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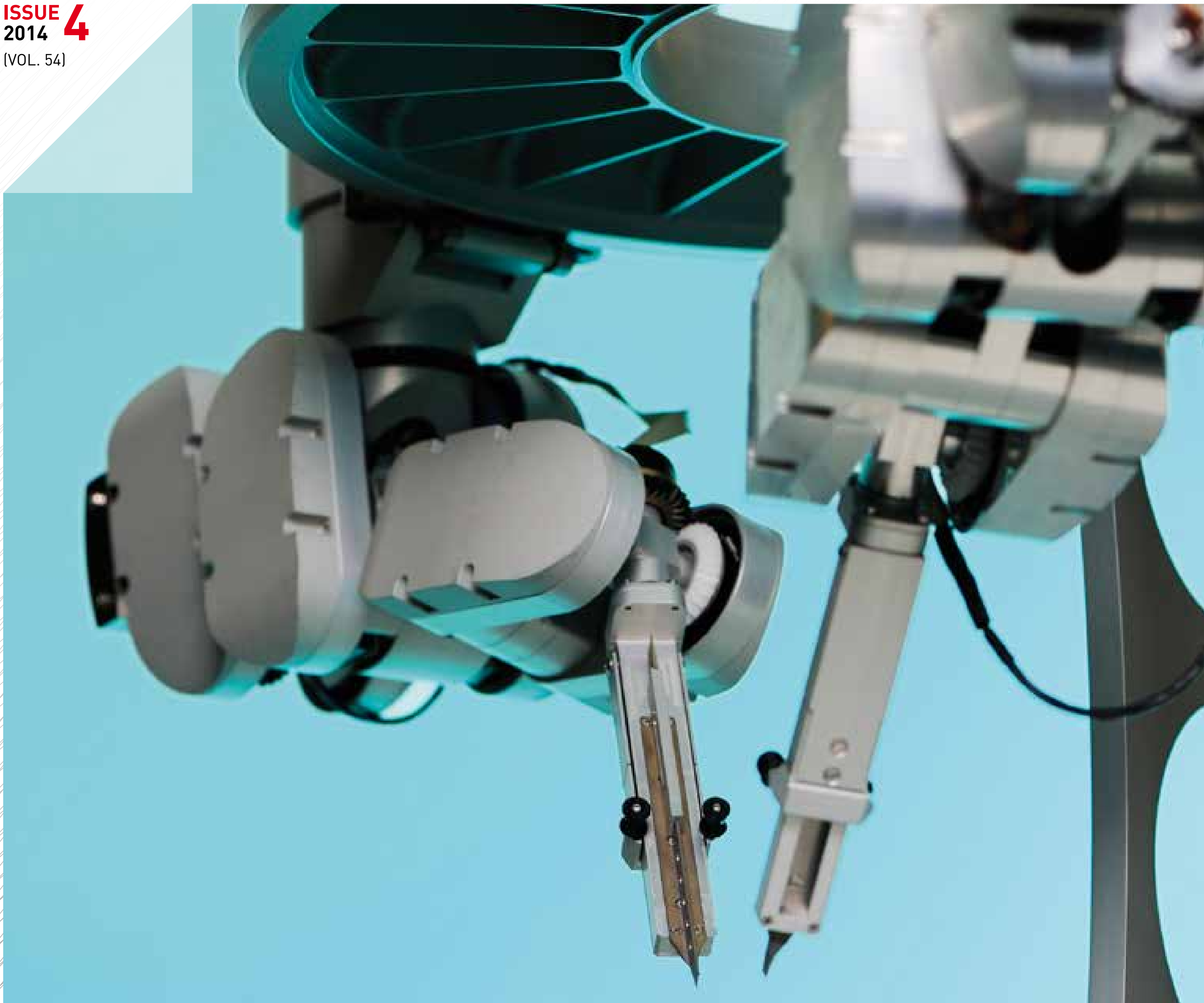
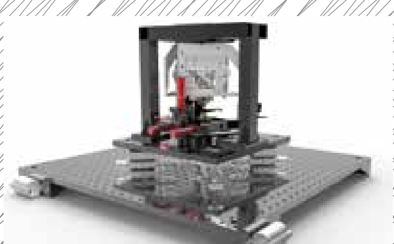
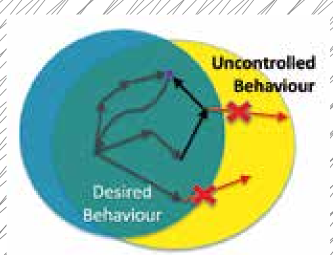
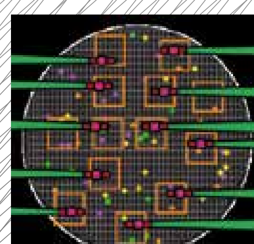


- HIGH-PRECISION **SURGICAL ROBOT**
- **DIE-BONDING** MODELLING AND CONTROL
- **PHOTOCHEMICAL ETCHING** OF ALUMINIUM
- **DSPE CONFERENCE 2014** CATALOGUE







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The main cover photo (MicroSure surgical robot system) is courtesy of Bart van Overbeeke.

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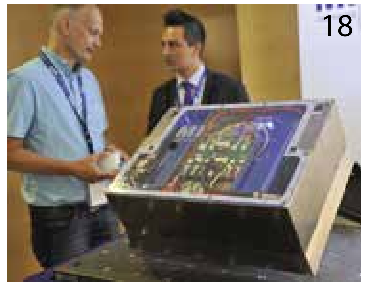

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FEATURES

INTERNATIONALISATION MADE TO MEASURE

Internationalisation is a prominent issue in any university's policy. Rightfully so, because science is a global business, certainly with open access becoming more general. Yet the action points tend to focus on attracting M.Sc. students and comparison with universities abroad. While certainly important for the financial situation and reputation of our universities, it is also interesting to take a view from the ground, i.e. the daily business of a research group. A quick CV scan of a group's population learns that a typical postdoctoral researcher has B.Sc. and M.Sc. degrees from different universities, sometimes even from different countries, obtained a Ph.D. at another continent, oftentimes naturalised in the host country, and had various short stays at yet other institutions in other remote countries. This type of international exposure is deemed increasingly important, for instance to obtain personal grants such as an NWO Veni.

I tell my students to not take me as an example. For someone born in Hengelo, the Netherlands, it may have been some step to study at Delft but for the rest my international mobility has been limited to two six-month research stays abroad. I did develop a variety of international activities though, and surely these stays and activities have meant a lot to me personally, my career and my view on academia.
For all of these reasons I encourage my students to go out and explore. Indeed, an important responsibility of the university is to put young people in a profitable starting position for their career, B.Sc., M.Sc., Ph.D. students and young entrepreneurs alike. Many students do part of their M.Sc. graduation at befriended labs abroad, often resulting in a joint paper. For those not able to go out there are other options, such as organising international symposia. Either way, it is a valuable experience: the contacts, the way things work in another academic group, managing the project, and handling the independence, which after all is the main assessment criterion for any academic degree.

Arranging an international stay, however, is not always easy. Particularly, finance is usually not trivial, even for Ph.D. students on a funded project. Travel budget is limited and not tailored to stays other than a regular conference. There are some grants to fill this gap, but not too many. Given the importance we attach to international experience, it would be appropriate to make funding available to this end. Conversely, if we are sending our students all over the world, it is not more than appropriate to host roughly as many foreign students over here. Financially this tends to be even more difficult. Budgetting a few thousand euros annually for each Ph.D. project would already be a great step.

In spite of its importance, internationalisation is not a guarantee or necessity for success. This holds for individuals, but also for conferences or scientific organisations. This is evident from the same quick CV scan but now focussing on the higher ranked faculty, where one finds among many foreign names also many reputable individuals with steady positions at the same institute throughout their career. By the way, at home they provide a firm base for internationalisation. It is also clear from the many highly valued conferences organised by national professional or scientific bodies. One such example is the biennial DSPE conference, which stands out in the plethora of international conferences by a clear focus on high-tech industry. In all other respects it has the components of a regular scientific conference, but keeping this focus will strengthen its position and it will see rising interest across industry and academia.

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MICROSURE, FOR MAXIMUM SAFETY

Robotic technology is regarded by microsurgeons as a high-potential solution. In 2008, a Dutch collaboration between Maastricht University Medical Centre and Eindhoven University of Technology was set up to develop a new 7-DoF (degree of freedom) robotic system specifically for microsurgery. This has led to the realisation of a prototype, which is now being developed by spin-off company MicroSure.

RAIMONDO CAU AND FERRY SCHOENMAKERS

(Photo: Bart van Overbeeke)

Breast cancer is the world's most frequently occurring type of cancer among women. One out of nine women will, at some point in her life, be affected by this disease. In the Netherlands, this amounts to 14.000 new cases of breast cancer each year. In half of these cases, treatment is done by completely removing one or both breasts. After the amputation, these patients can apply for surgical reconstruction of the breast.

Patients are able to choose between several reconstruction options. The simplest option is to use a prosthetic breast, i.e. a plastic breast that is worn against the body. Another option is to insert silicone implants at the site of the defect. Since silicone is a foreign material, the implant feels and behaves unnaturally and will be encapsulated by the surrounding tissue. In the long term, i.e. after five to ten years, silicone implants can cause pain or irritation and need to be replaced. A more natural approach would be to reconstruct the breast by using the patient's own tissue.

AUTHORS' NOTE

Raimondo Cau obtained his Ph.D. [1] with Prof. Maarten Steinbuch of the Control Systems Technology (CST) group in the Department of Mechanical Engineering, Eindhoven University of Technology (TU/e), the Netherlands. Ferry Schoenmakers holds an M.Sc. in Mechanical Engineering, obtained within the same group. They both now work at TU/e spin-off MicroSure, under the umbrella of Medical Robotic Technologies, which develops robotic technology for medical applications, starting from research results of the CST group.

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In these procedures a piece of skin and fat tissue, including supply vessels and nerves, is dissected from a part of the body where it is less needed, e.g. the belly or buttocks. The tissue is then reattached at the site of the amputation. Small nerves and blood vessels (Ø 1.0-2.0 mm) are reconnected to restore circulation and sensation. The tissue is then remodelled to the shape of the original breast. The result is a new 'living' breast similar to the rest of the body.

Leading microsurgeons have indicated a trend of increasing demand for this type of surgical procedures, yet an increasing shortage of surgical capacity. The most difficult part of these procedures is to reconnect the blood vessels and nerves, using a surgical needle and suture wire of Ø 0.1 mm or smaller. This is done manually by two collaborating microsurgeons using a microscope and very fine instruments (Figure 1). Concentration and precision are essential. Microsurgical techniques demand specific knowledge, dexterity, and an extremely steady hand.

1 Conventional microsurgical set-up showing two microsurgeons operating cooperatively using a shared microscope and microsurgical instruments.

2 Intuitive Surgical's DaVinci system consists of a large slave device controlled by surgeons working through a console. Its limited precision makes it unsuitable for microsurgery.

Microsurgery is not only applied during breast reconstruction, but also in recovery procedures for other types of cancer patients, victims of severe accidents, burn wounds, and congenital birth defects. Per year up to 5,000 microsurgical procedures are performed in the Netherlands alone. This number should be higher, but is limited by surgical capacity.

Young microsurgeons lack dexterity and experience to perform complex procedures, while manual precision of aging surgeons is deteriorated by hand tremor. This leads to a small number of surgeons actually capable of performing microsurgery, and correspondingly long waiting lists. Until they can be treated, patients are required to live with a handicap, causing physical discomfort and inability to work.

Aside from that, there are limits to the precision that can be achieved using conventional (manual) microsurgical techniques. Vessels and nerves smaller than 1.0 mm cannot be restored. For instance, the repair of lymphatic vessels after cancer treatment is currently impossible, leading to painfully swollen limbs and reduced joint flexibility among many patients. The only treatment option is wearing compression garments and frequent surgical draining of lymphatic fluid build-ups. Following the trend of less-invasive treatment methods and faster recovery, it is becoming more important to perform targeted and accurate surgical procedures. To continue this progress in surgical treatment, technological assistance can provide a solution.

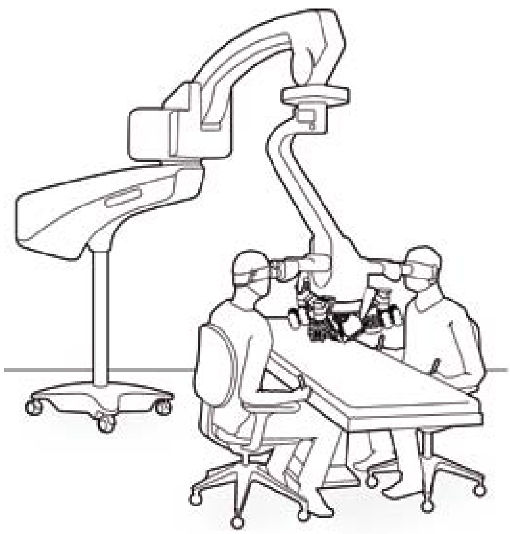
Robotic technology

These days, robotic technology provides an opportunity to enhance surgical capacity. The main advantages offered by such mechatronic systems are their precision and reproducibility. In a telemanipulator set-up, a robotic arm behaves as a slave device, to be controlled in real time by a surgeon through a master device. This configuration allows implementation of performance-enhancing control software between the operator and workspace. A motion scale factor between the master and slave makes it easier to perform microscale manipulation. Moreover, tremor and other undesired movements at the master device can be filtered out. In this way, a surgeon operating through a telemanipulator system is able to perform beyond human capabilities.

In 2007, plastic surgeon Prof. Van der Hulst used the DaVinci surgical robot system to perform the world's first robot-assisted breast reconstruction. The master-slave set-up was found to be particularly useful in reducing tremor and facilitating the procedure in terms of ergonomics and accessibility. The operating time was twice as long as before, and the surgical outcome of the procedure was not significantly improved.

The DaVinci was developed for laparoscopic procedures. Its long and slender instruments need support points on the patient's body to achieve good performance. Even then, its positioning error is in the range of 1.0-2.0 mm, which is sufficient for its original purpose. The system is not suitable for microsurgical procedures, which require a reproducible absolute positioning error down to 0.1 mm. The 1.8 million dollar device currently also lacks true microsurgical instruments, capable of handling microneedles and sutures. The size and weight of the system (550 kg for the slave device) require drastic changes in operating room set-up and surgical workflow for the entire surgical staff (Figure 2).

