafer table can achieve. As piezo-electric actuators are limited in the electrical field strength that they can sustain (about 1.3 kV/mm in either direction, for PZT, if biased correctly) the absolute voltage found during the CWL procedure has to be optimised. The problem is thus a non-convex nonlinear problem of the 'minimax' type, optimising towards minimising the maximum absolute voltage, or conversely, the maximum curvature for a fixed electric field. The optimisation results have been made dimensionless for confidentiality reasons.

As a variety of wafer shapes are encountered depending on the IC design, the optimisation has been done for all combinations of positive and negative curvatures. All curvatures have been normalised to a maximum absolute value of $\boldsymbol{K} = 0.044$, which corresponds to a 300-mm 'bowl' wafer with a peak-to-valley displacement of 0.5 mm (i.e., $\boldsymbol{K} = [0.044\ 0.044\ 0]^T$). Before loading the wafer, $\boldsymbol{\varepsilon}^0$ can be freely chosen, while after the wafer has been placed onto the wafer table, $\boldsymbol{\varepsilon}^0$ should remain fixed so as not to stretch the neutral plane of the wafer. The entire sequence of deforming the wafer table towards the wafer and flattening the clamped combination has been calculated for each selected geometry.

As a first optimisation step, the thickness of the clamp layer $\bar{t}_C$ was varied from 0 to 1. For each $\bar{t}_C$, the thickness of the piezo-electric layers t_p was then optimised. The resulting optimal dimensions are shown in Figure 7a. Clearly, the thinnest possible deformable wafer table is found at a $\bar{t}_C$ of around 0.6. Figure 7b shows the corresponding maximum required voltage for each geometric configuration. Here, we

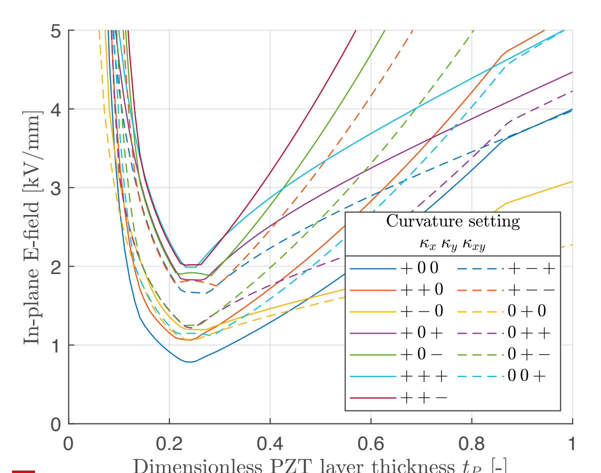


7a



7b

Initial optimisation results. Differently coloured lines represent all different wafer curvature combinations (designated by +, – and 0) for which a simulation was run.
(a) Clamp layer thickness vs. PZT layer thickness.
(b) Electric field requirement corresponding to the data in (a).



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Required electric field with a constant $\bar{t}_C$ = 0.6.

also find an optimum around a $\bar{t}_C$ of 0.6: the most compact design also results in the lowest electric field strength required. A lower $\bar{t}_C$ reduces the lever arm available for the piezo-electric layers to introduce a bending moment, while for a higher $\bar{t}_C$ layer, the parasitic in-plane stiffness will dominate.

From these figures however, it is not easy to identify the optimum piezo-electric layer thickness t_p. A second optimisation step has been done, where $\bar{t}_C$ was kept constant at 0.6. The results are displayed in Figure 8. Here, an optimum is found around 0.25. A thinner piezo-electric layer is limited by its force density, while a thicker piezo-electric layer is limited by its maximum strain.

In addition to the thickness optimisation, the electrode width was optimised using COMSOL Multiphysics. To efficiently optimise the design, a microscopic unit cell, comprising only the direct neighbourhood around a single electrode, was simulated. The results were then used as the material parameters in ***P***, ***Q***, ***R*** and ***F***. The result in Figure 8 shows an optimum around 0.1. However, for manufacturability, a wider electrode is preferred, so for an upcoming prototype, 0.25 was selected initially, yielding about 70% of the maximum design performance.

Summary

The basic design principles for an actuated wafer table have been presented. By stacking six piezo-ceramic PZT layers, both the in-plane and curvature degrees of freedom can be controlled. An interdigitated electrode embedded in the PZT layers applies an in-plane directed electric field, which results in each layer applying a strain in a different direction. The actuator dimensions have been optimised using a top-down approach, by modelling the behaviour of the entire actuator instead of individual components. Using this strategy, a set of optimal dimensions has been obtained. In the near future, a prototype will be built to validate the models used and further characterise the actuator. Additionally, segmentation of the layers will be investigated to address higher-order deformations.

REFERENCES

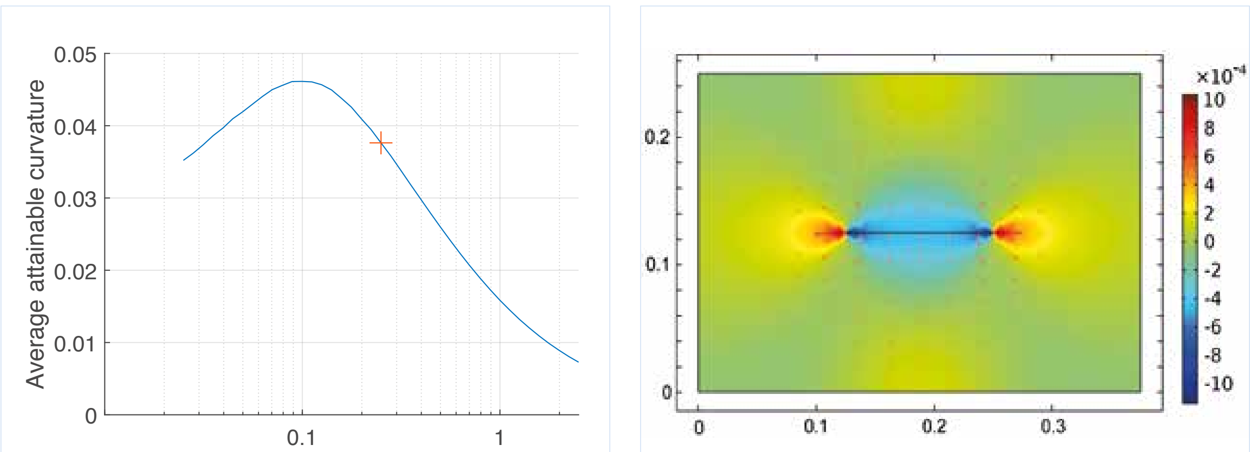
[1] K.T. Turner, S. Veeraraghavan, and J.K. Sinha, "Relationship between localized wafer shape changes induced by residual stress and overlay errors", *J. Micro/Nanolith. MEMS MOEMS*, 11 (1), 013001, 2012.

[2] S.J. Hermanussen, M.B.I. Habets, M.F. Heertjes, and J.P.M.B. Vermeulen, "Conformal slip-free wafer chucking using an actuated wafer table", *7th International Conference on Control, Mechatronics and Automation (ICCMA)*, pp. 278-282, 2019.

[3] R.F.M.M. Hamelinck (2010), "Adaptive deformable mirror based on electromagnetic actuators", Ph.D. Thesis, TU/e, 2010.

[4] J. Holterman, and P. Groen, *An Introduction to Piezoelectric Materials and Applications*, Stichting Applied Piezo, ISBN 978090-819361-1-8, 2013.

[5] Mallick, P., *Fiber-Reinforced Composites*, CRC Press, Boca Raton, FL, USA, 2007.



9a 9b

Electrode width optimisation. The optimum of 0.1 is found where the strain in horizontal direction is zero on average, and all functional strain is found parallel to the IDE 'fingers' (going into the paper).

(a) Curvature at a fixed electric field for varying electrode width, averaged across all curvature settings. The cross indicates the dimensions selected for an upcoming prototype.

(b) Unit cell (see cross-section in Figure 6) COMSOL simulation result at the optimum of 0.1 dimensionless electrode width. Colours indicate strain [-] in horizontal direction; arrows indicate electric field direction and magnitude.

PREVENTING THE FREEZING OF VACCINES IN A COLD CHAIN

Vaccines containing aluminium salt adjuvants lose potency when exposed to freezing temperatures. Freezing of vaccines can be prevented by using a passive thermal buffer layer between ice packs and the vaccine compartment. The selection of the material and optimising the geometry of the passive thermal buffer layer is an exciting engineering design task which comes up all too often in the precision engineering field. This article models the problem using simple equations, while verifying it with finite-element analysis and using it to optimise the buffer design parameters.

AKSHAY HARLALKA

Background

Today, massive efforts and resources are being leveraged globally to develop a vaccine for COVID-19. But, a vaccine is just a formula. Distributing and administering these vaccines to masses effectively will be at least as difficult of a hurdle to cross. Most vaccines need a cold chain maintaining temperature to a narrow band of 2-8 °C to remain effective.

Counter-intuitively, for some vaccines, especially those containing aluminium salt adjuvants, exposure to freezing can be more damaging than exposure to heat. At freezing temperatures, these adjuvants, which are required to trigger an immune response, cluster together and become damaged, causing the vaccine to lose potency. Loss of vaccine potency leaves the vaccinated people at the risk of disease. Various studies have reported that vaccines are frequently exposed to freezing temperatures. In some countries, up to 100 per cent of the vaccine shipments are known to be exposed to freezing temperatures during their journey across the cold chain [1].

The problem

One of the reasons for vaccines being exposed to freezing temperatures is dependence on ice packs to keep the vaccines in the right temperature range. A health worker in charge of administering vaccines to people in their community, uses a vaccine carrier to store these vaccines while travelling (Figure 1). The main function of this carrier is to maintain the temperature of the vaccines at 2-8 °C when the ambient temperature can be as high as 43 °C (Figure 2).

These vaccine carriers are typically made up of an HDPE housing with a CFC-free polyurethane insulation material. Four ice packs are typically used to keep the vaccines at the right temperature. The problem is that when these ice packs are extracted from the freezer, they can be at temperatures as low as –25 °C. Using these ultra-cold ice packs with the vaccines greatly risks freezing. Therefore, healthcare workers are instructed and trained to condition these ice packs to about 0 °C before putting them into the vaccine carrier. However, this step requires time and advanced planning, increasing health worker burden, and introduces a risk of human error leading to wastage of precious vaccine resources.

1

Vaccine carriers play a critical role in providing access to vaccines at the world's most remote locations [2].

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Types of vaccine carriers.
(a) (Existing) standard type [3].
(b) With freeze-preventive barrier [4].

Existing solutions and the gap

In 2016, PATH, a leading non-profit health organisation, filed a research disclosure [5], detailing the concept of a freeze-preventive vaccine carrier that avoided the need for the thermal conditioning of ice packs. A buffer layer between the vaccine storage compartment and the ice packs helped in preventing direct contact of the vaccines with the freezing ice packs. However, the addition of the thermal buffering layer also reduced the available volume in the vaccine storage compartment.

According to the PQS Verification Protocol for Vaccine Carriers with Freeze Preventive Technology [6], the minimum available volume in the vaccine storage compartment should be at least 0.5 ℓ for short-range models and at least 1 ℓ for long-range models. However, if the thermal buffering layer is added to the existing vaccine carriers, the available volume in the storage compartment falls to 0.42 ℓ.

Figure 3 compares the available volume for vaccine storage between standard vaccine carriers and those with a freeze-preventive barrier added. Vaccine carrier manufacturers who wanted to integrate the freeze-preventive barrier technology hence had to increase the overall size of the vaccine carriers. This also reduced the attractiveness of integrating a buffering layer into existing vaccine carriers.

However, this development was before COVID-19 struck. With the whole world rallying resources to develop and distribute vaccines to every human as soon as possible, it is worth taking a fresh look at whether a cheap, modular thermal buffering layer could be developed without compromising the volume limitations of the vaccine storage compartment. The thermal model described in this article could aid in this discovery.

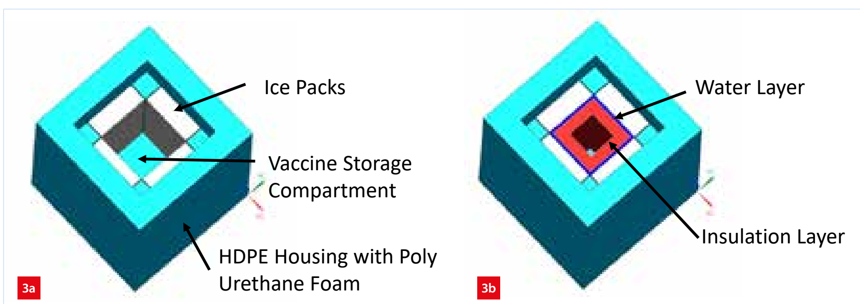
Analytical thermal model set-up

To optimise the performance of the freeze-preventive thermal buffer given the volume limitations, a thermal model needs to be developed. This model should predict the temperature profile of the key parts of the vaccine carrier system including the vaccine solution, ice pack and insulation layer. Since temperatures of the ice pack, vaccine solution, etc., will change as a function of time, we will need to resort to transient heat transfer equations.

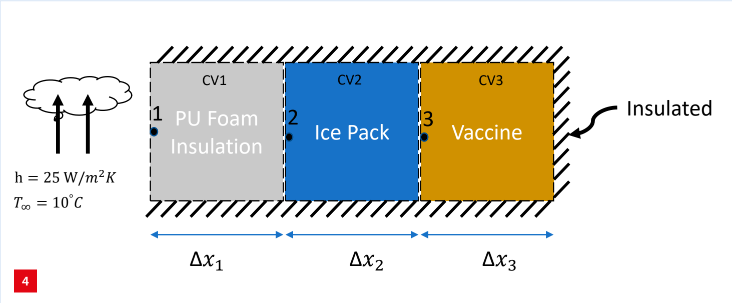
There are a number of ways to solve transient heat transfer problems, including:

1. Lumped-capacitance method.
2. Numerical methods.
3. Approximate solutions to the heat diffusion equation, using Heisler charts.
4. Analytically solving the heat diffusion equation.

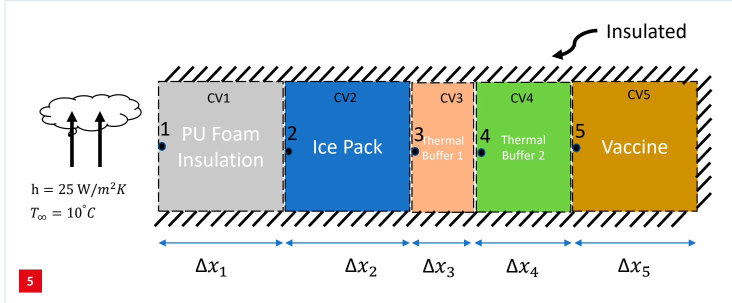
For the analytical model in this article, the 1D unsteady heat transfer equation will be solved using the explicit finite difference method. The problem will be formulated in the Python programming language (code available from the author).



Design details.
(a) Existing vaccine carrier.
(b) Existing vaccine carrier + freeze-preventive barrier.



Thermal model representation of existing vaccine carriers.



Thermal model representation of an existing vaccine carrier with freeze-preventive barrier.

A simplified representation of the thermal model for the existing vaccine carriers is shown in Figure 4. To solve the problem, we define three different control volumes (CV1, CV2 and CV3) and three nodes (1, 2 and 3). Node 1 is exposed to the ambient environment and therefore a natural convection boundary condition is applied on that node. All other boundaries are considered to be perfectly insulated. The lengths of the different control volumes are given as Δx_1, Δx_2 and Δx_3. The density, specific heat capacity and thermal conductivity of different control volumes are represented by ρ, c and k, respectively. To find temperatures at different nodes at various time steps, an energy balance equation needs to be formulated for each control volume. As an example, the energy balance equation for CV1 is formulated below.

Example energy balance equation for CV1

Rate of change of internal energy of CV =

Heat influx due to convection from ambient air +

Heat influx from conduction from ice pack.

$$\frac{dE_1}{dt} = hA(T_\infty - T_1) + \frac{k_1 A(T_2 - T_1)}{\Delta x_1} \quad \text{(Equation 1)}$$

$$\rho_1 c_1 \Delta x_1 \frac{dT_1}{dt} = hA(T_\infty - T_1) + \frac{k_1 A(T_2 - T_1)}{\Delta x_1}$$

$$\frac{dT_1}{dt} = \frac{hA(T_\infty - T_1)}{\rho_1 c_1 \Delta x_1} + \frac{k_1 A(T_2 - T_1)}{\Delta x_1{}^2 \rho_1 c_1}$$

$$\frac{T_1^{p+1} - T_1^p}{\Delta t} = \frac{hA\left(T_\infty - T_1^p\right)}{\rho_1 c_1 \Delta x_1} + \frac{k_1 A\left(T_2^p - T_1^p\right)}{\Delta x_1{}^2 \rho_1 c_1}$$

$$T_1^{p+1} = T_1^p + \frac{hA\Delta t\left(T_\infty - T_1^p\right)}{\rho_1 c_1 \Delta x_1} + \frac{k_1 A\Delta t\left(T_2^p - T_1^p\right)}{\Delta x_1{}^2 \rho_1 c_1} \quad \text{(Equation 2)}$$

Equation 2 provides the temperature at node 1 at the next time step using the parameters at the current time step. Solving the energy balance equations for the other two control volumes will also provide such equations for nodes 2 and 3. These equations can then be coded in a programming language like Python to generate a temperature profile at various nodes as a function of time. The parameters used to generate the solution for existing vaccine carriers are shown in Table 1. If a finer resolution solution is required, the control volumes can be subdivided further.