Recent publications have pointed out that when compared to a manual approach, the use of a DaVinci robot leads to higher cost of surgery, whereas results are not significantly improved. Still, robotic technology is regarded by microsurgeons as a high-potential solution. This is



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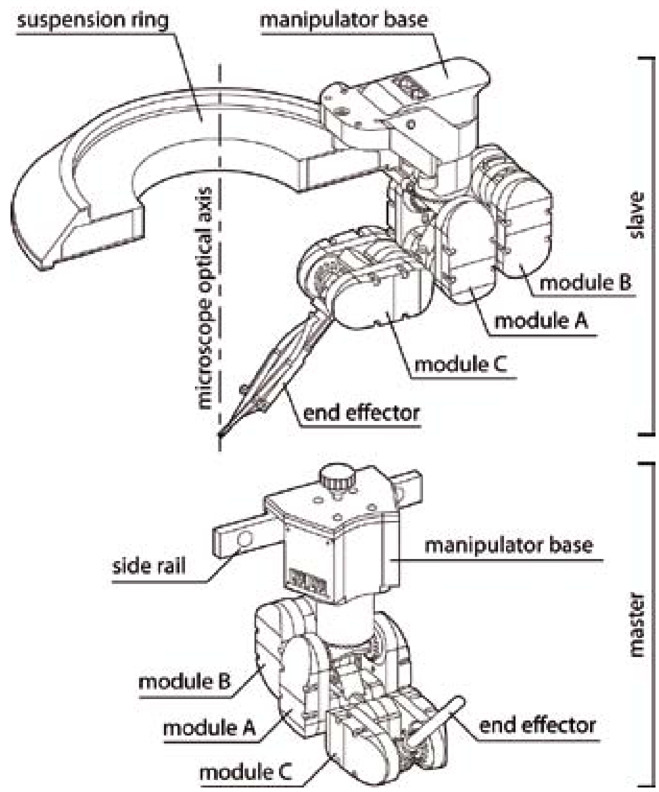

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especially true for procedures that require performance close to the limits of human capability, or are impossible to do by hand. In these cases, robotic assistance can facilitate procedures by offering superhuman precision and better accessibility to hard-to-reach surgical sites. In 2008, a collaboration between Maastricht UMC (University Medical Centre) and Eindhoven University of Technology (TU/e) was set up to develop a new low-cost, yet high-precision 7-DoF (degree of freedom) robotic system specifically for microsurgery, called MicroSure.

Performance requirements

An analysis of conventional microsurgical techniques has been performed to determine the minimum performance requirements for the MicroSure robot, as shown in Table 1. The novel system combines proven methods of conventional microsurgery with the benefits offered by robotic technology. A large number of design specifications and attributes are left identical to those belonging to conventional microsurgery, thus creating an intuitive system that is easily implemented into the operating room. The size and weight of the system are deliberately kept small, such that it does not require any significant changes in operating room layout and planning.

3 *The MicroSure system consists of up to four slave manipulators suspended above the patient by a suspension ring mounted to the microscope. Surgeons control the robotic arms by master manipulators mounted to the side rail of the operating table.*

4 *Master and slave manipulators are identical and consist of three identical, serially linked 2-DoF drive-train modules (A, B, and C).*

Design

MicroSure's design principles revolve around three key features, found in this order: safety, ease of use, and cost efficiency. The system can be configured in a variety of set-ups. A set-up consists of up to four master-slave combinations, in which the master manipulators are mounted to the surgical table and the slave manipulators are mounted to a suspension ring, as shown in Figure 3.

Table 1 *Performance requirements of the MicroSure robot, compared to conventional microsurgery.*

	Conventional microsurgery	MicroSure robot
Precision	0.15 mm	0.05 mm
Controllable DoFs	7 [a]	7
Number of manipulators	Up to 4	Up to 4
Type of instruments	Microsurgical instrument set, sterilisable	Microsurgical instrument set, sterilisable
Vision	Surgical microscope	Surgical microscope
Motion scaling	-	5-100%
Tremor filtering	-	> 4 Hz
Size	-	450 x 450 x 300 mm^3
Mass	-	< 10 kg

[a] Measured from the surgeon's wrist.

5 *Left: master interface with simulated surgical forceps handles. Right: Slave manipulator with genuine microsurgical instrument.*

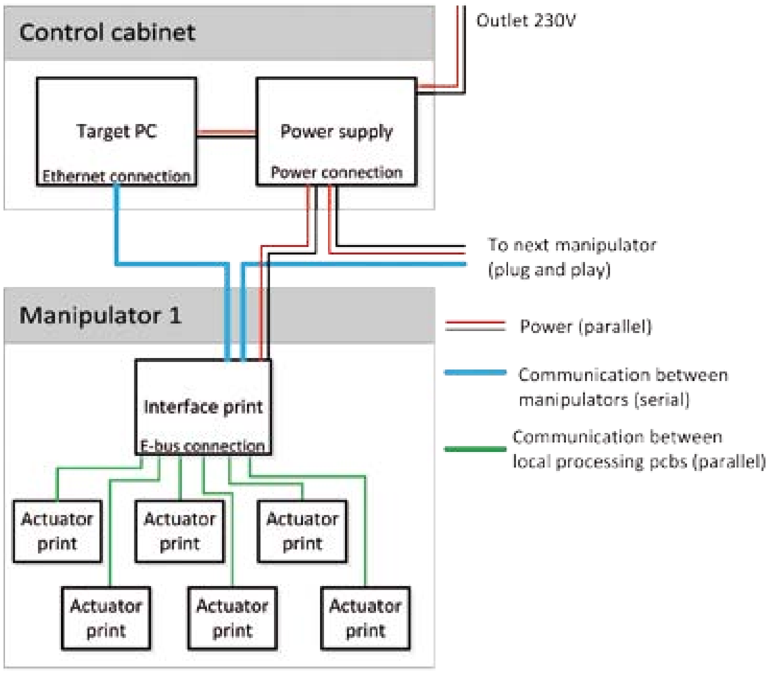
6 *Manufacturing of the first prototype by the TU/e EPC.*

Compared to conventional microsurgery, the surgeons remain seated close to the patient. This allows them to use the existing surgical microscope, but also provides a safety barrier. The surgeon has a direct view of the patient and the operation site, at all times. In case of failure of any of the system's components, the surgeon is able to quickly switch to a manual approach.
The system is modular; allowing e.g. single-handed, double-handed, or multi-person robotic assistance, depending on what is actually required during a certain surgical procedure. Slave manipulators can easily be attached to, or removed from, a suspension ring mounted to a standard surgical microscope. Master devices are attachable to the side rail of the operating table. Master and slave kinematic layouts are identical, forming compact and lightweight (1.5 kg) manipulators. Each manipulator consists of three identical, serially linked, fully backdrivable 2-DoF drive-train modules as shown in Figure 4.

The slave manipulator holds and actuates a genuine microsurgical instrument, whereas the master interface simulates the handles of surgical forceps; see Figure 5. The kinematic order of the three drive-train modules is based on the kinematics of a human hand holding a microsurgical instrument, whereas the wrist of the hand is held steady. The layout of the manipulator links is such, that six out of seven DoFs are unaffected by gravity, without using additional balancing mass. Each drive-train module contains a differential gear, producing a pitch and roll motion of the next module.

A drive-train module contains two dc motors, each of which drives one side of the differential gear via a transmission. Driving both motors in the same direction produces a rotation of the outgoing gear around the roll axis. Driving them in opposite directions causes the outgoing gear to rotate around the pitch axis. Rotations are measured by two absolute optical encoders, and verified by a pair of redundant secondary incremental encoders.

The patented design is optimised toward minimal manufacturing costs, by reducing the amount of components on the part list and using commonly available stock products as much as possible. The first prototype (Figure 6) has been manufactured by the TU/e Equipment & Prototype Center (EPC), with production costs a factor 20 smaller than the selling price of currently available surgical robots.



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Control

To minimise wiring and provide a robust, cost-effective and reliable system, the EtherCAT protocol was adopted for real-time communication between masters, slaves and control pc. All data acquisition, signal processing and motor current amplification is done on the robot's modules. A standard Ethernet cable between the devices transmits all the required digital signals in real-time at 4 kHz. A single power line runs from the control cabinet to all devices and no other cabling is needed.

7 *Overview of the system interface.*

8 *The author demonstrating the MicroSure prototype.*

8

A master or slave device contains one central processing PCB to transfer data over standard Ethernet. Via E-Bus the central processing PCB is linked to six identical actuator PCBs inside the manipulator, which take care of local control for each DoF. Figure 7 provides a schematic overview of the interfacing.

Each DoF is controlled by a feedback control loop, using an absolute optical encoder and a dc motor. A feed-forward controller compensates for gravity and provides an advanced position-dependent friction correction. This leads to a relative tracking error between the master and slave manipulator equal to 50 μm at the end-effector.

Into the clinic

The MicroSure system is compatible with surgical equipment already present in the operating room and does not take up any extra floor area. This causes the surgical methodology and infrastructure in the operating room to remain unchanged. Moreover, the hospital is able to clean and sterilise the instruments used by the robot. The result is a high-tech solution with low implementation and operational costs for hospitals.

Currently, the prototype is being developed further (Figure 8). In collaboration with leading microsurgeons, the device is being tested in a clinical setting at Maastricht UMC. The first clinical test results are expected this year.

Using the MicroSure robot, surgical capacity can be increased by offering more surgeons the ability to perform microsurgery. Moreover, the microsurgical robot allows the hospital to develop and offer new, more complex and more accurate microsurgical procedures that are currently impossible to perform by hand. This means that quality of healthcare can be improved by performing more procedures, thus treating more patients, and simultaneously reducing waiting lists. ■

REFERENCE

[1] R. Cau, *Design and realization of a master-slave system for reconstructive microsurgery*, Ph.D. thesis, Eindhoven University of Technology, ISBN: 978-90-386-3551-4, 2013.

MODEL-BASED DESIGN AND SERVO-CONTROL SIMULATIONS

SEGULA Technologies Netherlands is developing a machine for automatic high-precision bonding of miniature semiconductor components (dies). The bonding is realised by a low-temperature solder connection. This article covers the thermal processes taking place during the die-bonding, a model-based design of the machine components dedicated to these processes, and the results of servo-control simulations that illustrate the quality of the design.

DRAGAN KOSTIĆ, İSA ERTÜRK AND HENK NIJMEIJER

Introduction

Development of advanced mechatronics systems, such as high-precision robot arms, fast printers, and intelligent vehicles, is a priority business for SEGULA Technologies Netherlands. These systems usually feature servo-controlled processes characterised by multiple simultaneous physical phenomena and diverse interaction mechanisms. An illustrative example is a machine for high-precision bonding of miniature semiconductor components (dies) [1], depicted in Figure 1. This machine bonds pairs of dies in an automatic way using eutectic soldering, and is composed of several modules. The Feed-in Module provides die pairs to the nozzles in the Heating-clamping Module, one of which is handled by the Position Module. The relative *xy* positions between the dies are measured by the Measurement Module, a mirror-lens-camera system.

The Position Module utilises the measurement to accurately align the dies in the *x*- and *y*-directions. After position alignment, the Z Force Module brings the dies to contact with each other in the vertical direction and provides an adequate contact force. Meanwhile, the heaters rapidly heat up the dies via the nozzles until a setpoint bonding temperature is reached. The temperatures of the dies are kept within narrow bands around the setpoint until solder material is melted. After the bonding is accomplished, rapid cooling takes place to reduce the nozzle temperatures to the acceptable levels for further processing steps. Bonding is performed in a highly conditioned environment with tight limits on humidity, pressure, temperature, particle contamination and mechanical interferences.

Thermodynamics and temperature control of the die-bonding process are described in this paper. This process is a multi-physical problem due to interaction between thermal and mechanical dynamics, as well as motion and force servo-control algorithms. To predict interactions among different physical domains and to facilitate the achievement of challenging thermal and positioning requirements, SEGULA carries out product development in systematic and theoretically sound fashion. In particular, it incorporates various advanced model-based design and

AUTHORS' NOTE

Dragan Kostić (Ph.D. thesis, "Data-driven Robot Motion Control Design", Eindhoven University of Technology (TU/e), the Netherlands, 2004) is a mechatronics architect. İsa Ertürk (Ph.D. thesis, "Modelling creep and anelasticity in particle strengthened alloys with strain gradient crystal plasticity", TU/e, 2012) is a CAE specialist. They both work for SEGULA Technologies Netherlands, based in Eindhoven. Prof. Henk Nijmeijer is head of the Section Dynamics and Control at the Department of Mechanical Engineering at TU/e.

This article covers in detail several topics addressed at the DSPE Conference 2014 poster presentation "Model-based development of die-bonding machine".

SEGULA Technologies Netherlands is a developer of advanced intelligent systems for high-tech and automotive industries in the Benelux. As a project organisation, the company applies knowledge of system architecture and modelling, mechanics, mechatronics, electronics, software, system integration, and calibration, to the design of nonlinear mechatronic systems. Spearheads include thermal and flow control, robotics and the development of autonomous multi-physics systems.

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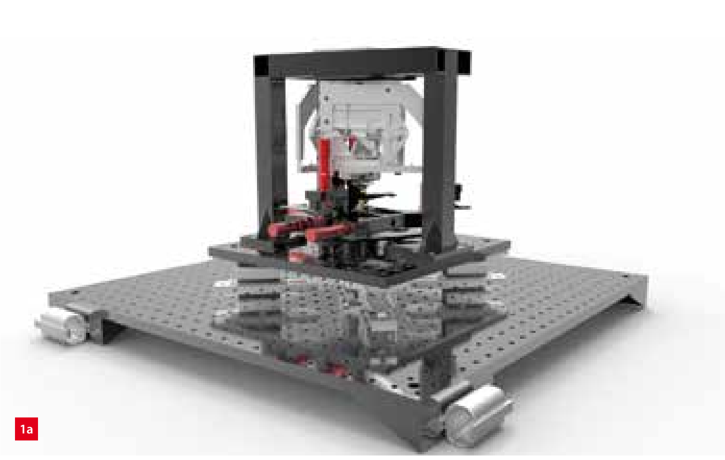
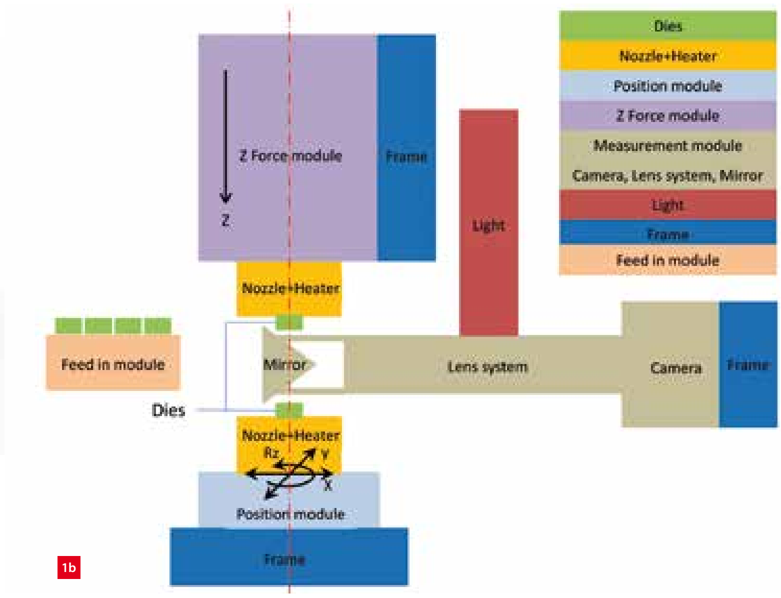




analysis techniques, including CAD, FEM (finite-element modelling), model-based control, dynamical and servo-control simulations. This paper illustrates the model-based approach.

The rest of the paper is organised as follows. The system components that are relevant for the thermal processes are described first. Then, the FEM and analytical models of these components are presented. The consistency between these models is verified in the time domain. After that, a model-based control design for the heating phase of the die-bonding process is explained. The quality of this design is illustrated by servo-control simulations. Finally, the conclusions and future perspectives are presented.

Key components for thermal processes

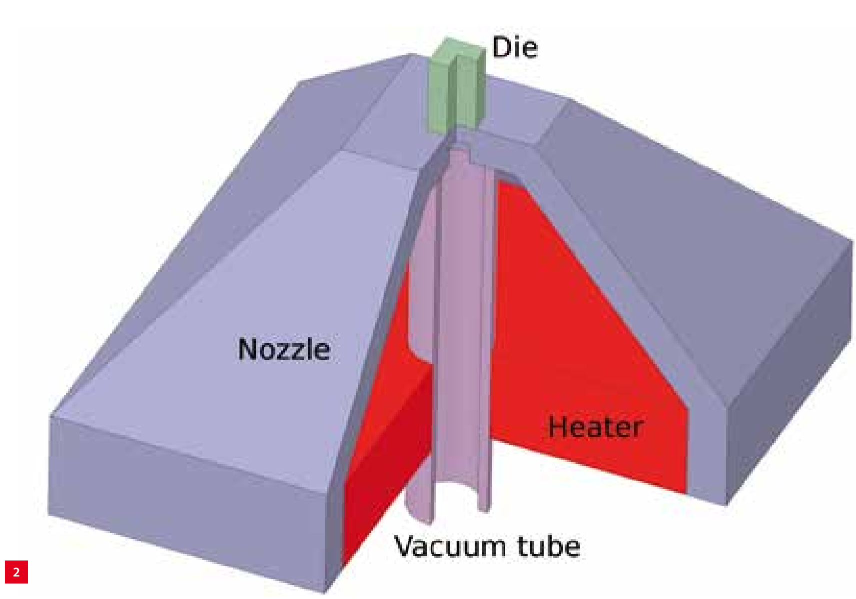
The key components for thermal processes in the bonding machine are shown in Figure 2 and explained below:

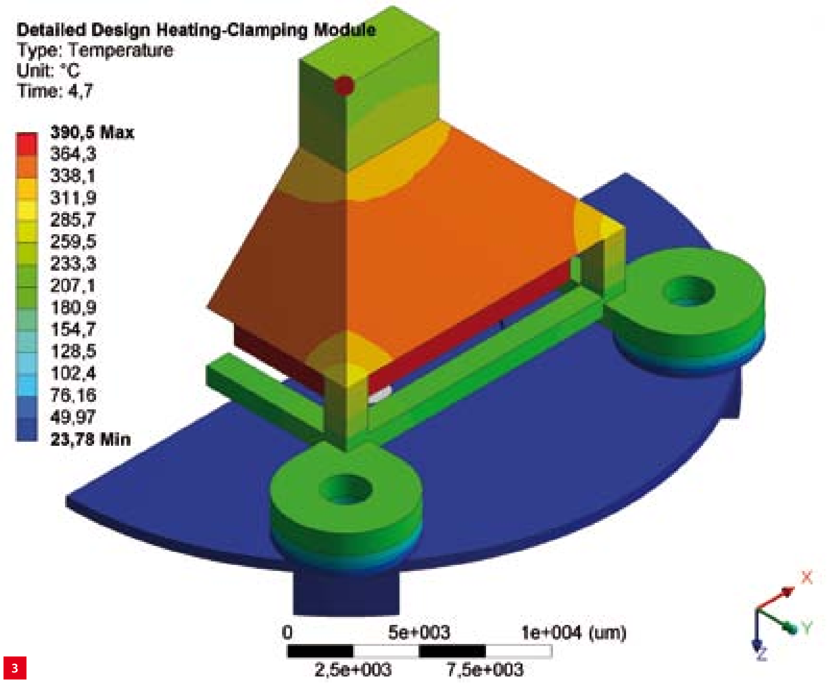
1. The die is a silicon semiconductor component with maximum dimensions of 1 mm, 1 mm and 2 mm in *x*-, *y*- and *z*-directions, respectively. For thermal analyses, it is modelled as a solid of fused silica.
2. Ultramic advanced ceramic heaters of Watlow [2] are used to heat up the dies according to the prescribed temperature setpoint profile. These heaters are made of aluminium nitride and feature negligible temperature gradients within their volume of 12 mm, 12 mm and 2.5 mm in *x*-, *y*- and *z*-directions, respectively. The maximum input power, rate of temperature rise, and operating temperature of these heaters are 200 W, 150 °C/s and 400 °C, respectively. The heaters are glued to the nozzles with a highly conductive thermal paste.
3. The aluminium nozzles hold the dies and transfer the heat from the heaters to the dies. They have a hollow pyramid shape with a flat top. Their inner surfaces are anodised and the outer ones are polished. Hence, both surfaces show low emissivity, which in turn reduces radiation to the environment. The heat is transferred to the dies mainly via conduction.
4. An aluminium vacuum tube is inserted in the nozzles through a central hole in the heaters to supply vacuum for holding the dies tight. The vacuum tube is welded to the nozzle. It has a glued contact with the heater, wherein a thermal paste is used to enhance the conductivity.

1 Machine for automatic die-bonding.
(a) Rendering.
(b) Schematics.

2. Components of the Heating-clamping Module with cross section.

The components described above are modelled in ANSYS [3] and Matlab/Simulink [4] for thermal finite-element analyses (FEA), time- and frequency-domain dynamical analysis, as well as servo-control simulations.





3 *Temperature profile near the steady state, from a transient thermal finite-element simulation. A detailed design is shown including interfaces with the other modules. Only half of the structure is modelled due to symmetry about the y-plane.*

Thermal analysis

The thermal analysis methodology discussed here constitutes a portion of SEGULA's product development strategy aiming at "first time right" products without failure costs. Similar methodology is also successfully applied for the thermal analysis of wind turbines and substrate carriers in other projects. Modelling material and structural anisotropy, thermal contact conductivities and inhomogeneous boundary conditions play a significant role in capturing thermal behaviour of the structure. The FEA is used to reveal the dominant heat transfer mechanisms and main heat transfer paths. Simultaneously, the 1D thermal circuit models are used for the first-order estimation of the heat transfers, efficient time simulations, and servo-control designs.

Due to the die-bonding machine's complex 3D geometry, it is not straightforward to fully describe its heat transfer with a low-dimensional analytical model. This problem can be overcome using FEM, which facilitates the incorporation of relevant heat transfer modes (i.e. conduction, convection and radiation) and non-linear parameters such as temperature-dependent thermal conductivity and thermal contact resistances. The relative contribution of different heat transfer mechanisms to the overall machine thermodynamics can be determined by an FEA. Based on the outcome, a low-dimensional analytical model is derived, which is required for time-efficient simulations of the machine thermodynamics and servo-control design.

FEA

The quality of FEM results strongly depends on the type of the elements used and the mesh density, which are to be optimised for the desired accuracy and computational cost. A conceptual design of the Heating-clamping Module is shown in Figure 2. The module is meshed with linear hexahedral elements. The assembly is kept in an environment of inert gas (e.g. nitrogen), which is suitable for eutectic soldering. The small volume of stationary air trapped inside the nozzle is explicitly modelled to take into account the conduction through air. Natural convection is considered in the inert gas environment. Radiation to the environment and enclosure radiation are considered on the outer and inner surfaces of the components, respectively. The heater is activated at its full power. The initial temperature of the bodies is equal to room temperature; the same holds for the fluid and environment temperatures.

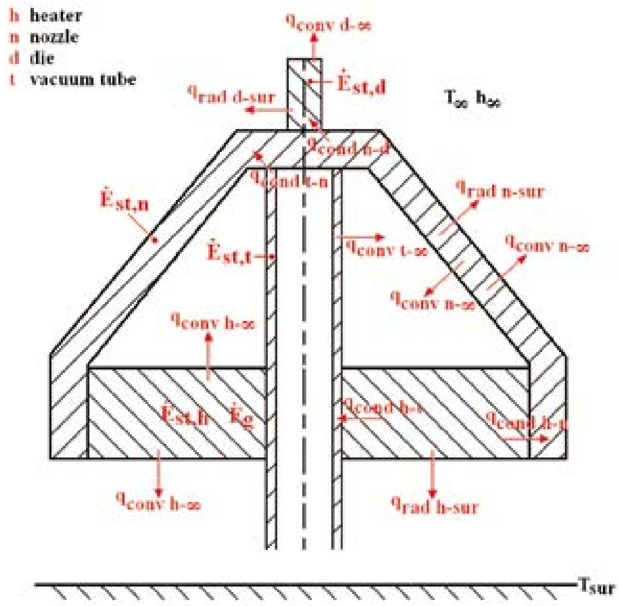
A transient thermal analysis is performed. The resulting temperature distribution when the setpoint temperature is reached is shown in Figure 3. Since the corner points at the top of the die are characterised by the lowest temperature in the die, one of these points (in brown) is taken as the most critical one for the thermal analyses. A mesh sensitivity study shows that a similar temperature distribution is obtained when quadratic elements with half of the current element size are used; the maximum temperature difference remains below 0.5 C, which is an acceptable precision for all relevant thermodynamics and heat transfers of the die-bonding process.

Analytical modelling

The various heat transfer modes, i.e. conduction, convection and radiation, are indicated in Figure 4; these modes have to be captured by analytical modelling. An analytical model is a set of differential equations derived from formal principles of thermodynamics [5]. The derivation can be simplified based on the following assumptions, each being justified using FEA:

- thermal parameters are considered to be constant (time-varying ones are set to their mean values);
- the fluid surrounding the assembly is sealed; it is stationary and has a constant volume;
- the influence of the vacuum tube can be neglected;
- enclosure radiation can be omitted;
- the temperature of the fluid (surface) T_{sur} is equal to the temperature of the environment T_∞: $T_{sur} = T_\infty$.

Heat diffusion can be interpreted in a way analogous to the conduction of electric charges. A thermal resistance represents the ratio between a driving potential and the corresponding heat transfer rate. The equivalent thermal circuit for the Heating-clamping Module is shown in



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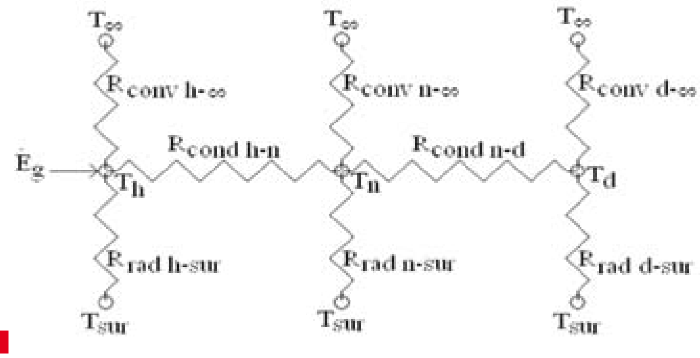

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Figure 5. Using this figure and the first law of thermodynamics (conservation of energy) [5], energy-balance equations are written for the heater, nozzle and die:

$$m_h c_{p,h} \dot{T}_h = \dot{E}_g - \frac{T_h - T_n}{R_{cond,h\to n}} - \frac{T_h - T_\infty}{R_{conv,h\to\infty}} - \frac{(T_h)^4 - (T_{sur})^4}{R_{rad,h\to sur}},$$
$$m_n c_{p,n} \dot{T}_n = \frac{T_h - T_n}{R_{cond,h\to n}} - \frac{T_n - T_d}{R_{cond,n\to d}} - \frac{T_n - T_\infty}{R_{conv,n\to\infty}} - \frac{(T_n)^4 - (T_{sur})^4}{R_{rad,n\to sur}},$$
$$m_d c_{p,d} \dot{T}_d = \frac{T_n - T_d}{R_{cond,n\to d}} - \frac{T_d - T_\infty}{R_{conv,d\to\infty}} - \frac{(T_d)^4 - (T_{sur})^4}{R_{rad,d\to sur}}.$$

Here, subscript $\alpha \in \{h, n, d\}$ identifies component such that h stands for the heater, n for the nozzle and d for the die. T_α, m_α, and $c_{p,\alpha}$ denote temperature, mass, and heat capacity, respectively, of component α. $\dot{T}_\alpha$ is the time-derivative of T_α and $\dot{E}_g$ is the rate of thermal energy generation. $R_{cond,\alpha\to\beta}$, $R_{conv,\alpha\to\beta}$, and $R_{rad,\alpha\to\beta}$ are resistances to conduction, convection, and radiation, respectively, from component α to medium $\beta \in \{h, n, d, sur, \infty\}$, where sur indicates the fluid and ∞ the environment. The above analytical equations are implemented in Matlab/Simulink for time-efficient simulations of the system thermodynamics and servo-control design.

Model verification

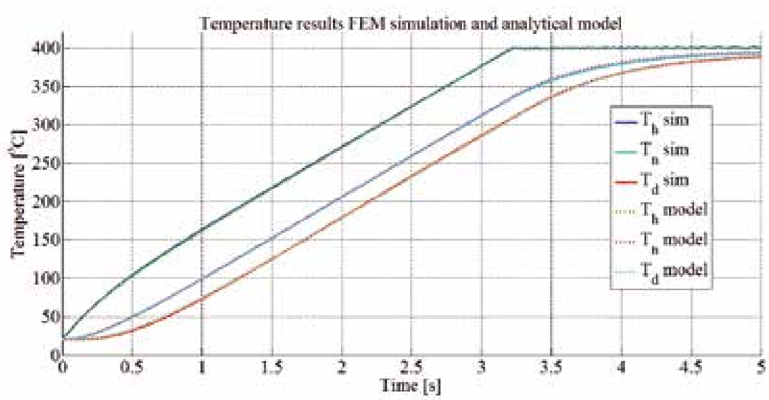
In Figure 6 the temperature transients computed using the FEM are compared with results of simulations in Matlab/Simulink. The apparent match between the FEM and Matlab/Simulink simulation data implies that the analytical model captures the physical behaviour of the system equally well as the FEM analysis. Consequently, it is justified to use the analytical model for thermodynamic analysis of the die-bonding process and servo-control simulations.

4 *Thermal processes considered in the analytical model.*
5 *Equivalent thermal circuit model.*
6 *Comparison of FEM simulation results (solid lines) with Matlab/Simulink simulations computed using the analytical model (dashed lines).*

Thermomechanical deformations

The die-bonding process requires a high-precision horizontal alignment of the dies, with an accuracy of 0.2 µm in the *x*- and *y*-directions. During the soldering, the machine is subjected to thermal expansion, which can result in both elastic and plastic deformations. These deformations may hamper the high accuracy of the die alignment. Note that, besides the misalignment in the *xy*-plane, the misalignment in the *z*-direction (in the form of a gap between the contacting surfaces of the dies) should also be prevented for an acceptable bonding. Temperature sensitivity of material properties, such as elastic modulus and yield strength, is an important factor to consider for the optimum structural design of the nozzles and their interfaces with the other modules.