Addition of the thermal buffers does not change the approach to the problem. It just increases its complexity slightly. As shown in Figure 5, there are now five control volumes to consider instead of three in the previous case.

Finite-element thermal model set-up

To verify the results generated from solving the heat balance equations, a FEM (finite-element model) analysis (FEA) was performed in NX Advanced Simulation software. A multi-body 3D CAD model representing the lengths of different control volumes in the system was prepared and the respective material properties were assigned accordingly. The FEM mesh and the boundary condition details are specified in Figure 6. The initial temperatures of the three different control volumes were specified in the model and can be seen in Figure 6b.

Results and Discussion

Existing vaccine carrier (no thermal buffer)

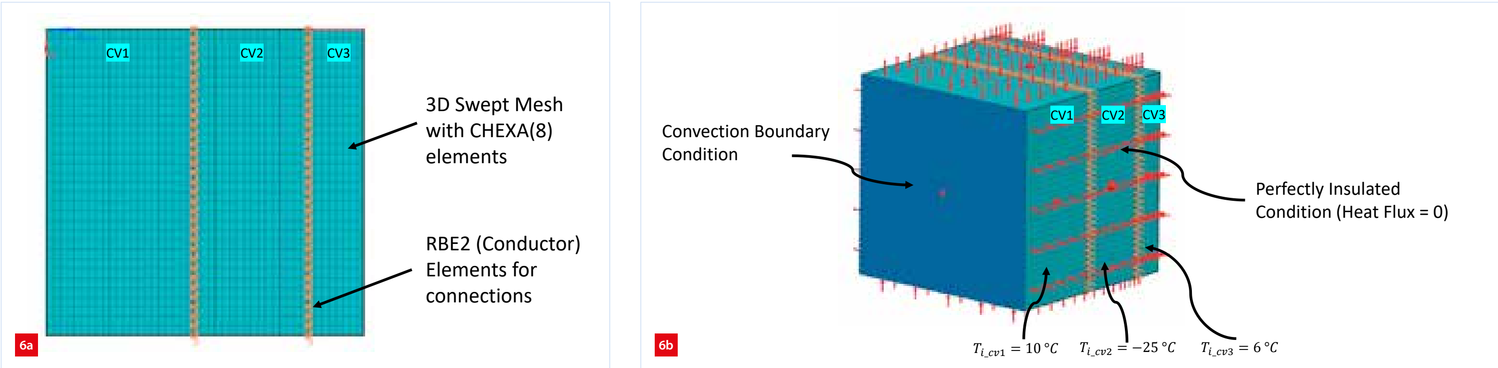
The heat balance equations were solved using Python and the temperature data of the vaccine solution as a function of time was exported. Temperature profiles at two different positions on the vaccine solution layer were generated – one near the ice pack (high risk of freezing) and the other in the middle of the vaccine solution (bulk temperature).

A comparison of the temperature profiles generated by analytical and FEA solutions is shown in Figure 7a. It can be observed that the analytical and FEA solutions match very well. The graph suggests that the vaccine bottles close to the ice pack will indeed be exposed to freezing temperatures.

Table 1

Parameters used to evaluate the analytical solution.

Parameters	CV1 (PU foam)	CV2 (Ice pack)	CV3 (Vaccine)
Length (Δx) in m	0.0425	0.033	0.016
Density (ρ) in kg/m³	200	920	1,000
Specific heat capacity (c) in J/kg K	1,400	2,040	4,182
Thermal conductivity (k) in W/m K	0.026	2.22	0.6
Initial temperatures (T_i) in °C	10	–25	6



FEM model.
(a) Mesh details.
(b) Simulation boundary condition details.

In fact, these vaccine solutions are exposed to freezing temperatures within 30 minutes of putting them in the compartment. The temperature heat map at t = 0.5 h is shown in Figure 7b. As can been seen, the temperature of the vaccine solution near the ice pack is –9.3 °C while the bulk temperature is around –8 °C.

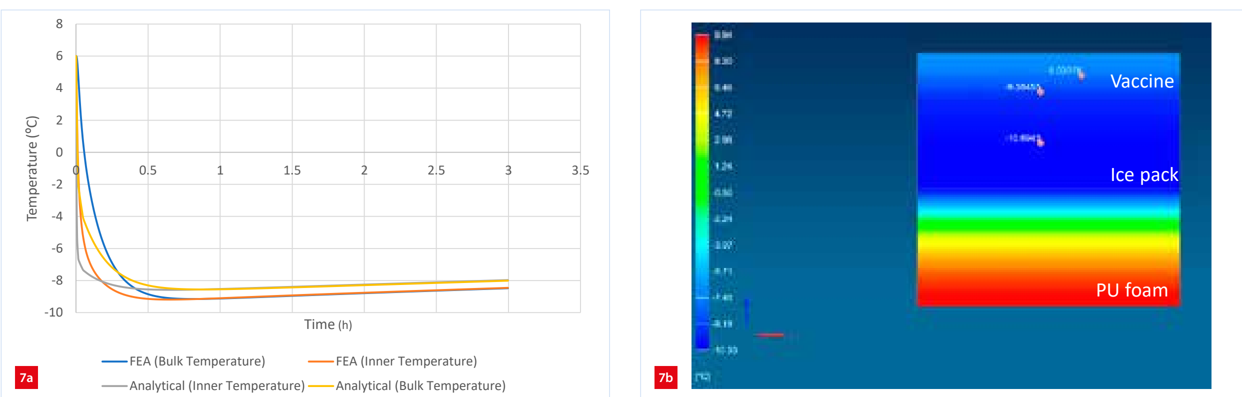
Freeze-preventive vaccine carrier
The idea of adding a thermal buffering layer is to increase the thermal mass near the ice packs enough so that the these ice packs get 'conditioned' to 0 °C before the vaccine compartment temperature reaches that level. The resultant temperature profile of the vaccine and the temperature distribution plot of the complete thermal system are shown in Figure 8. Compared to the temperature profiles for an existing carrier without thermal buffer as shown in Figure 7, the slope of the vaccine temperature vs time graph in Figure 8a is much more shallow. The lowest temperature the vaccine is exposed to is in the range of –1.6 to –1.8 °C. This is a much greater improvement than the previous case where the lowest temperature was –9.3 °C.

It needs to be noted that the thermal model does not take into consideration the interface resistance to heat transfer of, for example, the glass bottle that the vaccine is stored in and the HDPE plastic casing the ice packs are stored in. Consideration of these details could lead to a more accurate thermal solution (probably yielding an even better result, i.e. higher temperatures) to the problem but also add more complexity.

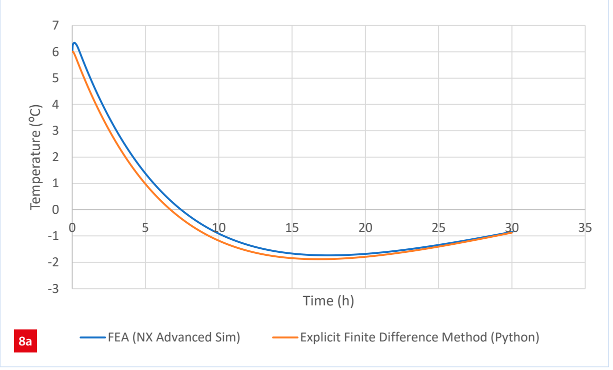
Design optimisation of thermal buffer

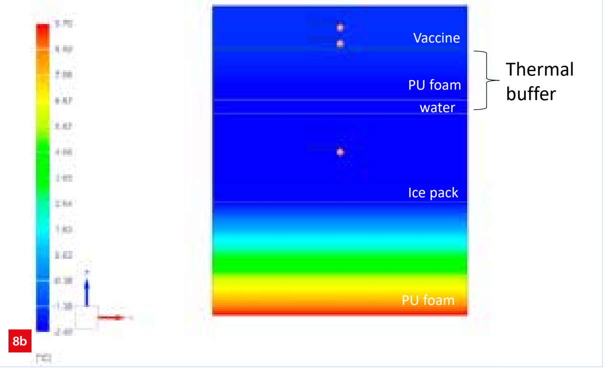
Once enough confidence had been established in the FEA model and the Python code, various design options were evaluated to determine if there is any room for improvement in the geometry and the material selection of the buffer layers. The current insulation material PU foam seems to be appropriate for use given its cost-effectiveness and low thermal conductivity. Selection of water as the other buffer layer is also appropriate because of its high specific heat capacity, which greatly slows down the temperature fall.