The final design of the Heating-clamping Module features plane symmetry together with cyclic symmetry, both relative to the nozzle as the centre area. Thanks to these symmetries, mechanical deformations caused by thermal expansion become similar to each other and act in opposite directions relative to the centre area. Consequently, the resulting die misalignments in the *x*- and *y*-direction are reduced.



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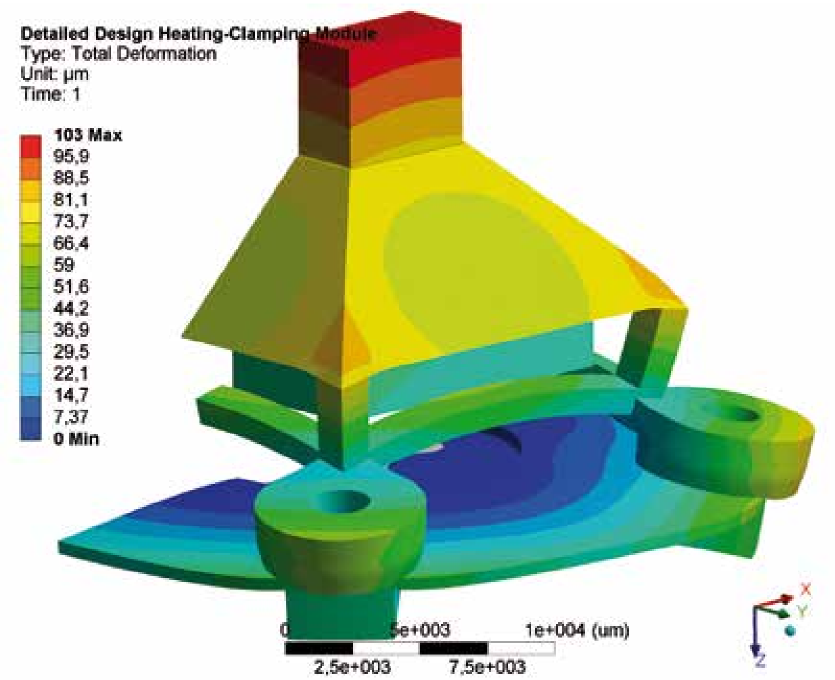

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7 *Thermomechanical deformation of the Heating-clamping Module. Only half of the structure is modelled due to symmetry about the y-plane. To improve visibility, the deformed shape is 22 times exaggerated in the figure while showing actual numerical values.*

The thermomechanical deformations and stresses of the heater-nozzle assembly are determined as the solution of a thermoelastic problem, which is coupled in a staggered manner. The heat transfer problem is solved first; then, the resulting temperatures are imported into static structural simulations as thermal loads. Hence, an inherent assumption of this one-way coupling is a negligible influence of the mechanical deformations on the thermal behaviour of the structure. The total deformation in the assembly is shown in Figure 7 at a time when the critical setpoint temperature has been reached. The maximum resultant deformation occurs on the top of the die and is equal to 103 µm. This is the absolute displacement measured with respect to the initial position of the structure. The evaluation of the misalignment is done using the relative displacements between the two dies.

Analytical calculations of the displacements and stresses for a given temperature profile are rather complicated and thus computationally inefficient, due to the structural complexity. Nevertheless, the numerical results can still be supplemented by analytical calculations for the parts where the geometry is relatively simple and symmetry conditions apply (such as the y-displacement of the die), for instance, via the linear directional expansion formula for solids:

$$\Delta L = \alpha_T \cdot \Delta T \cdot L$$

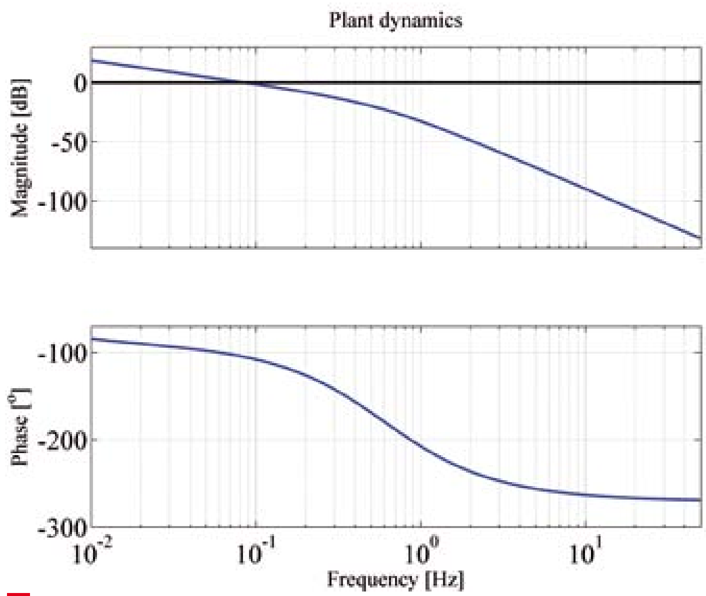
Here, ΔL is the change in length L due to a temperature change of ΔT, and α_T is the thermal expansion coefficient.

Servo control of die-bonding thermodynamics

The simulation results depicted in Figure 6 confirm that the analytical energy-balance equations for the heater, nozzle, and die properly describe the thermal dynamics of the Heating-clamping Module. Since the temperature transients can be calculated in a few seconds using the analytical model, this model is used to simulate the thermodynamics of the module being subject to a temperature servo-control algorithm.
The objective of the servo-control algorithm is the accurate tracking of the temperature setpoint profile for the dies during their soldering. The Bode plot of the control plant is shown in Figure 8. This plant is determined using the analytical model and represents a transfer function from the rate of change of the thermal energy generation ($\dot{E}_g$) to the temperature of the die (T_d) at the critical point. By inspection of the Bode plot, one may conclude that the thermodynamics of the Heating-clamping Module is characterised by a servo-control bandwidth of only 0.09 Hz; here, the servo-control bandwidth is determined by the frequency at which the magnitude characteristic has a gain equal to 1.

For the given plant, the temperature servo controller is determined in the frequency domain using a loop-shaping control design method [6]. The designed controller incorporates an integral action and two lead-lag filters [7]. The corresponding open-loop gain is depicted in Figure 9. The open-loop gain represents a product of the transfer functions of the plant and the feedback controller. This product reveals a servo-control bandwidth of 6 Hz for temperature control during the die-bonding. The higher servo bandwidth should significantly increase the ability of the Heating-clamping Module to achieve the desired temperature characteristic during bonding in comparison to the servo capability of the natural thermodynamics of this module as depicted in Figure 8.

To verify servo-control performance improvement thanks to the advanced temperature control design, servo-control simulations are carried out in Matlab/Simulink based on the analytical model of the system thermodynamics. In the first simulation, the conventional on/off algorithm is applied to control the temperature of the die [7]. This algorithm enables the heater at maximum power as long as the temperature of the die is below its setpoint value. The resulting temperature transients are shown in Figure 10 together with the setpoint profile for the die temperature. Apparently, the conventional temperature controller features limited performance in tracking the setpoint; the



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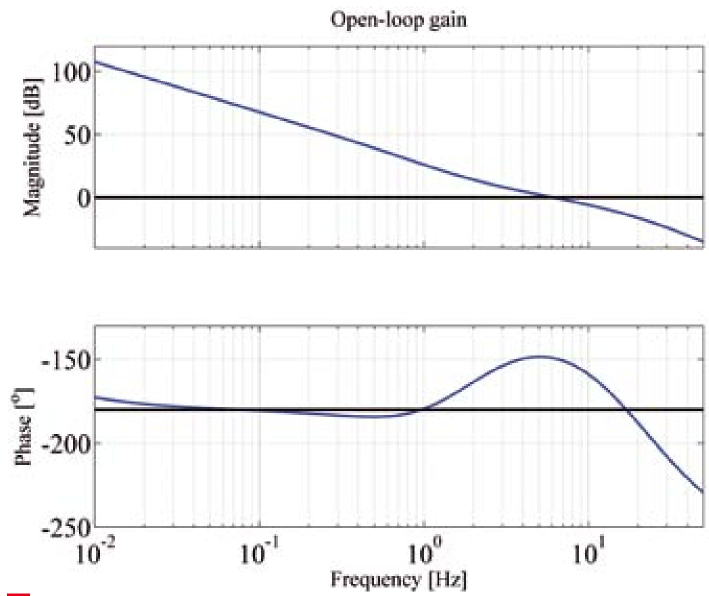

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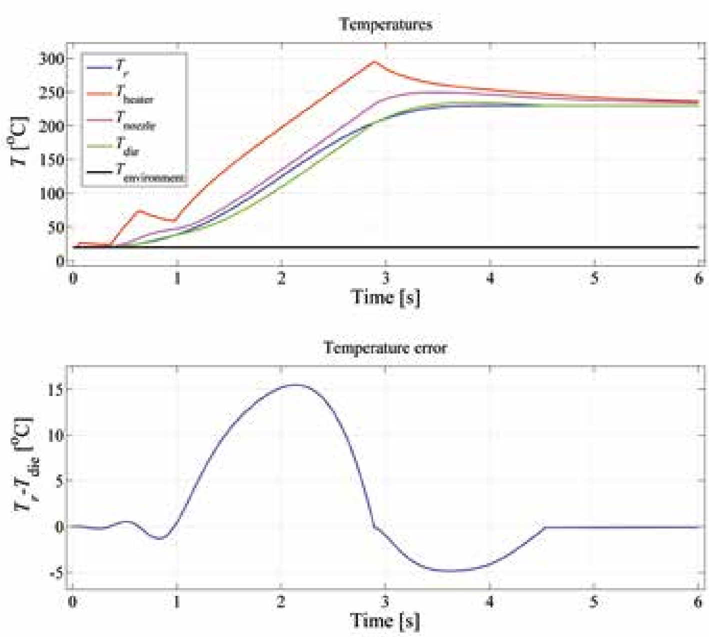
8 *Dynamics of the die-bonding temperature process to be servo controlled.*

9 *Open-loop gain of the temperature servo-control loop.*

10 *Temperature transients under on/off temperature control (top); difference between the setpoint and actual temperature of the die (bottom).*

11 *Temperature transients under advanced temperature control (top); difference between the setpoint and actual temperature of the die (bottom).*

temperature of the die at the critical point deviates from the desired value as much as 15 °C; such a temperature error is not acceptable during die-bonding. The poor temperature control performance is a consequence of the low servo-bandwidth characteristics of the natural thermodynamics of the module. For reference, temperature transients of the heater and the corresponding nozzle are also shown in Figure 10. As intuitively expected, temperatures of these elements are higher than of the die.



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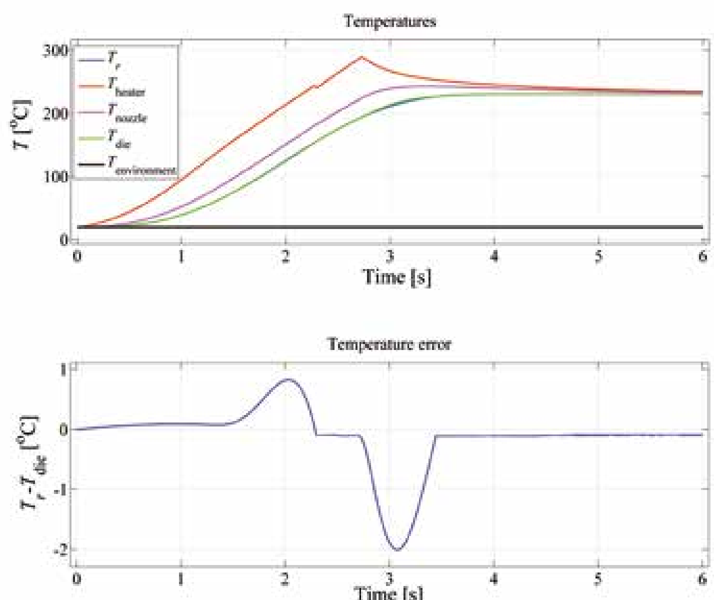

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In the second simulation, the advanced temperature controller is used instead of the on/off one. The results of this simulation, shown in Figure 11, verify performance improvement due to high-bandwidth servo control; the achieved temperature error does not exceed 2 °C, which is acceptable for eutectic soldering. Consequently, the advanced temperature servo controller is adopted for implementation in the die-bonding machine.

Conclusion

As development partner for many OEM companies in the automotive, healthcare, high-tech, and systems industry, SEGULA Technologies Netherlands contributes with new concepts and innovative solutions to various highly strategic engineering projects. One such project, the development of a machine for automatic die-bonding, is addressed in this article. The described model-based product development framework of SEGULA is generically applicable to diverse mechatronics domains, including lithographic machines, robots, automotive systems, printers, wind turbines, etc. ■

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UPCOMING **EVENTS**

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

DSPE Conference on Precision Mechatronics

Second edition of conference on precision mechatronics, organised by DSPE.
See page 48 ff. for the full programme.

WWW.DSPE-CONFERENCE.NL

4 September 2014, Eindhoven (NL)

Annual conference High Tech Platform

First edition of the annual conference of the Mikrocentrum platform. The theme of this event in the Evoluon – the former Philips technology showcase – is "Inspiration & Innovation".

WWW.MIKROCENTRUM.NL/HIGH-TECH-PLATFORM

12 September 2014, Eindhoven (NL)

Official opening of Objexlab

Objexlab is the physical manufacturing lab of the new Fontys Centre of Expertise High Tech Manufacturing & Materials at Fontys University of Applied Sciences.

WWW.FONTYS.NL/OPENINGOBJEXLAB

30 September - 3 October 2014, Utrecht (NL)

World Of Technology & Science 2014

Four 'worlds' (Automation, Laboratory, Motion & Drives and Electronics) will be exhibiting in the Jaarbeurs Utrecht. With the co-location of Macropak, European Dairy Industry Show and Industrial Processing the largest industrial show of the Netherlands arises.

WWW.WOTS.NL

8 October 2014, Bussum (NL)

12th National Cleanroom Day

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

WWW.VCCN.NL

9-14 November 2014, Boston (MA, USA)

29th ASPE Annual Meeting

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

ASPE.NET

12-13 November 2014, Veldhoven (NL)

Precision Fair 2014

Fourteenth edition of the Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum. Some 275 specialised companies and knowledge institutions will be exhibiting in a wide array of fields, including optics, photonics, calibration, linear technology, materials, measuring equipment, micro-assembly, micro-connection, motion control, surface treatment, packaging, piezo technology, precision tools, precision processing, sensor technology, software and vision systems.

WWW.PRECISIEBEURS.NL

19-20 November 2014, Den Bosch (NL)

Bits&Chips Smart Systems 2014

First edition of the annual event on embedded systems and software, focussed on the development of networked technical information systems. Combination of Bits&Chips Embedded Systems (since 2002) and Bits&Chips Hardware Conference (since 2008). The target group includes academia, researchers, designers, engineers and technical management.

WWW.BC-SMARTSYSTEMS.NL

19-20 November 2014, Padova (IT)

Special Interest Group Meeting: Structured Freeform Surfaces 2014

Topics include replication techniques (such as embossing and imprinting), structured surfaces to effect function, precision freeform surfaces, and large-scale surface structuring (including roll-to-roll and printed electronics).

WWW.EUSPEN.EU

20 November 2014, Utrecht (NL)

Dutch Industrial Suppliers Awards 2014

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

WWW.LINKMAGAZINE.NL

25-27 November 2014, Nuremberg (DE)

SPS IPC Drives 2014

International exhibition and conference on electric automation, systems and components.

WWW.MESAGO.DE/EN

ADDITIVE, CONTROL, ENERGY, MEDICAL AND OTHER HOT TOPICS

The 14th International Conference of the European Society for Precision Engineering and Nanotechnology (euspen) was held in Dubrovnik, Croatia, on 2-6 June 2014. Among the hot topics discussed were additive manufacturing (AM), motion control in precision systems, renewable energy technologies, and precision engineering for medical products. The lowlands (i.e. the Netherlands and Belgium) were well represented in Dubrovnik. A (lowlands-biased) report.

DANNIS BROUWER

AUTHOR'S NOTE

Dannis Brouwer is an associate professor in the department of Mechanical Automation & Mechatronics at the University of Twente, the Netherlands. For this article, he would like to acknowledge the input he received from Rob Munnig Schmidt, Director at RMS Acoustics & Mechatronics and Professor of Mechatronic System Design at Delft University of Technology, the Netherlands.

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Euspen's 14th International Conference & Exhibition was held in Dubrovnik, Croatia, once an important Adriatic maritime republic and now a UNESCO World Heritage Site. The welcome reception for the conference was held in the old town of Dubrovnik (see Figure 1).

1 *The ASML-sponsored welcome reception in a hotel in the old town of Dubrovnik. (Photos courtesy of euspen)*

Once again, the euspen conference was a great opportunity to explore the latest advances in precision engineering fields such as metrology, ultra-precision machines and ultra-precision manufacturing and assembly processes. This year's event saw several new topics addressed in the oral sessions, such as "Precision Engineering for Medical Products", "Additive Manufacturing for Precision Engineering", "Renewable Energy Technologies", and "Motion Control in Precision Systems". Some 190 contributions and two workshops reported on the latest developments and fuelled the discussion between industry and scientists to improve and accelerate these developments.

The lowlands were well represented in Dubrovnik: one tutorial, six oral presentations (out of a total of 35), a strong presence at the exhibition, one oral presentation award and no less than three poster presentation awards (for Prof. Dominiek Reynaerts' group from KU Leuven).

Tutorials and workshops

The conference was preceded by two tutorials and one workshop. The first tutorial, "Advanced Mechatronic System Design", was given by Prof. Rob Munnig Schmidt (Delft University of Technology) and Dr Adrian Rankers (Mechatronics Academy); see Figure 2. They covered the

performance of actively controlled precision motor systems and controlled system dynamics, paying special attention to non-collocated actuation and sensing. The second tutorial, “Optical Surface Topography Measurement”, by Prof. Richard Leach of the National Physical Laboratory in the UK, covered instrument basics and types, traceability, calibration, verification, adjustment, instrument response, and good practice.

The first workshop was on large-volume metrology (LVM), the ability to measure, in situ, items that are too large for measurement using conventional coordinate measuring machines. As this is a key enabling tool for high-value advanced manufacturing in Europe, five European national metrology institutes and three universities embarked on a joint research project, funded by the European Metrology Research Programme (EMRP), to tackle the issues that are currently limiting the effective and widespread adoption of LVM techniques in the manufacturing industry. Various solutions were addressed during the workshop, as was measurement accuracy. One promising approach to achieve the highest 3D accuracy on large volumes is ‘multilateration’ using the Global Positioning System (GPS), which may yield a relative measurement uncertainty of approximately $5{\cdot}10^{-7}$.

The second workshop, which concluded the conference, presented results from an EMRP project on thermal design and dimensional drift. This workshop covered topics such as methods of ultra-high-resolution interferometry for the measurement of thermal dilatation and the aging of materials and joints, together with the use of nano-indentation techniques for creep measurements. A few examples for the preparation of suitable joints for direct interferometric measurements were given. Also on the menu were methods of thermal modelling for the improved design of precision engineering tools and their application for designing new cooling elements and thermal controllers.

2 The “Advanced Mechatronic System Design” tutorial.

3 Paul Atherton delivering his keynote, “Creating Wealth Through Advanced Engineering”.

Keynotes

The three conference keynotes covered a wide variety of subjects:

- “Creating Wealth Through Advanced Engineering”, by Paul Atherton (Figure 3), a technology entrepreneur and venture capitalist/investor (e.g. Queensgate Instruments, C2V and NaturalMotion) from the UK.

4 *Denis Loncke of ASML on the relevance of AM for precision engineering.*

- "Technological Advances in Super Fine Finishing", by Dr Anthony Beaucamp, Zeeko Research Lab, Chubu University, Japan.
- "Evolution and Development of In-Situ Automated Optical Inspection Applied to the Macro-, Micro-, and Nano-scale", by Prof. Liang-Chia Chen, National Taiwan University.

Solar

With three presentations, the "Renewable Energy Technologies" oral session focussed on solar energy. The first was on the replication of a large-size Fresnel-type concentration lens for photovoltaic solar cells using spin coating. A report from the European Union's Seventh Framework Programme NMP (nanosciences, nanotechnologies, materials & new production technologies) project, SolarDesign, covered on-the-fly alterable thin-film solar modules for design-driven applications. To conclude, the design and fabrication of a coating research machine to explore the nanometer-scale coating of glass tubes for Concentrating Solar Power (CSP) systems was discussed. There was one further presentation, which addressed the production and accuracy challenges for wind energy systems.

Medical

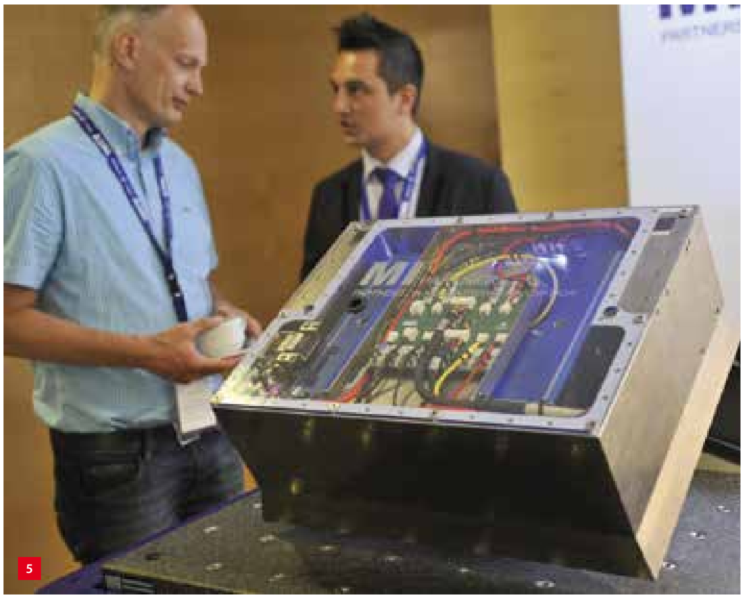
The "Precision Engineering for Medical Products" oral session featured two presentations on manufacturing aspects of biomedical products and one on X-ray computed tomography for wear measurement of prosthetic components. Andy Gijbels of KU Leuven in Belgium gave a presentation on the development of a tele-operated robotic system for retinal surgery. The developed system consists of a haptic joystick and a surgical manipulator. The surgeon's control actions are scaled down and tremor is filtered before being sent to the surgical manipulator. In addition, the interaction forces between the instrument and the retina are measured with a force sensor that is integrated in the instrument and fed back to the haptic joystick after being amplified up to 10 N. This allows the surgeon to feel how much force they are exerting on the delicate retinal tissue, so that they can react appropriately.

Additive manufacturing

In the "Additive Manufacturing for Precision Engineering" oral session, a presentation by Denis Loncke of ASML (Figure 4) showed that AM is not just another research hype, but a serious enabling process for weight reduction and optimising cooling channels in precision equipment. That said, it does not necessarily result in a cost reduction yet. The other presentations in this session addressed manufacturing issues, quality assurance for the complete AM process chain and the chemical vapour polishing of AM parts.

Motion control

In the "Motion Control in Precision Systems" oral session, three of the four presentations came from the Netherlands. Dennis Bruijnen of Philips Innovation Services gave a lecture on feed-forward (FF) design for high-precision motion systems. When enabling double FIR (finite impulse response) FF for a motion control system, a rigid design is no longer strictly necessary to be able to obtain good settling performance. This allows the mechanical designer



5 Demo of MI-Partners' design for a seismic vibrator.

6 Discussion at the 3TU booth, featuring the reconfigurable parallel kinematic platform.

to consider alternative design options. To obtain good settling performance, linear and reproducible behaviour is sufficient.

Gijs van der Veen of Delft University of Technology gave a presentation on the design of high-performance mechatronic systems using topology optimisation. The idea is to directly optimise closed-loop systems by using an integrated approach of topology optimisation and controller design. Bram Krijnen of Demcon talked about the vacuum performance and control of a MEMS stage with integrated thermal position sensor, for which he won the oral presentation award. The fourth presentation in this session was by Carl Zeiss SMT, on optimising mirror manipulator performance by means of robustness analysis of dynamics and control.

Dutch presence at the exhibition

Although Dubrovink is not that close to the Netherlands, several Dutch high-tech system developers and suppliers and the federation of the three Dutch universities of technology (3TU) had booths at the commercial exhibition.

Demcon showcased a precision eye surgery pump for D.O.R.C. The newly developed pump is a mechatronic system that interacts with a sterile disposable cartridge. The pump comprises a pressure sensor, a compensation piston, an inlet valve, a pump piston and an outlet valve. The pistons and valves are actuated using flexure-based rotation mechanisms comprising reinforced leaf springs which convert direct-drive actuator displacement into precision motion.

MI-Partners showed a small ground shaker, a seismic vibrator capable of applying precision low-frequency forces to the ground. One of the issues in tunnel boring is the uncertainty about the ground that lies in front of the tunnel boring machine (TBM). Therefore, it is desired to have a system and method for making predictions about the ground ahead of the TBM. This new vibrator, based on linear motor technology, was developed for installation on a TBM (Figure 5).

In the IBS Precision Engineering booth, a roll-to-roll concept using New Way Air Bearings products was on display. A cylinder-shaped porous media air bearing was developed to manipulate thin materials called webs without physically touching the web. The new process offers distinct advantages over current processes, such as contactless pre-load control of the web.

The 3TU booth featured several demonstrations, including a reconfigurable parallel kinematic 6-DoF platform (Figure 6), a UV-laser cutting method for silicon MEMS prototyping and a three-DoF, large-range-of-motion MEMS-based precision stage with integrated feedback.

2015

All in all, the 2014 euspen conference was well worth attending. Next year, precision engineers from industry and academia in the lowlands cannot use distance as an excuse for not attending. euspen's 15th International Conference & Exhibition will be held on 1-5 June 2015 at KU Leuven in Belgium. ■

INFORMATION
WWW.EUSPEN.EU

FREQUENCY DOMAIN MODELLING AND PERFORMANCE OPTIMISATION OF NONLINEAR SYSTEMS

AUTHORS' NOTE

David Rijlaarsdam, group leader, and Pieter Nuij, senior system architect, both work at NTS Systems Development in Eindhoven, the Netherlands. Maarten Steinbuch is full professor in the department of Control Systems Technology at Eindhoven University of Technology. Johan Schoukens is full professor in the department of Fundamental Electricity and Instrumentation at the Free University of Brussels (VUB), Belgium.

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Concluding a series of three, this article deals with frequency domain methods when applied to systems subject to nonlinear dynamical effects. To meet increasing system requirements, techniques have to deal with the performance-degrading effects of nonlinearities. When applied with care, frequency domain methods provide practically applicable tools to model and optimise the performance of nonlinear systems. This article provides a brief overview and experimental examples of existing modelling techniques, as well as a novel method for performance assessment and optimisation using frequency domain based tooling.

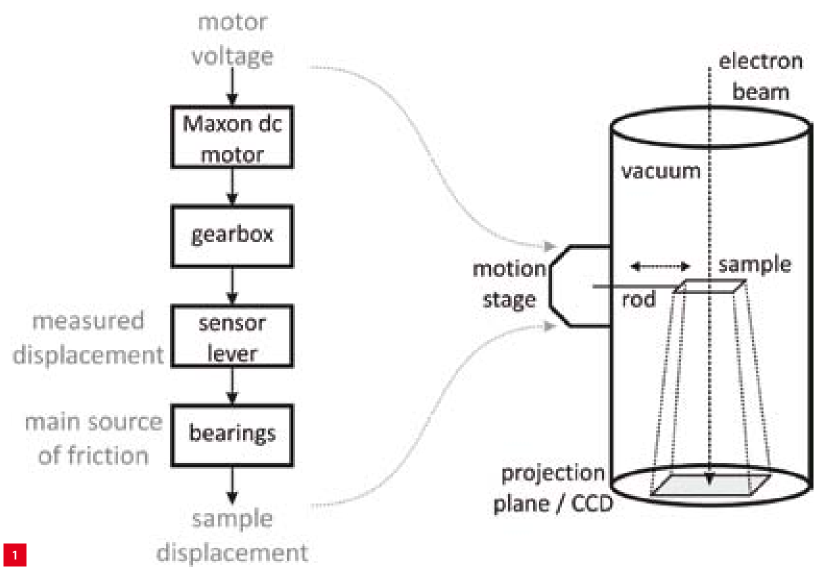
DAVID RIJLAARSDAM, PIETER NUIJ, MAARTEN STEINBUCH AND JOHAN SCHOUKENS

Three articles

In a series of three articles on Frequency Response Function (FRF) measurements, this third article focusses on the extension of frequency-domain methods towards nonlinear systems and the application of such methods to define and optimise the performance of such systems. The first article [1] covered the steps necessary to convert a time-continuous signal into a discrete spectrum. Potential errors caused by aliasing and leakage were explained and solutions were presented. An overview of several types of test signals was presented. The second article [2] introduced the FRF, explaining the choice of test signals in relation to the coherence function and the measurement of the FRF in open- and closed-loop systems. Each article is illustrated with examples.