However, after running various design cases, it seems that the division of thicknesses between the two buffer layers can be optimised further. As per the current design of the freeze-preventive barrier designed by PATH, 5 mm is the thickness of the water layer and 19 mm is the thickness of the PU foam layer. Using the Python code, two other scenarios were run – 12 mm foam layer & 12 mm water layer and 7 mm foam layer & 10 mm water layer. The performance of both these design options was compared against the PATH design as shown in Figures 9. The 12 mm PU foam + 12 mm water thermal buffer



Results for an existing vaccine carrier (no thermal buffer); environmental temperature is 10 °C.
(a) Temperature profile generated via FEA solutions.
(b) Temperature distribution plot at t = 0.5 h (scale from –10.93 to 9.94 °C).





Results for a freeze-preventive vaccine carrier; environmental temperature is 10 °C.
(a) Temperature profiles generated via FEA solutions.
(b) Temperature distribution plot at t = 15 h (scale from –2.4 to 9.7 °C).

combination seems to perform slightly better at low ambient temperatures than the existing design used by PATH. This design option exposes vaccines to temperatures only as low as –1 °C, as compared to –2 °C for the PATH design. Under high ambient temperatures, this design option still maintains the vaccine temperature below 8 °C within its specified 30-h cold life.

There may also be options to reduce the volume footprint of the thermal buffer layer. For example, the 7 mm foam + 10 mm water option performs only slightly worse than the PATH design. It is possible that by increasing the foam thickness slightly, the performance of this option can be made comparable to that of the PATH design. In such cases, equivalent performance can be reached in a reduced volume footprint, thereby leaving more space for the storage of vaccines.

Conclusion

The freeze-preventive vaccine carrier was used as a case study to show how passive thermal management solutions can be designed using simple heat balance equations and FEA models. The excellent correlation of the solutions achieved with these two approaches is very encouraging. Once the model had been verified, various design scenarios were evaluated in order to optimise the design of the thermal buffer layer.

A thermal buffer design option (12 mm PU foam + 12 mm water) seems to outperform the existing design used by manufacturers of the freeze-preventive vaccine carriers. This design option reduces the exposure of the vaccines to freezing temperatures when the ambient temperature is low, while still keeping them cold enough when ambient temperatures are at their peak. Practitioners in the precision engineering industry could take inspiration from this passive thermal management system that requires no moving parts and energy source while adding minimal cost.

REFERENCES

[1] Matthias, D.M., et al., "Freezing temperatures in the vaccine cold chain: a systematic literature review", *Vaccine*, 25 (20), pp. 3980-3986, 2007.

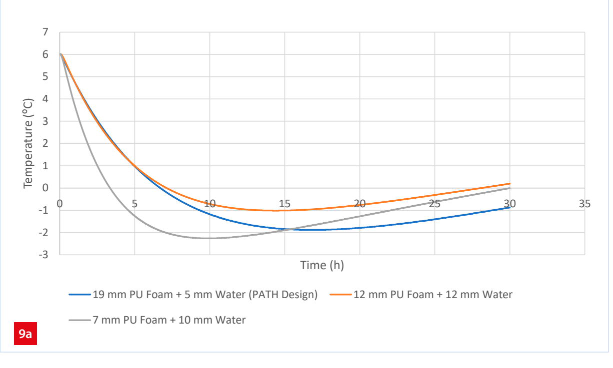
[2] "Getting vaccinations to the world's most hard to reach places", Dec. 1, 2019. Accessed on: Nov. 29, 2020, *www.ivaccinate.org/in-photos-getting-vaccinations-to-the-worlds-most-hardest-to-reach-places*

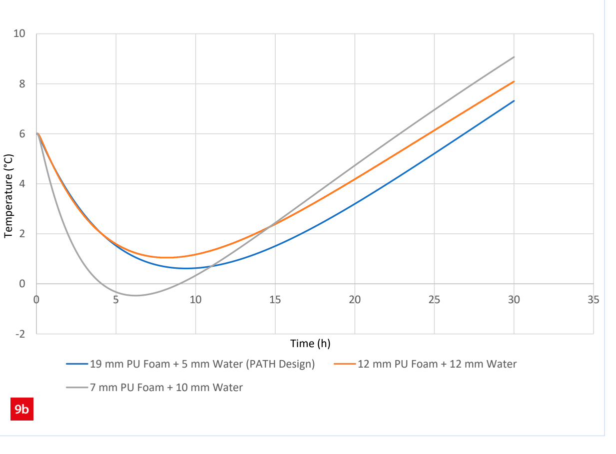
[3] "UIFF Vaccine carrier AOV AFVC46 E004/050", Accessed on: Nov. 29, 2020, *supply.unicef.org/s0002475.html*

[4] "Nilkamal Limited Vaccine carrier LR BCVC46", Accessed on: Nov. 29, 2020, *www.technet-21.org/en/pqs-cce/item/293-_nilkamal_limited_vaccine_carrier_lr_bcvc46_*

[5] Research Disclosure: "Freeze-prevention design for vaccine carriers, cold boxes and other passive cold chain equipment to prevent freezing of vaccines, drugs or pharmaceuticals in the cold chain", Accessed on: Nov. 29, 2020, *rd.orbit.com/OrderForm/PublicationPreview.aspx?disNum=622008*

[6] Requirements Document: [WHO_PQS_E004_VC02-VP.1]_Vaccine carrier with freeze-prevention technology PQS verification protocol, Accessed on: Nov. 29, 2020, *apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/catdocumentation.aspx?id_cat=18*





Performance of various design scenarios.
(a) Lowest ambient temperature (10 °C).
(b) Highest ambient temperature (43 °C).

HIGH-SPEED ACTIVE SCANNING

Nobby Assmann received a ZEISS #measuringhero Award 2020 in the Outstanding Application - Smallest measured Component category, for accurately measuring a tiny hearing aid component with a volume of only 0.0048 mm^3. He used a Zeiss Contura coordinate measuring machine with an integrated VAST XT Gold active scanning head featuring a probe diameter of only 300 μm. An impressive achievement, which draws attention to the advantages of active scanning in contrast to passive point-by-point touch-trigger probing.

FRANS ZUURVEEN

One might think that Nobby Assmann is a measuring specialist from some larger manufacturer of precision parts. But he is not only the proprietor of the Assmann Verspaningstechniek company, he is – besides his still active parents – also the only employee, see Figure 1. His firm delivers precision products made by wire- or die-sinking (electrical discharge machining), lapping, honing and grinding, and also provides warranted measuring reports, see Figure 2, resulting from innovative measuring with his Zeiss Contura CMM (coordinate measuring machine). “I love precision machining and measuring technology. Getting paid for doing the things I enjoy, is just amazing”.

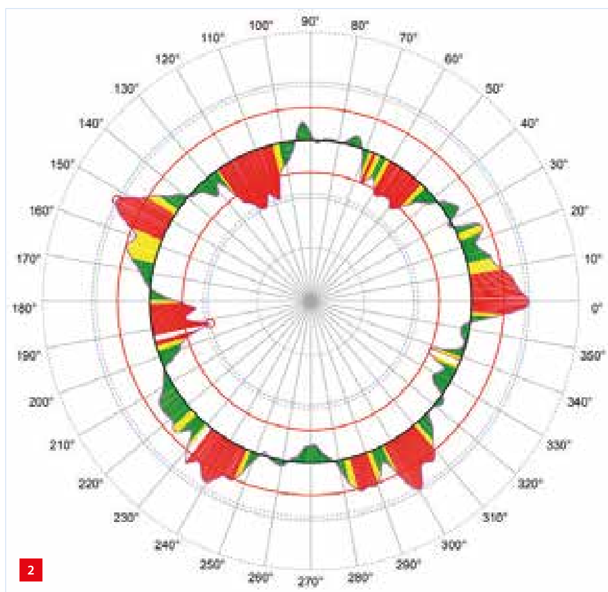
The Contura CMM (Figure 3) has a measuring range of 1,000 mm x 700 mm x 600 mm. Of particular interest is its active scanning head, which allows the measuring of tiny objects such as Assmann’s award-winning part. This is the Zeiss VAST XT Gold scanning head (where VAST is the abbreviation for ‘Variable Accuracy and Speed probing Technology’), and it triggers the question whether active scanning should be preferred above passive point-to-point measuring. Firstly, the advantages of active scanning will be discussed, using the example of measuring out-of-roundness of cylindrical shafts and holes.

Out-of-roundness

Centerless grinding is notorious for causing out-of-roundness of an accurately machined shaft. Internally honing a precision hole causes the same problem. But when checking the diameter of the shaft or hole with a micrometer screw gauge the machined products seem to be perfectly round. Why? Because the lack of a fixed central point causes three-lobed (triangular) out-of-roundness, see Figure 4. This figure also demonstrates the definition of out-of-roundness Δ*r*, in ISO 12181 (also VDI/VDE 2617 sheet 2.2), designated as RONt (roundness total).

1

Nobby Assmann with his Zeiss Contura coordinate measuring machine with VAST XT Gold active scanning head.



2

A measuring report from Assmann Verspaningstechniek.

AUTHOR’S NOTE

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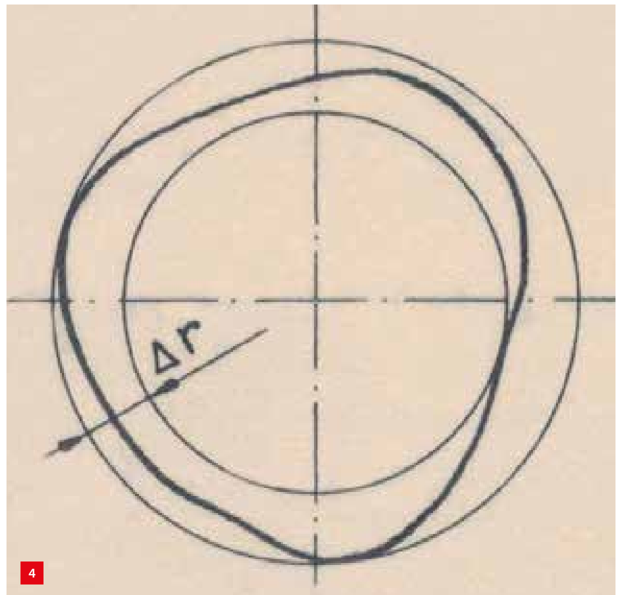
Generally, the appearance of an odd number of equally divided unroundness lobes means that a simple two-point diameter measurement does not show any diameter deviation. Hence, a continuous radius measurement, as shown in Assmann's measurement report (Figure 2), is a much better method for discovering geometrical deviations.

Traditionally, such measurements can be performed with a Talyrond roundness tester, see Figure 5, from Taylor Hobson. Such instruments are fitted with a highly accurate air bearing. However, a combination of a Zeiss Contura CMM with a VAST XT Gold scanning head can measure geometrical shaft or hole deviations as well, thanks to the CMM and probe mechanical accuracies on the one hand and Calypso and Navigator software on the other hand.

Passive and active scanning

When conventionally measuring a workpiece with a spherical touch-trigger probe, the probe is fitted with an internal mechanical switch, which produces an electrical pulse when touching the object with a pre-defined force. About sixty years ago, the measuring room specialist then had to write down on paper the positions of the X-, Y- and Z-slides of the measuring machine and subsequently calculate the deviations from the tolerances prescribed on the workpiece drawing. Current CMMs are equipped with software that controls the orbit of the touch probe according to CAD data. The software then automatically provides geometrical errors in μm's.



Definition of out-of-roundness: the smallest difference Δr between the radii of the best-fitting external and internal circle with the same centre. (Drawing by the author, 1963)

A Zeiss Contura CMM.

In passive measuring systems the measuring force is generated by a mechanical spring. During the movement of the CMM slides the spring force can increase to unacceptable values. In order to avoid a too high spring force and deflection of the stylus, the CMM needs to move its X-, Y- and Z-axes. In order to achieve acceptable results, the passive scanning speed has to be quite low.

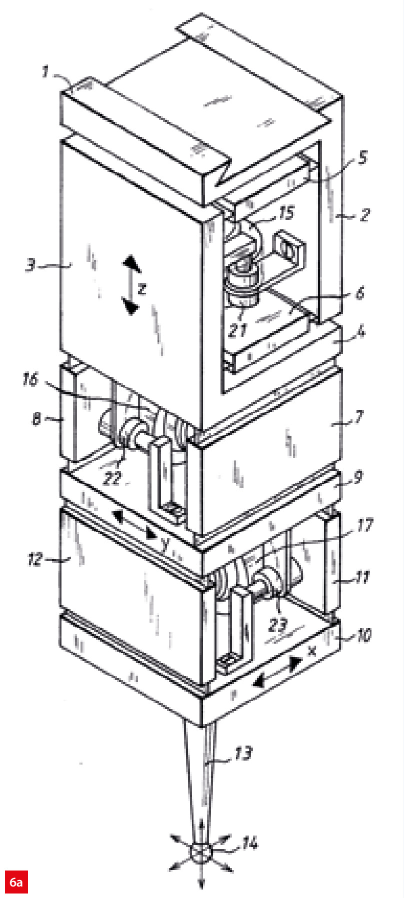
On the other hand, the VAST active measuring system consists of separate linear drives that generate the probing force inductively through iron moving inside a coil. Instead of continuously moving the air-beared X- and Y-slides (and sometimes the Z-slides) in passive systems, the CMM slides keep their fixed positions when the separate active scanning system measures deviations from the prescribed orbit, a helix for example. The separate active scanner only needs to have a limited stroke of ±2 mm, thus somewhat larger than the dimensions of the anticipated divergences. Conceptually, this resembles the long-stroke, short-stroke wafer stage design in modern lithography systems.

Scanning principle

The VAST Gold active scanner has a stroke of ±2 mm, whereas the XT version covers ±3 mm. The principal advantage of these active scanners, besides accuracy, is their speed: up to 300 mm/s. A constant touching force down to 50 mN – virtually zero – is also remarkable, with a maximum of 1,000 mN on the other hand. For the measuring of large components, the VAST scanning head can handle stylus configurations up to 500 mm in length and 500 grams in weight. After calibration, the Zeiss Navigator software, among other things, corrects for dynamic and static bending errors. The combination of software and active scanning probe yields high scanning speeds and accuracies.

Figure 6 shows a drawing accompanying Zeiss' patent application and the actual mechanical lay-out. To quote from the patent text: "The invention relates to a probe for coordinate measuring machines with measuring systems for measuring the deflection of the resilient part of the probe and electromagnetic force generators for generating measuring forces of predeterminable size and direction."

The figures demonstrate the stacking of three devices, each responsible for either an X-, Y- or Z-movement. Spring parallelograms allow these 3D movements. Inductive systems take care of generating the probing force, as well as measuring the separate deflections. Ultimately, each separate measuring point provides a distance value MS, which is the sum of the measuring machine displacement MT and scanning head displacement SV: MS = MT + SV. The inductive devices act as some sort of 'electronic springs' for generating constant probing forces. This is in contrast to the functioning of a passive probe, which requires continuous displacements of the CMM slides in order to correct the excited probing force.



6a

6b

Schematics of a VAST active scanning head.
(a) Drawing from Zeiss' patent application.
(b) Open view of the actual mechanical set-up.

5

A Talyrond roundness tester with an extreme radial air-bearing accuracy. (Photo courtesy of Taylor Hobson).

To conclude

It is entertaining to learn how the accurate measuring of a tiny hearing aid component provided Nobby Assmann with an international Zeiss measuring award. In addition, it put Mikroniek on the trail of a small measuring device inside a larger measuring machine.

INFORMATION

ASSMANN VERSPANINGSTECHNIEK
WWW.3DMETEN.NL

ZEISS
WWW.ZEISS.COM/METROLOGY/HOME.HTML
WWW.ZEISS.COM/METROLOGY/CAMPAIGNS/MEASURINGHERO.HTML

WIM VAN DER HOEK AWARD GOES TO TU/E ALUMNUS TEUN VAN DE SANDE

During the online programme of the 2020 Precision Fair, the Wim van der Hoek Award was presented under the auspices of DSPE. The prize went to Teun van de Sande, who graduated from Eindhoven University of Technology (TU/e) on the design of a complex motion mechanism. The mechanism has to function under tight space constraints and extreme low temperatures. "To that end, Teun eminently applied Van der Hoek's design principles", according to the jury. "He has been very conscientiously in setting up and elaborating this multidisciplinary design."

On Wednesday afternoon, 18 November, during the online programme of the 2020 Precision Fair, DSPE organised the presentation of the Wim van der Hoek Award. This award (also known as the Constructors Award) was introduced in 2006 to mark the 80th birthday of the Dutch doyen of design engineering principles, Wim van der Hoek, who passed away early last year at the age of 94. Prior to the award ceremony, the presentation of the book on Wim van der Hoek (see the next page) took place.

The Constructors Award is presented every year to the person with the best graduation project in the field of design in mechanical engineering at the Dutch (and Belgian) universities of technology and universities of applied sciences. This award includes a certificate, a trophy made by LiS (Leidse instrumentmakers School) and a sum of money, sponsored by HTSC; the TU/e High Tech Systems Center.