Introduction

Increasing performance requirements on high-performance (motion) systems require novel techniques to deal with performance-degrading effects of nonlinearities. For linear and time-invariant (LTI) systems, frequency domain methods are widely accepted in the engineering community for modelling as well as performance optimisation purposes. Although systems may be specifically designed to minimise nonlinear effects, nonlinearities such as magnetic fields may be inherently present in the design. In particular, some applications require the presence of nonlinear effects, such as friction in the motion stage of an electron microscope. Whether performance is measured by speed, accuracy, reproducibility, smoothness, or other performance measures, the effects of nonlinearities become increasingly important in high-precision applications.



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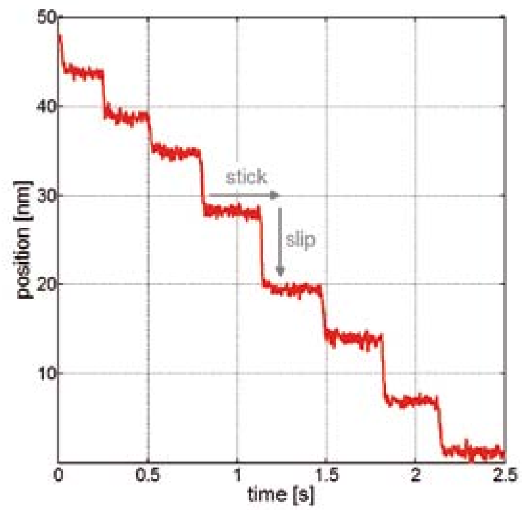

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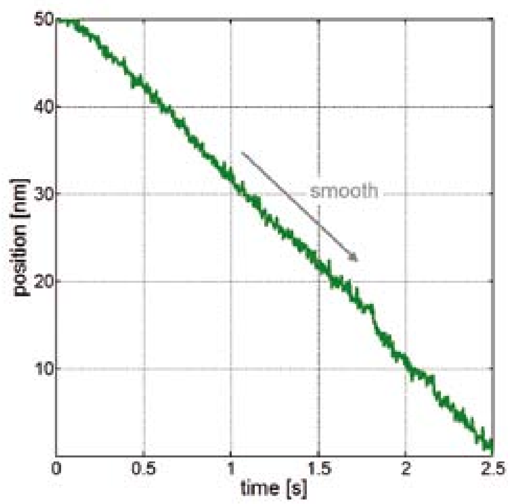

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To accurately detect, analyse and compensate performance-degrading effects in controlled nonlinear dynamical systems, practically applicable tools are required. Therefore, following up on [1] and [2], this article discusses the pitfalls and potential gains when using frequency domain techniques to model and optimise the performance of nonlinear systems. Note that this article aims to provide an accessible, but very brief overview of existing methods to address nonlinear systems in the frequency domain. For a more complete and formal overview and comparison, see, for example, [3].

The main carrier throughout this paper is an industrial case study of optimal friction compensation in a Transmission Electron Microscope (TEM) system as depicted in Figure 1.

1 *Schematic depiction of the (motion module) of the TEM system. For simplicity, only one direction of motion is depicted. All transfer functions in this article are computed from the motor voltage to the measured displacement.*

2 *Low-speed jogging response of the TEM system and the effect of optimised friction compensation.*
(a) No Coulomb friction feed forward.
(b) Optimal Coulomb friction feed forward.

Certified Precision Engineer competencies

The content of this series of three articles is in part covered in the "Experimental Techniques in Mechatronics" course from Mechatronics Academy, offered to the market by The High Tech Institute. This course has been selected for the DSPE Certification Program (see page 46).

Certified by the Dutch Society for Precision Engineering
CPE
Certified Precision Engineer

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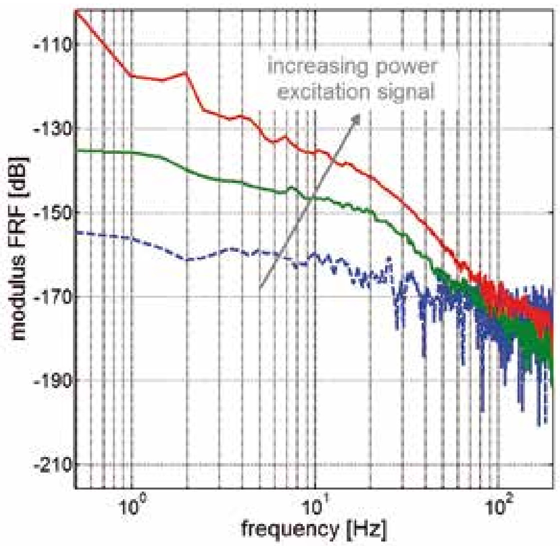
Based on this example the effects of nonlinearities in the frequency domain are introduced as well as state-of-the-art modelling techniques. Moreover, a practically applicable method is introduced to analyse, visualise and optimally compensate performance-degrading nonlinear effects in dynamical systems. Application of this technique has resulted in a reduction of the achievable smooth jogging motion to a level of 20 nm/s in an industrial TEM (Figure 2) [4].

Frequency domain modelling of nonlinear systems

Overview of modelling techniques

Frequency domain methods are widely accepted and have been an impetus for the development of modelling and



3 *Frequency response function of the TEM for varying input levels.*

control design techniques for LTI systems. Although the linearity assumption can rarely be satisfied in practice, linear models and analysis often suffice when systems are operated around a given working point. Given the widespread acceptance and success of frequency domain methods for LTI systems, several approaches exist that extend frequency domain methods towards nonlinear systems, e.g. the Generalised Frequency Response Function (GFRF) [5], nonlinear FRF [6], describing functions [7] and linear approximations [8]. Table 1 provides an overview of such methods and the nonlinear effects / information captured by each model.

The success and popularity of frequency domain methods for LTI systems is largely due to the combination of Fourier analysis and the fact that a sine wave is an eigenfunction of LTI systems, which satisfy the properties of superposition and homogeneity. For nonlinear systems, this is generally not the case, which implies that a conventional frequency domain model captures only a part of the system's dynamics, as illustrated by Figure 3.

Figure 3 depicts three Frequency Response Functions (FRFs) of the TEM system depicted in Figure 1. These FRFs are measured using white-noise inputs with three different rms values. It becomes clear that the FRF captures only a subset of the system's dynamics as the dependence of the dynamics on the input amplitude is not captured by a single FRF. This effect, called 'gain compression / expansion', is one of several effects of nonlinear behavior in the frequency domain, such as desensitisation, intermodulation and the generation of harmonics (see Table 1). Moreover, although the coherence of a single FRF (not shown) may indicate nonlinear behavior if the excitation signal is random, it provides no indication of nonlinearity if the system is subject to a deterministic excitation signal such as a multi-/swept sine [8].

Hence, traditional frequency domain tools and models fail in the presence of nonlinearities, requiring an extension of conventional frequency domain methodologies if nonlinearities are present. Two modelling approaches will be discussed that allow detection and modelling of a subset of nonlinear effects in the frequency domain. Moreover, it

Table 1 *Overview of frequency domain modelling approaches for nonlinear systems.*

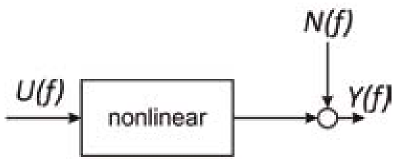
Legend:

green:
effect captured / info available

red:
effect not captured / info not available

orange:
effect partly captured / info available, requires additional processing

		Gain compression / expansion	Desensitisation	Intermodulation	Harmonics	Content at frequencies present in input		Content at frequencies not present in input	
		dependence of gain on input excitation level	dependence of response at one frequency on input at another frequency	combination of input frequencies to produce new frequencies in the output	generation of frequency components in output at multiples of input frequency	gain	phase	gain	phase
Conventional FRF		red	red	red	red	green	green	red	red
Generalised FRF [5]		green	green	green	green	green	green	green	green
Nonlinear FRF [6]		green	red	red	green	green	green	green	green
Describing function	sinusoidal	green	red	red	red	green	green	red	red
	generalised	green	green	red	red	green	green	red	red
	HOSIDF [7]	green	red	red	green	green	green	green	green
Best linear approximation [8]		green	green	orange	orange	green	green	orange	red



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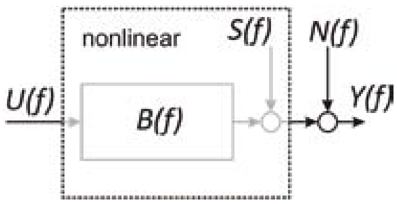

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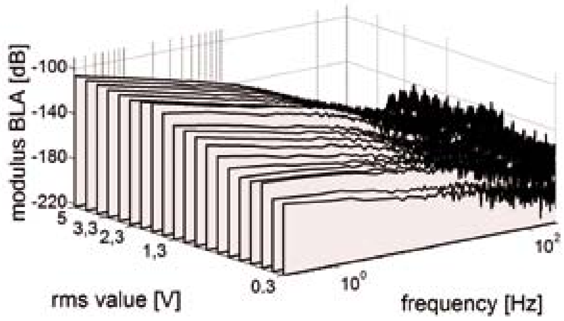

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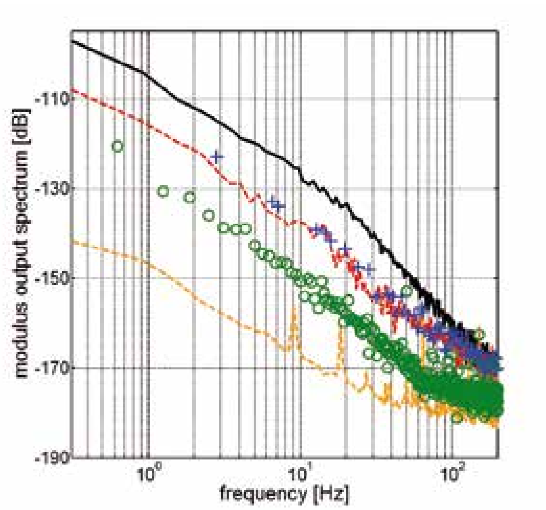


5b

will be shown later on that analysis of nonlinear effects in the frequency domain provides a useful way to define and optimise the performance of nonlinear systems.

4 Transformation of a nonlinear system to a best linear approximation (BLA) and corresponding nonlinear distortion. (a) Nonlinear system. (b) BLA and nonlinear distortion.

5 Analysis of the TEM system. (a) Best linear approximation. (b) Output spectrum: average (black), variance due to nonlinearities (red) and stochastic disturbances (orange), also energy appearing at odd (blue) and even (green) non-excited frequencies.

Experimental results

In the following, two approaches to modelling the nonlinear TEM system are illustrated based on experimental results. The best linear approximation (BLA) and Higher Order Sinusoidal Input Describing Function (HOSIDF) are selected from Table 1 as they provide models that are easily computed from measured data and provide insightful representations, which are usable in practice. First, a best linear approximation of the TEM system is derived, yielding separate quality measures relating to random disturbances (noise) and nonlinear influences. Second, the HOSIDF is used to explicitly investigate nonlinear effects in the TEM system.

Linearised modelling: best linear approximation

In this section, the estimation of a linear model in the presence of nonlinearities is addressed. Consider a nonlinear system as depicted in Figure 4a and assume the system can be transformed to a structure as in Figure 4b (for existence and invariance of this transformation, see [3]). In Figure 4b, the Fourier transform of the output $Y(f)$ then depends on the input $U(f)$ and consists of a component that is generated by an LTI system $B(f)$, a distortion $S(f)$ due to nonlinearities and an output disturbance $N(f)$, i.e.

$$Y(f) = B(f)U(f) + S(f) + N(f)$$

Then, the pair $(B(f), S(f))$ is defined as the best linear approximation (BLA) [8], if it satisfies:

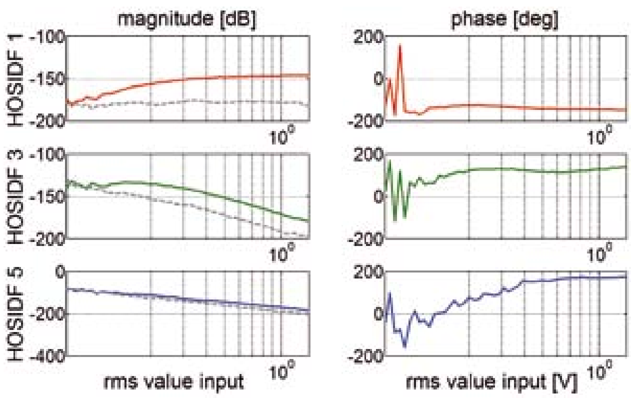
$$B(f) = \arg\min_{B(f)} E\{(y(t) - B(f)u(t))^2\}$$

Here, $E\{\ \}$ denotes the expected value. Several studies concerning the existence and uniqueness of the BLA can be found [3] [8]. In this section, however, attention is focussed on practical identification of the BLA and the information available therein.

In this example, the BLA is derived by exciting the TEM system with a set of so-called 'special random, odd multisines', i.e. different realisations of multisine signals with equal amplitude spectra, but randomised phase realisations [8]. The adjectives 'special' and 'odd' refer to the fact that the multisine signal is constructed only from sinusoids which are an odd multiple of some base frequency and some of these odd multiples are set to zero in the excitation spectrum ('special'). Such specially designed signals allow to:

1. compute the BLA on spectral lines which are present in the excitation signal;
2. detect nonlinearities by energy appearing at non-excited spectral lines (intermodulation, harmonics);
3. assess model quality by separately quantifying variance due to nonlinearities and output disturbances.

For details on the analysis required to attain the information mentioned above, see [3]. Figure 5a shows the BLA of the TEM system for different excitation levels (rms values of the multisine signal). Furthermore, Figure 5b shows the output spectrum generated by the BLA and the separation between the variance on this average due to nonlinear effects and due to output disturbances. Moreover,



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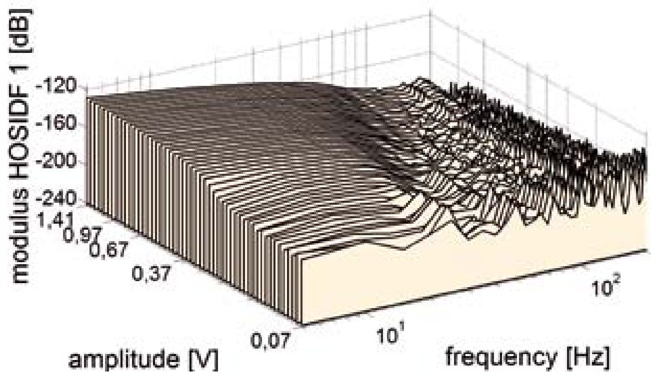


6b

6 *Higher-order sinusoidal describing functions (HOSIDFs) of the TEM system.*
(a) First, third and fifth HOSIDF for f_0 = 20 Hz (grey: variance on average).
(b) First HOSIDF.

it shows the energy level at non-excited odd and even multiples of the base frequency of the multisine which are not present in the excitation signal.
This shows that the variance caused by nonlinearities is mainly due to odd nonlinear effects, which points towards a point-symmetric nonlinearity such as (Coulomb) friction (a point-symmetric nonlinear function of the system's velocity). Hence, using the BLA when working with nonlinear systems not only provides a best approximation of the FRF, but yields both quantitative measures of the type and level of nonlinearities present and the quality of the measurement (signal-to-noise ratio).

Nonlinear modelling: Higher Order Sinusoidal Input Describing Functions
The second modelling approach specifically models the generation of harmonics due to nonlinearities. Due to its similarity to the classical sinusoidal describing function, the model is referred to as the Higher Order Sinusoidal Input Describing Function (HOSIDF) [7]. The HOSIDFs are defined for sinusoidal inputs with frequency f_0. The k^{th} HOSIDF $H_k(f_0, a)$ is a function of both frequency f_0 and amplitude a and is defined as follows:

$$H_k(f_0, a) = Y_s(kf_0, a) \,/\, U_s^k(f_0, a)$$

Here, the subscript s refers to the single-sided spectrum of the input $U(f)$ and output $Y(f)$. For k = 1, the above definition equals the definition of a conventional FRF under sinusoidal excitation and that of a conventional sinusoidal describing function. The added value of the HOSIDFs comes from explicitly – both in gain and phase shift – modelling the generation of harmonic frequency components by the nonlinear system.

Figure 6a shows the first three odd HOSIDFs for the TEM system at f_0 = 20 Hz for varying input amplitude.

Furthermore, Figure 6b shows the first HOSIDF as a function of frequency and excitation amplitude. The fact that the even HOSIDFs are close to zero and the behaviour of the gain characteristics of the odd HOSIDFs, both point towards a point-symmetric nonlinearity, the effect of which reduces with increasing excitation amplitude, e.g. friction.

Apart from providing insight into and quantification of the nonlinear effects present, the HOSIDFs have been shown to allow computation of the parameters defining the non-linearity. Moreover, the HOSIDFs can be used to optimally design nonlinear compensators to reduce performance-degrading effects in nonlinear systems. This is addressed in the next section.

Frequency domain performance optimisation of nonlinear systems

Time versus frequency domain performance
While the previous section dealt with modelling nonlinear effects in the frequency domain, this section focusses on using frequency domain analysis to optimise the performance of nonlinear systems [3] [4]. Defining and optimising performance of nonlinear systems in a practically applicable manner is nontrivial. For example, performance indicators for LTI systems such as bandwidth, sensitivity and gain/phase/modulus margin cannot be used and global optimisation of a given performance indicator is not straightforward.

The method introduced in the following is based on the concept behind the HOSIDFs, i.e. nonlinear effects generate harmonics when the system is subject to a sinusoidal input (often harmonics are indeed a necessary and sufficient condition for the existence of nonlinear behaviour [3]). The method also assumes that the nonlinear effects are performance-degrading and should therefore be compensated. However, before moving to performance optimisation, consider the essential difference between time and frequency domain based performance assessment; see Table 2.

Table 2 illustrates the difference between optimisation based on time and frequency domain analysis with respect to performance in terms of tracking and compensation of nonlinear effects. If a control system is optimised based on tracking error, the output of such a system will approximate the sinusoidal reference in both amplitude and phase (light red). The controller will, however, sub-optimally compensate the nonlinearity as the input-dependent term in the performance measure clouds the influence of the harmonics generated by the nonlinearity (dark red). The resulting controller only provides optimal tracking for the amplitude and frequency of the signal applied during tuning.

If instead the harmonics are optimally compensated by minimising the corresponding frequency domain performance measure only (dark green), the corresponding output will match the input in frequency, but possibly differ in amplitude and phase (light green) resulting in a sub-optimal tracking error. The solution comes from separating the problem and using the appropriate performance measure for each job [4]. Hence, first optimise a nonlinear controller to optimally compensate nonlinear effects based on a frequency domain performance measure (e.g. dark green) and then optimise a conventional LTI controller to achieve tracking performance and disturbance attenuation, e.g. using loop shaping.

Next, an example of frequency domain based friction compensation in a TEM is presented to illustrate the above.

Frequency domain based friction compensation

As indicated in Table 2, nonlinear effects can be assessed in the frequency domain by considering harmonics present in the output when the system is subject to a sinusoidal input. For example, the ratio between the energy present at harmonics and at the excitation frequency (Table 2, dark green) provides a suitable and practically measurable performance measure. Note that optimising nonlinear compensators by removing harmonics in the output of a system provides a globally optimised controller for a large class of systems, including magnetic fields, actuator/sensor nonlinearities and several forms of friction. Hence, a static nonlinear compensator optimised in this way, provides optimal compensation for any input/reference signal, although it was tuned using a sinusoidal input only [3].

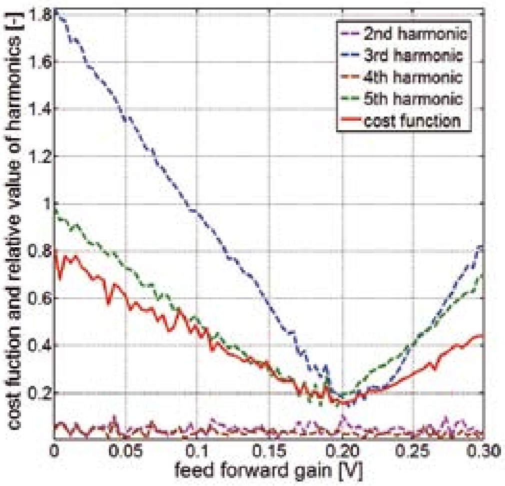
The method described above has, so far, been applied to optimise the performance of a military surveillance camera, linearise amplifier characteristics and compensate friction in a TEM motion module [4]. Moreover, simulations are successful in linearisation of the influences of magnetic fields in maglev applications and fully automated, adaptive implementations have been successfully applied in practice. For the purpose of this article, attention is focussed on the application of friction compensation in a TEM.

The TEM system depicted in Figure 1 is subject to conventional Coulomb friction feed forward and the corresponding feed-forward gain is to be optimally tuned. In this application the feed-forward gain is incrementally increased while the system is subject to a sinusoid with a frequency significantly below the bandwidth of the closed-loop system. The results are depicted in Figure 7.

Figure 7a shows the energy present at the individual harmonic lines in the spectrum as a function of the feed-forward gain. Moreover, the cost function combining all statistically relevant harmonics is depicted. From Figure 7a it becomes clear that around 0.2 V the overall energy at harmonics in the output is minimised (individual harmonics have slightly different optima due to the nature of the nonlinearity and compensator). As observed in Figure 7b, the harmonics in the output spectrum have indeed been reduced significantly when comparing the uncompensated (red) and optimally compensated (green) situation.

Table 2 *Time and frequency domain performance measures for optimal tracking and nonlinear compensator design.*

	Time domain	Frequency domain
Optimal nonlinear compensator	$A\cos(2\pi f_0 t + \varphi_0)$ $\downarrow$ $B\cos(2\pi f_0 t + \psi)$	minimise harmonic disturbance $\sum_{k=0, k\neq 1}^{K} \frac{\lvert Y(kf_0)\rvert}{\lvert Y(f_0)\rvert}$
Optimal tracking	$A\cos(2\pi f_0 t + \varphi_0)$ $\downarrow$ $A\cos(2\pi f_0 t + \varphi_0)$	minimise tracking error and harmonic disturbance $\sqrt{\lvert Y(f_0) - U(f_0)\rvert^2 + \sum_{k=0, k\neq 1}^{K} \lvert Y(kf_0)\rvert^2}$



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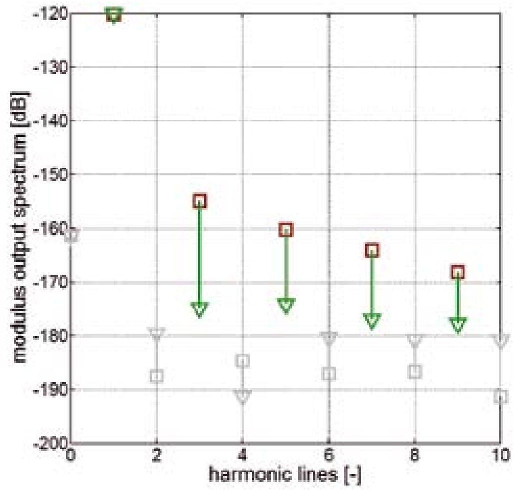

7b

7 *Frequency domain based optimisation of Coulomb friction feed forward in the TEM system.*
(a) First five harmonics and performance measure (Table 2, dark green) as a function of controller parameter.
(b) Difference between the output spectrum without (red) and with (green) optimised Coulomb friction feed forward. Grey lines indicate statistically non-significant data.

The practical implications and global nature of the optimised tuning become clear from Figure 2. Comparing Figure 2a and 2b yields that selecting the optimised parameter setting based on the frequency domain based performance measure depicted in Figure 7a yields a significant performance improvement in terms of smoothness during low-speed jogging motion at 20 nm/s.

Conclusions

Although frequency domain methods are widely applied and accepted for modelling and performance optimisation of linear and time-invariant system, their applicability to systems containing nonlinearities is nontrivial. However, increasing performance requirements on high-performance systems require novel techniques to model and deal with the performance-degrading effects of nonlinearities. When applied with care, frequency domain methods provide practically applicable tools to model and optimise the performance of nonlinear systems. This article provides a brief overview of existing frequency domain based modelling techniques for nonlinear systems and a novel method to assess and optimise the performance of such systems. Both the modelling approach and performance optimisation are illustrated using a TEM (Transmission Electron Microscope) system suffering from the performance-degrading effects of friction during low-speed jogging motion.

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Sensitec – magnetoresistive sensors for high-precision measurement

Sensitec, founded in 1999 in Lahnau, Germany, is a leading supplier of magneto-resistive (MR) sensor technology and magnetic microsystems. Sensors from Sensitec are used wherever movement is to be controlled or where angle, linear motion, position, electrical current or magnetic field strength are to be detected or measured.

Sensitec's core capabilities lie in the design, development, production and marketing of sensor solutions for the measurement of magnetic, electrical and mechanical variables according to the requirements of customers in a wide range of different application fields. Numerous patents and licences for the production and application of MR sensors, backed by a broad spectrum of experience and knowledge in this field, provide the foundation for these capabilities.

At the location in Mainz, Sensitec possesses Europe's most efficient and modern wafer factory for the production of MR chips. Here, microchips are manufactured using thin-film technology to satisfy automotive requirements. At the location in Lahnau, the chips are integrated into modules and systems to satisfy the requirements of a demanding, world-wide market.

Application areas

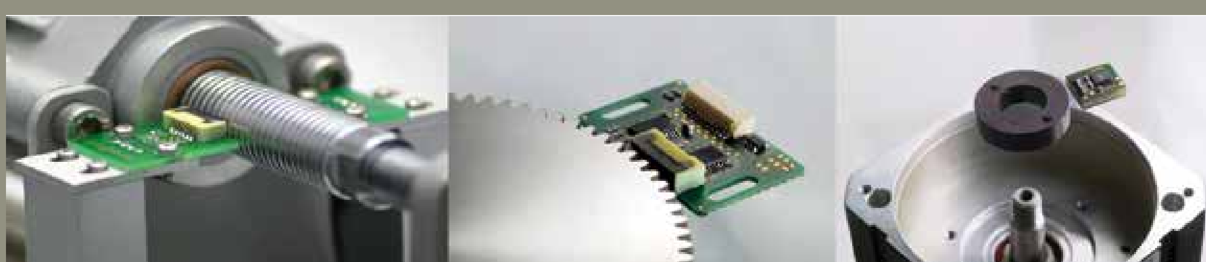
MR sensors offer high accuracy, high resolution, robustness, high sensitivity and high reliability. They are wear-free and easy to integrate. The advanced and innovative solutions from Sensitec can be found in many areas, such as:

- industrial automation,
- automotive applications,
- measurement and control equipment,
- medical equipment,
- laser technology,
- aerospace,
- etc.

Mars Rover "Curiosity"

Sensors from Sensitec can be used under extreme operating conditions, which makes them the ideal choice for aerospace applications. In November 2011, NASA launched one of the most complex projects in the history of spaceflight. The Mars Rover "Curiosity" was sent off on its mission to search for evidence of life on Mars. On-board are high-precision sensors from Sensitec. The miniaturised sensors are used to detect the angle (position) of the wheels, the suspension, the robot arm, the camera head and the communications antenna. The extreme temperature fluctuations and high radiation levels on the surface of Mars demand the use of robust, reliable sensors.

Sensitec has become a regular on Mars missions. Following its successful contribution to the "Spirit" and "Opportunity" mission, "Curiosity" marks the second trip to the Red Planet for the Lahnau-based company. "Curiosity" has already achieved a number of scientific breakthroughs on Mars. ■



Applications of Sensitec sensors can be found in rotation measurement on cogwheels, longitudinal position sensing on shafts and pistons, and general length measurement.

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SYSTEMATIC PROCESS DESIGN WITHOUT REQUIRING AFTER-DESIGN VERIFICATION

Successful development of mechatronic and precision-oriented systems depends on the employment of high-end scientific and technological advances as well as on the (systems engineering) processes involved. Owing to their multidisciplinary nature and increasingly higher technical-business expectations these processes become complex, rendering traditional process design approaches ineffective or problematic. Here, the design of such processes is formulated as a supervisory control problem using the models of possible workflows and process requirements. This approach is illustrated through designing a mechatronics development process.

AMIN MANNANI

Introduction

Complexity is an intrinsic property of many advanced mechatronic systems, service robots, networked infrastructures, etc., which impacts their development time-to-market, quality, operation and maintenance significantly. Product complexity is often the result of the interwoven dependencies among the relatively many subsystems of a system either through their structural-informational connections or because of their required collaboration to achieve a common goal. Addressing this type of complexity, using modularity and physical rules, forms the mainstream in engineering disciplines.

However, as systems becomes complex, their associated processes for development, manufacturing, maintenance and the like become complex too. The corresponding process(-level) complexity is driven by the multidisciplinary nature of the systems and their requirements, outsourcing activities, business decisions, complicated integration and system verification-validation activities, product variants, and market fluctuations, among others.

Process complexity has received little attention and is generally unaddressed. This is mainly because a) the experts' time is primarily devoted to handling scientific-technological intricacies of complex products, and b) there have been ineffective process design techniques in the past. Traditional process design approaches use a lot of human intervention and interpretation, especially in an interdisciplinary environment, and follow best practices to suggest a process, which needs to be tested. If it fails, design is repeated; if it passes, the process generally bears no correctness-effectiveness guarantees.

With the recent advances in modelling and control of discrete-event systems, we propose to design processes through solving a supervisory control problem using the models of all possible workflows and the desired process requirements. Besides offering all the advantages of a model-based design, including clear interpretations, this approach yields processes that need no after-design verification.