Teun van de Sande, winner of the Wim van der Hoek Award 2020, receives the book about Wim van der Hoek from jury chairman Jos Gunsing. Between them are the certificate and the trophy that go with the prize. (Photo: Julie van Stiphout)

Eight nominations

Criteria for the assessment of the graduation theses include quality of the design, substantiation and innovativeness, as well as the suitability for use as teaching materials. The jury, under the presidency of DSPE board member Jos Gunsing (MaromeTech), received a total of eight nominations from two universities of technology and two universities of applied sciences. "In all cases it concerned high-quality work", the jury said. The nominees have been invited to attend the DSPE Conference on Precision Mechatronics 2021 free of charge.

The online Wim van der Hoek Award ceremony, with the chairman of the jury, Jos Gunsing, in the upper left corner and below him the award winner, Teun van de Sande.

Eminent application of design principles

The Wim van der Hoek Award 2020 eventually went to Teun van de Sande, who studied Mechanical Engineering at TU/e. This summer, he graduated on the design of a complex motion mechanism. He performed his graduation work at Prodrive Technologies in Son (NL), where he was challenged to design a mechanism that has to function under tight space constraints and extremely low temperatures.

He started his assignment with a system decomposition resulting in two major design issues to solve. In the first place, the design of a non-overdetermined support of a fragile sensor including its strict requirements on cooling. Secondly, the design of a linear-guidance-based retraction mechanism with a well-defined pretension and without end-of-stroke collision forces. "

Teun's analytical and experimental skills, enthusiasm and eagerness to learn, together with the ability to transfer newly obtained knowledge in a structured manner to team members, allowed him to solve both issues and to create a fully integrated product design as well", his supervisor at Prodrive, Ron Hendrix, states. The jury adds: "In his design, Teun eminently applied Van der Hoek's design principles. He has been very conscientiously in setting up this multidisciplinary design. Various concepts were elaborated well, he substantiated his design choices thoroughly and his report is a pleasure to read."

Online book presentation

After the passing away of Wim van der Hoek, in early 2019, DSPE took the initiative to publish a book about the Dutch doyen of design principles. The presentation took place on 18 November 2020, during the online Precision Fair event. DSPE president Hans Krikhaar hosted a short ceremony that started with a video in which he presented the first copy to Van der Hoek's widow, Aat.
Next, in the studio of Precision Fair organiser Mikrocentrum, Krikhaar discussed the book and Van der Hoek's relevance with Jan van Eijk and Piet van Rens. Jan van Eijk, former CTO of Mechatronics at Philips Applied Technologies and emeritus professor of Advanced Mechatronics at Delft University of Technology, was Van der Hoek's colleague at Philips CFT (Philips Centre for Manufacturing Technologies) for a short while and continued to build on his work. Piet van Rens was one of Van der Hoek's students and later became his colleague at Philips CFT; he has also been an enthusiastic teacher of Van der Hoek's design principles.

The book (in Dutch) covers Van der Hoek's formative years, including World War II 'adventures', his career at Philips and Eindhoven University of Technology, where he developed his breakthrough ideas on achieving positioning accuracy and controlling dynamic behaviour in mechanisms and machines, and their reception and diffusion. It concludes with his busy retirement years in which he continued to tackle – technical as well as social – design challenges, believing that technology should support people. The book can be ordered at the DSPE website.

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

Impression of the book presentation in the Mikrocentrum studio for the online event. From left to right: Jan van Eijk, Piet van Rens en Hans Krikhaar. (Photo: Julie van Stiphout)

Scan the QR-code for the video of the book presentation and the subsequent award presentation.

WWW.DSPE.NL

BRONZE ECP2 CERTIFICATE FOR JORDY NIEUWHOFF OF ASML

Jordy Nieuwhoff, optomechanical lead design engineer at ASML, has been awarded the Bronze certificate from the ECP² programme, a European certified precision engineering course that is a collaboration between euspen and DSPE. He is the fifth person to receive this certificate since the first one was presented in 2015.

Euspen's ECP² programme grew out of DSPE's Certified Precision Engineer (CPE) programme, which was developed in the Netherlands in 2008 as a commercially available series of training courses. Inspired by the success of this programme, euspen decided in 2015 to take certification to a European level. The resulting ECP² programme reflects industry demand for multidisciplinary system thinking and an in-depth knowledge of the relevant disciplines. In 2019, euspen gained Erasmus+ funding from the European Union for developing a European framework for training in precision engineering for the advanced manufacturing sector, to increase the availability of specialised training courses in multiple European countries.

Back to the Netherlands now, home of both the certification scheme and winner Jordy Nieuwhoff. As a boy, Jordy spent many hours with his father at home and at his father's work as an instrument maker. Later, Jordy went on to study fine-mechanical engineering in Utrecht, where his assignments included the design of instrumentation for both astronomy (at University of Utrecht and at TNO) and free-electron lasers and masers for use in nuclear fusion research at FOM Nieuwegein (now DIFFER in Eindhoven). Thus, he was acquainted with optomechatronics from his early days.

Jordy Nieuwhoff (right) has received the Bronze certificate (and flowers) from the hands of Jan-Willem Martens. (Photo: Julie van Stiphout)

After graduating from the University of Applied Sciences Utrecht in 2004, he enrolled at ASML in Veldhoven as a junior optomechanical design engineer and started working on the development of a level sensor for wafer metrology. Next, he spent for three and half years as a lead production engineer at an ASML site in Taiwan, in charge of production transfer, site extension and training. In 2011, he returned to Veldhoven to become an optomechanical lead design engineer concerned with laser beam alignment for the EUV source of ASML's NXE platform, including tooling, metrology and actuation for beam steering.

Over the last few years, driven by ASML's training policy, Nieuwhoff has undertaken a large number of courses, including several ECP²-certified courses, such as Design Principles, Applied Optics, Basics & Design Principles for Ultra-Clean Vacuum, and Mechatronic Systems Design (part 1 and 2). He has earned 28.5 points so far, which qualifies him for the Bronze certificate (it requires 25 points, while 45 points qualifies a participant for a Gold certificate and the title 'Certified Precision Engineer'). In October, he was presented with the Bronze certificate by Jan-Willem Martens, the godfather of the DSPE certification programme.

Reflecting on the programme, Nieuwhoff mentions that he especially enjoyed the Summer school Opto-Mechatronics, which he attended in 2012 at TNO's in Eindhoven. "It gave me a headstart in my 'old' field after returning from my operational job in Taiwan. The case we had to elaborate (the design of an actively controlled delay line for interferometry over large distances, ed. note) brought back a lot of memories. I would recommend this Summer school (which is currently not on the course calendar, ed. note) to anyone who wants to get an overview of the field. It creates awareness and will help people in communicating with their colleagues in multidisciplinary teams working on optomechatronic designs."

WWW.ECP2.EU

SPECIAL DSPE CONFERENCE EDITION IN 2021

The DSPE Conference on Precision Mechatronics 2020 had to be cancelled because of the worldwide COVID-19 pandemic. Initially, the idea was to simply postpone the conference for a full year. However, the conference's advisory board and organising committee concluded that the current situation is still too uncertain to plan for a full-blown conference in 2021. Instead, it was decided to postpone the regular conference until 2022 and organise a smaller event next year.

The 2021 conference on 14-15 September will be a mixed real-life/online event combining two elements:

1. Inspirational presentations by several invited international speakers from adjacent application areas, such as bio-inspired mechatronics, robot-assisted surgery, virtual reality, artificial intelligence, and more.
2. The opportunity for the community to meet/network and exchange ideas in a pleasant atmosphere, including a BBQ.

There will be a new call for proposals for the 2021 event. All contributors to the 2020 conference are invited to submit their current (updated) proposal or a new proposal, for review by the advisory board. They also have the option to submit their current work for publication in Mikroniek.

All participants will come together at the location of the *Academisch Genootschap* (Academic Society) in Eindhoven (NL) and follow the online presentations on a large screen in a theatre-like setting. A host will facilitate the Q&A sessions. After the presentations there will be drinks and a BBQ. The event will start with an afternoon/evening session featuring four guest speakers, among others from the US, and will continue the next morning with a session featuring another four guest speakers, including those from Asia.

Board and committee expect this concept to address the need of the community to meet and network face-to-face instead of just teleconferencing and to be inspired by colleagues worldwide, while providing the flexibility to reshape the conference towards a full online event if circumstances do not permit large groups coming together.

The Academisch Genootschap will provide the venue for the mixed real-life/online DSPE Conference on Precision Mechatronics 2021. (Source: www.ag-zaalverhuur.nl)

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WWW.DSPE-CONFERENCE.NL

PCV Group – solving high-tech challenges

PCV Group is a product and technology development consultancy firm based in the Netherlands. Combining their knowledge of engineering and project management, PCV Group's experts handle the most challenging assignments from many clients throughout Europe and beyond. Their experience with complex problems, such as developing low-cost dispensing and dosing systems, keeps bringing PCV Group into the next areas of innovation.

In the firm's villa in Enschede (NL), about 40 employees work on solving high-tech challenges every day, drawing upon the engineers' experience in several areas of expertise for many clients. All senior staff members have worked in top positions for multinationals, providing PCV Group with a unique understanding of the R&D challenges global companies face. Besides the in-house team of engineers and managers, PCV Group maintains an extensive network of specialists. Whether a project requires knowledge of material properties, FEM (finite-element method) or CFD (computational fluid dynamics) calculations, software development or project management, each project team will be tailored to the client's needs.

The type of products PCV Group usually works on can be described as low-cost, high-volume, high-tech. Examples of precision engineering include mass-produced injection-moulded mechanisms and embedded systems in professional appliances. These systems are developed and extensively tested in the in-house labs, where testing and measuring methods are continuously improved.

Precision engineering

PCV Group has recently joined DSPE to supplement its broad experience in mechanical engineering and to grow its knowledge and network in the field of precision engineering even further. As an example of diving deep into the physics of a problem, the article "Precision Coffee" was contributed to the June 2020 issue of Mikroniek. It concerned the difficulties in precision water heating in

Douwe Egberts Promesso packaging with single-use gear pump for dosing of the concentrate.

The Surgical Company's Fluido Compact blood warmer with disposable.

consumer appliances; this knowledge has been used for customers like Miele, Bosch, Siemens and Lavazza.

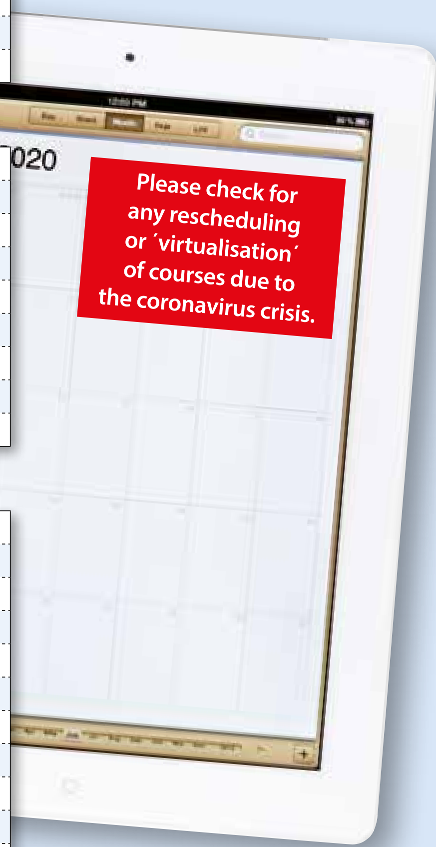
An example of precision engineering by PCV Group is the Promesso disposable pump. This gear pump is integrated into the packaging of coffee or milk concentrate and doses the exact amount every time in a hygienic manner. A big challenge in this project was the pumped liquid, as coffee concentrate contains a lot of solids and milk concentrate contains fat, proteins, sugars and calcium – each of these substances can affect pump performance.

The Fluido Compact of The Surgical Company (previously The 37Company) warms blood or fluids before administering to the patient. It needs to warm blood to a very specific output temperature, while it is not possible to obtain measurements of the temperature of the fluid while passing through the heater. Overheating of blood is not acceptable. PCV Group developed the system around the disposable heat exchanger in such a way that reliable and precise operation is guaranteed over the entire lifetime of the product.

INFORMATION
WWW.PCVGROUP.COM

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	12 April 2021
Mechatronics System Design - part 2 (MA)	5	HTI	8 November 2021
Fundamentals of Metrology	4	NPL	to be planned
Design Principles	3	MC	10 March 2021
System Architecting (S&SA)	5	HTI	1 March 2021
Design Principles for Precision Engineering (MA)	5	HTI	to be planned (Q2 2021)
Motion Control Tuning (MA)	6	HTI	14 June 2021
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	2 November 2021
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned
Actuation and Power Electronics (MA)	3	HTI	29 June 2021
Thermal Effects in Mechatronic Systems (MA)	3	HTI	to be planned
Dynamics and Modelling (MA)	3	HTI	to be planned
Manufacturability	5	LiS	to be planned
Green Belt Design for Six Sigma	4	HI	1 February 2021
RF1 Life Data Analysis and Reliability Testing	3	HI	15 March 2021
Ultra-Precision Manufacturing and Metrology	5	CRANF	19 January 2021
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	1 November 2021
Advanced Optics	6.5	MC	4 March 2021
Machine Vision for Mechatronic Systems (MA)	2	HTI	upon request
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned
Modern Optics for Optical Designers (T2Prof) - part 1	7.5	HTI	22 January 2021
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	to be planned (Q3 2021)
Tribology	4	MC	9 March 2021
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	to be planned (Q1/Q2 2021)
Experimental Techniques in Mechatronics (MA)	3	HTI	5 July 2021
Advanced Motion Control (MA)	5	HTI	11 October 2021
Advanced Feedforward & Learning Control (MA)	2	HTI	23 June 2021
Advanced Mechatronic System Design (MA)	6	HTI	to be planned (2021)
Passive Damping for High Tech Systems (MA)	3	HTI	to be planned (Q2 2021)
Finite Element Method	2	MC	to be planned
Design for Manufacturing (Schout DfM)	3	HTI	8 April 2021



ECP² program powered by euspen

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

WWW.ECP2.EU

Course providers

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

Content partners

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

New "AI-enabled Manufacturing and Maintenance" lab

Together with a number of industrial partners, Eindhoven University of Technology (TU/e) has set up a new ICAI-lab, to improve decision making in manufacturing and maintenance using artificial intelligence (AI). The new EAISI lab "AI-enabled Manufacturing and Maintenance" (AIMM) is the first ICAI-Lab in Eindhoven (NL). ICAI is a Dutch network aimed at technology and talent development between knowledge institutes, industry, and government in the area of AI.

TU/e has had a multi-disciplinary Smart Manufacturing and Maintenance research programme for several years, in order to develop better data science techniques and information from complex systems to improve manufacturing and maintenance. With the establishment of TU/e's AI institute EAISI last year and the growing trend of using AI to accomplish even more sophisticated tasks, it is an obvious evolution of the programme to establish the EAISI AIMM lab. It aims to promote research in cooperation with high-tech industry, in particular the four industrial partners Nexperia, KMWE, Marel and Lely.

As part of the initiative, seven Ph.D. candidates will perform joint research at the business partners and the TU/e. The areas of research will directly interface with topics such as autonomous agents & robotics, computer vision, decision making, information retrieval, knowledge representation & reasoning, NLP and machine learning.

It is expected that the EAISI AIMM research lab will also become a fertile starting point for new initiatives, such as developing online trainings and placing master and final year bachelor students in projects with companies. The lab will also provide companies with better access to expertise in potential AI applications such as improved planning, detecting anomalies in production, predicting quality issues and enabling fast root-cause analysis.

WWW.ICAI.AI/EINDHOVEN
WWW.TUE.NL/EAISI

Intelligent motion control platform for smart mechatronic systems

Today, much of the equipment used to perform routine tasks or to manufacture common products, are complex, so-called cyber-physical systems. Improving the whole chain of systems requires sophisticated methods to identify detailed behaviour down to the level of physics. This continuous quest nowadays gets assistance from tools that autonomously assess and analyse industrial machines, looking for potential improvements.

The EU-funded I-MECH project developed a framework to employ advanced control solutions in industrial settings. The chosen approach is known as model-based systems engineering. The project developed 11 building blocks that (among other functions) monitor or control industrial processes to find incremental improvements. One example concerns manufacturing errors in electronic hardware. Advanced algorithms can learn what type of disturbance is causing erroneous performance, identify the repetitive nature of the fault and then start compensating for it via its control logic.

To simplify the complexity of cyber-physical systems, the I-MECH team identified three layers in industrial manufacture where such algorithms could be applicable. Some of I-MECH's building blocks focus on a single layer, whereas others contribute in all three.

The lowest, called the instrumentation layer, or Layer 1, interacts with the system physically. Building blocks at this level act as sensors or actuators. The team developed several rapid sensing devices, some of which are wireless. The next level is an industrial communications bus, which consolidates all Layer 1 inputs. At this layer, the algorithms control accurate machine motion. The third, or systems, layer functions as a container for algorithms that interact with system functions and operators for factory management systems. Here, the built-in intelligence automatically calibrates the system and predicts maintenance needs.

The layered approach allows for clear interfaces between engineers having different backgrounds. Engineers at Layer 3 work with a model of Layer 2, while Layer-2 engineers use a model of Layer 1. This supports interoperability. The team applied its building blocks to five pilot applications, which use machinery developed by project partners. The applications include a generic substrate carrier, which is the conveyor component of large-format inkjet printers, and a 12" wafer stage of semiconductor manufacture. The remainder cover a teabag machine, a CNC milling machine and a healthcare robot that moves an X-ray system around the patient lying on a table.

In each case, the systems received upgrades identified by the building blocks. Eventually, all building blocks, and an entire toolchain, will be available for industrial customers, who will be able to select just the building blocks they need for their specific application. Last September, I-MECH lead partner Sioux Technologies submitted the final proposal for a successor project. That will add artificial intelligence to the existing set of building blocks, for manufacturing systems where I-MECH left off. Specifically, the new project will develop a fourth layer that facilitates orchestration of multiple systems in the same factory.

WWW.I-MECH.EU

Fibre switches for easy spectrometer upgrade

Fibre switches based on the piezo principle offer a solution for analysing different light sources in the IR to UV range with only one spectrometer. Piezosystem jena, represented in the Benelux by Te Lintelo Systems, presents fibre switches that can switch up to 9 channels within milliseconds. Controlled by high-precision piezoelectric actuators, fibre switches have no internal optical components. Therefore, they avoid any form of optical aberration and are not susceptible to magnetic interference. The switches support fibre-core diameters from 50 µm up to 600 µm. Direct fibre face-to-face coupling limits insertion loss to max. 1 dB. The small size of the switching box and the easy control make this system suitable as an add-on to spectrometers or other metrology devices, for use in a wide variety of industries, from biological research to end-product quality control.

WWW.PIEZOSYSTEM.COM
WWW.TLSBV.NL

Production of a fibre switch with multimode fibres.

ABB acquires Codian Robotics

Global technology company ABB has acquired Codian Robotics, a leading provider of delta robots, which are used primarily for high-precision pick & place applications. The offering of Codian Robotics, located in Ede (NL), includes a hygienic design line, ideal for hygiene-sensitive industries. With the transaction, ABB is accelerating its engagement in the growing field of delta robots.

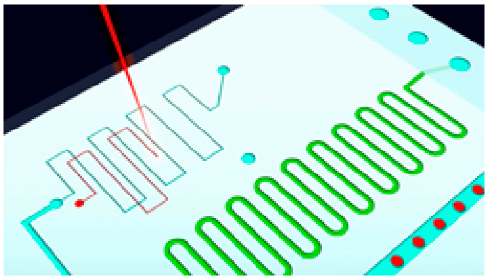
While today the majority of robots in the food and beverage industry are not designed for touching food, Codian Robotics has developed a hygienic design that allows safe, open food processing. "There is a strong need for pick & place robots that ensure high hygienic standards, accelerated by the COVID-19 pandemic. Our food & beverage, pharmaceutical and logistics customers are particularly interested in the potential of automation, enabling supply chains to continue to function, while protecting employee welfare", an ABB representative commented.

WWW.ABB.COM/ROBOTICS
WWW.CODIAN-ROBOTICS.COM

Laser printing for lab-on-a-chip production

Keiron Printing Technologies is working on a laser-printing method to create functionalities on microfluidic chips. Keiron is an Eindhoven-based start-up building the next-generation microfabrication machine, enabling its users to deposit almost any material on any substrate. It was founded in 2019 together with TNO Holst Centre and HighTechXL, aspiring to further develop and market the laser-printing technology researched and validated by Holst Centre. Last September, the start-up took part in the HighTechXL programme, which builds companies around existing and yet to be developed 'deep-tech'.

A microfluidic chip can be used to study liquids and gases on a micrometer scale, acting as a 'lab-on-a-chip' that has, for example, blood running through the chip and reacting to a diabetes test.



Direct-write laser-printing technology beats existing methods of microfluidic chip production on the market, with superior flexibility, speeds and resolutions, so Keiron claims.

This technology can save an enormous amount of time in the hospital and Keiron's ultimate goal is to make it available for testing at home. The aim is to develop a production method that is affordable, flexible, and scalable. On an empty chip, there are all sorts of mini-channels, connected to a point where liquids come together. A laser prints functionalities over the test lanes on the chip, as it were, for controlling the flow of the liquids. Holst Centre worked on this technology for ten years. Now, Keiron is developing a first machine that can produce microfluidic chips. Market entry is scheduled for 2025.

WWW.KEIRONTECHNOLOGIES.COM

Multi-axis controller for highly dynamic positioning

Maxon has launched its next generation of motion controllers with its new multi-axis MiniMACS6-AMP-4/50/10. The controller is ideal for use in applications where PLC solutions may be too expensive or cannot meet customer-specific requirements. It offers precise and highly dynamic control of up to six brushed DC motors or four brushless DC motors (up to 540 W continuous output power and 1.6 kW peak output power). The controller is an economical and compact solution for system designers who develop autonomous robots or shuttle systems. The new multi-axis solution is programmable with the comprehensive ApossIDE automation software and the license-free Motion Control Library (written in C).

WWW.MAXONGROUP.COM

Strategic partnership for high-throughput scanning probe metrology

Nearfield Instruments (NFI) and Technolution Advance have signed a memorandum of understanding to establish a strategic partnership for delivery and value engineering of several critical electronics modules for NFI's series products, starting with the QUADRA product line.

NFI, founded in 2016 as a TNO spin-off and located in Rotterdam (NL), develops innovative metrology solutions the semiconductor industry requires for current- and next-generation device manufacturing. Now, it has realised its first semiconductor metrology product, named QUADRA, based on the revolutionary mechatronics architecture of HT-SPM (high-throughput scanning probe metrology). HT-SPM enables an entirely new approach to in-line 3D process control metrology for both wafer fab process window discovery as well as process window expansion & control. QUADRA provides unique, angstrom-level precise, non-destructive high-aspect-ratio 3D metrology on even the most challenging critical layers, such as Gate and FinFET structures.

As NFI is preparing for series production, it has entered into a strategic partnership with Technolution Advance. Under its Advance brand, electronics and software integrator Technolution, headquartered in Gouda (NL), creates solutions for high-tech applications for the semiconductor industry and leading scientific institutions. Technolution Advance will develop, industrialise, and deliver QUADRA modules, with a focus on improving manufacturability, value engineering, SEMI compliancy and performance enhancement, closely related to NFI's product roadmap.

QUADRA, Nearfield Instruments' first semiconductor metrology product.

WWW.NEARFIELDINSTRUMENTS.COM
WWW.TECHNOLUTION.NL

Additive manufacturing is growing big

Additive Industries, developer and manufacturer of 3D metal printers for industrial manufacturing, has announced the development of its new flagship model MetalFAB-600. The company expects to present the new model towards the end of 2021.

The MetalFAB-600 will offer a build size of 600 mm x 600 mm and 1,000 mm Z-height, one of the largest volumes in the industry, and five times larger in volume than Additive Industries' current MetalFAB1, that already offers 420 mm x 420 mm x 400 mm. The MetalFAB-600 will work with a deposition rate up to 1,000 cc/hour, using ten 1-kW lasers. It is developed on a platform that allows even further expansion of the build volume and productivity in the future.

The MetalFAB-600 will build upon the knowledge and experience gained with the MetalFAB1 in robustness and automating key production processes. The automation will focus on powder handling, alignments and calibrations to ensure the highest possible output. The MetalFAB-600 is designed to achieve the lowest cost per part, targeting traditional casting and machining industry.

In view of the importance of this project, and other projects on the development roadmap of Additive Industries, acting CEO Mark Vaes will reassume his role as CTO and manage the development team of the MetalFAB-600. Vaes combined both roles over the past few months. Jonas Wintermans, co-founder of the company, will step in as acting CEO. To support the company's growth and development ambitions, Highlands Beheer, the Wintermans family investment company, has invested and committed a total of 28 million euros in 2020.

In addition, Additive Industries and Makino, a manufacturer of high-quality milling machines, signed a letter of intent last month, for a joint project to develop integrated process chains anticipating the upscaling of industrialised additive manufacturing. Instead of treating additive manufacturing of metal parts and post-processing as separate processes, the two companies aim to develop a hybrid process chain where their technologies seamlessly work together.

WWW.ADDITIVEINDUSTRIES.COM

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TBRM Engineering solutions (previously Segula Technologies Nederland B.V) is part of the TBRM Group. TBRM-ES is an engineering company which operates internationally and aims at supporting customers by providing services from consultancy to complete project solutions including delivery of hardware, which are carried out either at the customer's location or at TBRM-ES.

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