AUTHOR'S NOTE

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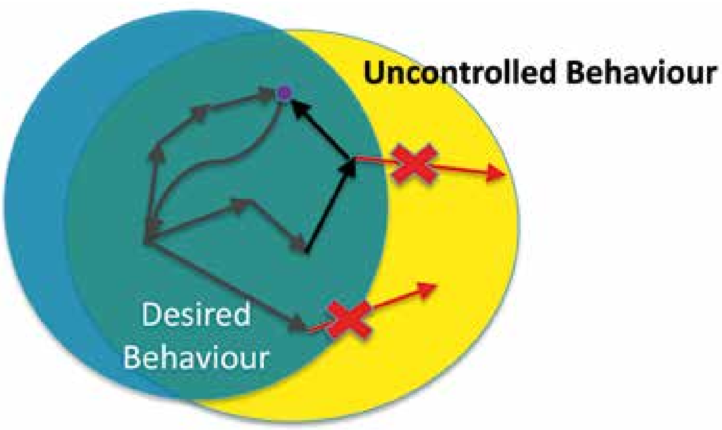

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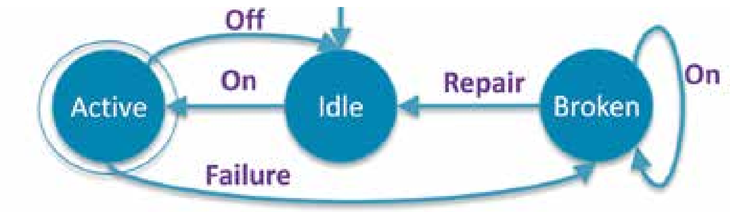

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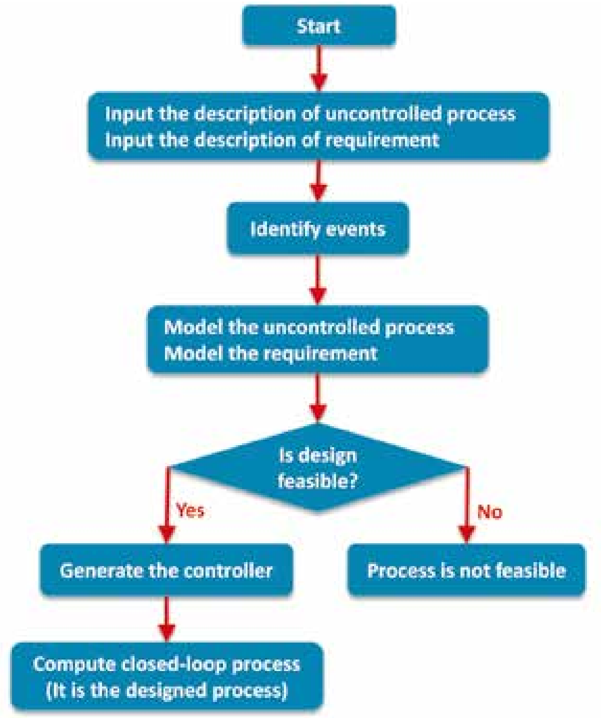


3

1 *Control theory at a glance.*
2 *An example of a discrete-event system model of a sensor.*
3 *Solution approach for automatic process design.*

Supervisory control theory

Figure 1 illustrates what control theory is about; given are an uncontrolled behaviour, which is called *plant* (in yellow), and a desired behaviour, which is called *requirement* (in blue). From the requirement's perspective, parts of the plant's behaviour may be undesired (red arrow), and there may be *final* states to reach (in violet), say to mark the completion of tasks. A controller shall be designed that enforces the requirements on the plant through eliminating the undesired behaviour (crossed arrows) and assuring that the target is reached. Supervisory control theory (SCT) [1] deals with discrete-event systems, i.e. the systems (e.g. plants or requirements) that change their states or outputs upon the occurrence of events.

In SCT, plant, requirements, and controller (also called supervisor) are modelled as finite-state machines. Figure 2 shows a simple discrete-event model of a sensor that has three states: *Idle*, *Active*, and *Broken*. It has four events (*On*, *Off*, *Failure*, and *Repair*), and five state transitions denoted by the arrows labelled by the events. *Idle* is the initial state, denoted by an incoming arrow, and *Active* is the final state, surrounded by an extra circle. The dynamics can be simply described as follows. Initially, *On* brings the sensor from *Idle* to *Active*. There, either *Off* brings back the sensor to *Idle* or *Failure* puts it in *Broken*. Execution of *On* at *Broken* does not change the system state (a self-loop). *Repair* brings back the sensor to *Idle*.

To use finite-state machines for control, SCT needs to know if an event is controllable, i.e. if it can be disabled by the controller if necessary. (Note: Events can be observable or not. For simplicity, we assume here that all events are observable.) In our example '*Failure*' is uncontrollable, while *On*, *Off*, and *Repair* are controllable. Given this information together with the models of uncontrolled behaviour, i.e. plant, and its requirement, SCT first determines if design is feasible. If yes, a controller is designed by SCT, which automatically enforces the requirement in the resulting closed-loop system.

For the processes that can be modelled as finite-state machines, we propose the design approach of Figure 3. Using the descriptions of the existing workflows, i.e. uncontrolled plant, and process requirements, identify the events (and their controllability status). Then, derive the models of the uncontrolled process and its requirement from their descriptions. Use these two models to verify if the design is feasible. If yes, use SCT to generate the controller, and compute the closed-loop process as the required process; otherwise the required process is not feasible. (Note: The remedies for such cases are beyond the scope of this article.) In what follows, we illustrate this approach on a use case. For the sake of readability, we skip technical details and refer the interested readers to [1, 2].

4 *A workflow for mechatronics HW and SW development.*

Use case: synthesis of a development process

Figure 4 shows a generic mechatronics development workflow, which consists of four phases of requirements analysis, design, local verification, and global verification. The terms local and global refer to disciplinary and multidisciplinary activities, respectively. In this example, there are two, hardware (HW) and software (SW), disciplines, each using the flow in the way described in Table 1 (uncontrollable behaviour).

Using the workflow, a development process shall be designed such that it has the properties R1 and R2 in Table 2 (requirements).

Modelling the workflow and requirements

Following Figure 3 we identify *events* first; for every local activity one HW- and one SW-related event. The result is summarised in Table 3.

The columns, from left to right, contain the description of events, their names, and their controllability status, i.e. whether they are controllable or not (Yes or No), respectively. For instance, RDH stands for 'HW requirements derived', and is controllable. Note that the only uncontrollable events are *Start*, as HW and SW are called by a higher process (see 1 in Table 1), and failure-modelling events *RFH*, *RFS*, *LFH*, *LFS*, *DRH*, and *DRS*, as failures happen uncontrollably. Also note that the identification of the events has been done through recognising the 'important happenings' in the descriptions given in Table 1 and 2.

Using the events and the description of the workflows, the two HW and SW components of the uncontrolled processes are modelled as the finite-state machines in Figure 5.

Table 1 *Use of the workflow by HW and SW.*

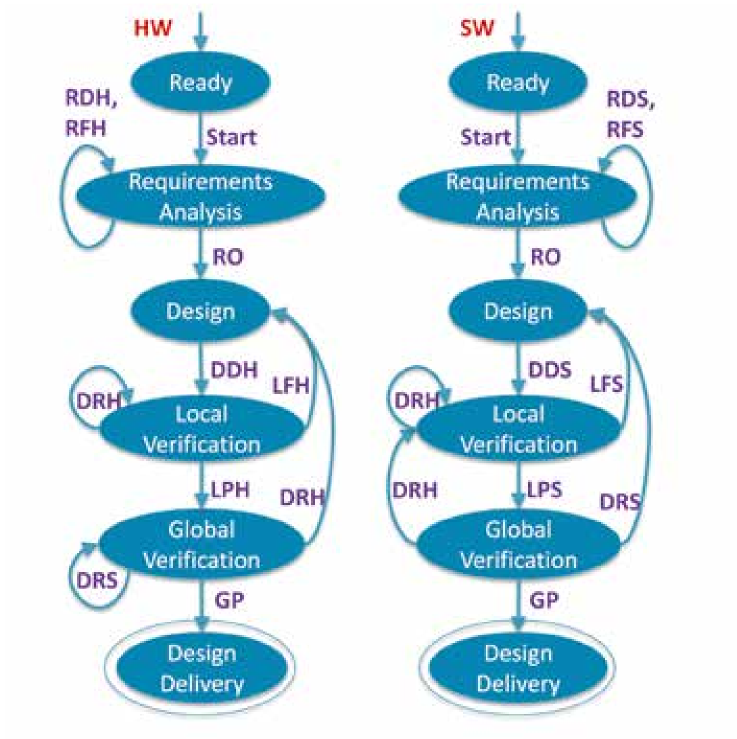
1	The workflow may be called by a higher process.
2	During the Requirements Analysis phase local product requirements are derived and analysed. This phase ends once HW and SW both agree on the results.
3	The Design phase ends once design is ready.
4	During the Local Verification phase the local design is verified against the local requirements. Either it passes the verification, or the design is repeated otherwise.
5	During the Global Verification phase HW and SW designs are verified to function together properly. a) If the HW design is found erroneous, a call for HW redesign and SW Local Verification is made. b) If the SW design is found erroneous, a call for SW redesign is made.

Table 2 *Requirements of the desired process.*

R1	Derivation of local requirements: a) HW and SW requirements may be derived in any order. b) If HW requirements are not good, then both HW and SW requirements shall be updated. c) If SW requirement fails, then only SW requirement shall be updated. d) Requirements derivation shall be OK only after both HW and SW requirements are derived.
R2	Local verification: SW design shall pass local verification only after HW design has done so.

Table 3 *Event names and controllability status.*

Event description	Event name	Controllable
Start the whole process	Start	No
HW requirements derived	RDH	Yes
SW requirements derived	RDS	Yes
HW requirements fail analysis	RFH	No
SW requirements fail analysis	RFS	No
Requirements are all OK	RO	Yes
HW design done	DDH	Yes
SW design done	DDS	Yes
HW design locally fails	LFH	No
SW design locally fails	LFS	No
HW design locally passes	LPH	Yes
SW design locally passes	LPS	Yes
HW design must be repeated	DRH	No
SW design must be repeated	DRS	No
Design globally passes	GP	Yes



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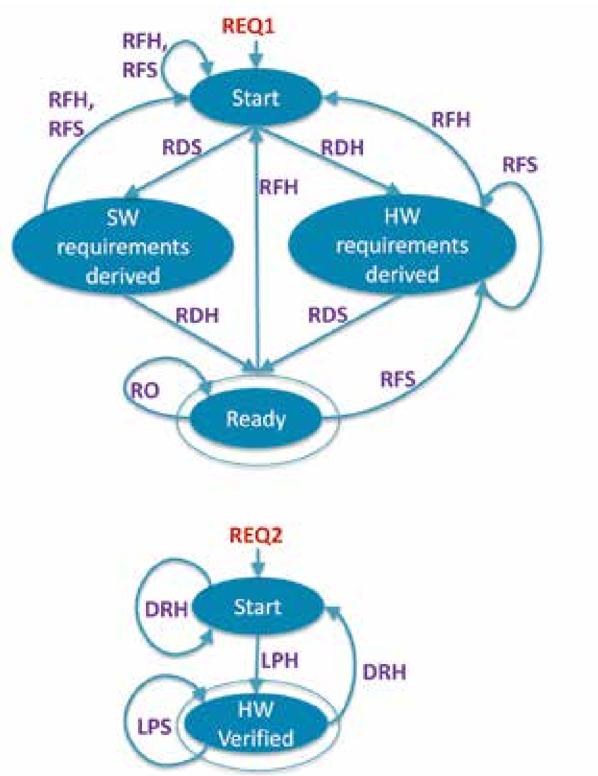

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5 *Models of uncontrolled HW and SW workflows*

6 *Models of the process requirements. Note that in each state machine the events of Table 3 that are not shown are self-looped at all the states.*

Considering the HW model, *Start* moves it from state *Ready* to *Requirements Analysis*, where local requirements are derived (*RDH*) and analysed to find errors (*RFH*). *RO*, modelling the joint HW-SW agreement on requirements, moves the process to state *Design*. When design ends (*DDH*), the process moves to *Local Verification*. If errors are found (*LFH*), design is repeated; otherwise the process moves to state *Global Verification*.
There are three possible outcomes at this state: either the verification is passed (*GP*), upon which the process comes to its end; or a HW error is found (*DRH*), upon which HW design is repeated; or a SW error is found (*DRS*), upon which the process does not change state.
The uncontrolled SW process is very similar to what was just described, except that a found HW error at state *Global Verification* moves the SW process to state *Local Verification* (see 5 in the workflow description). The end states of *HW* and *SW* are marked to identify when the local development is done.

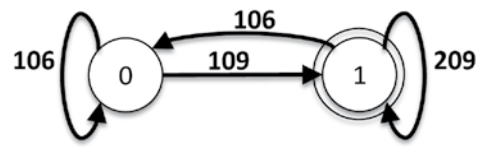
Figure 6 shows *REQ1* and *REQ2*, the models of R1 and R2 in Table 2, respectively. Note that R1 is about the interaction of four events *RDH*, *RDS*, *RFH*, and *RFS*. Observe that, for example, the left and right branches of *REQ1* model the free order of requirements derivation for HW and SW (see R1-a in Table 2). State *Ready* has been marked to indicate the completion of the requirements analysis phase, where *RO* occurs (see R1-d in Table 2). R2, hence *REQ2*, are about the order of local verification at HW and SW, i.e. about the events *LPH*, *DRH*, and *LPS*.

Synthesis of the desired development process

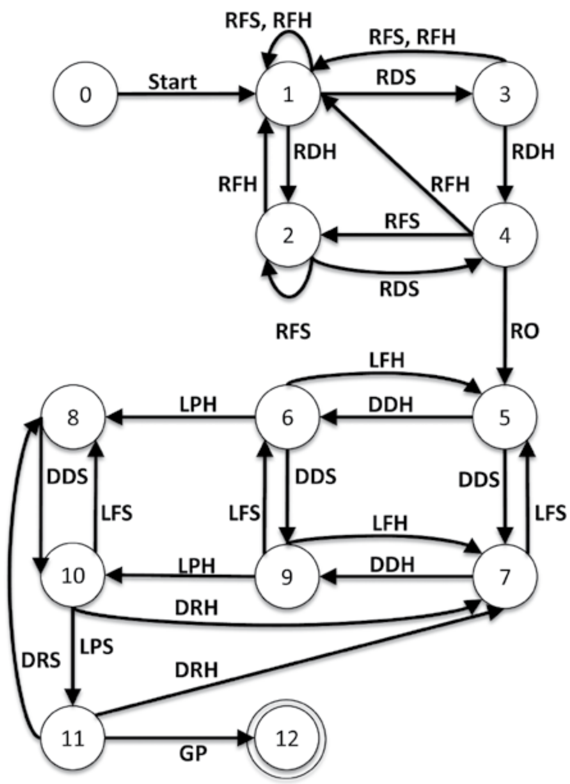
Design will be done with the help of the software tool TCT [3]. In TCT controllable and uncontrollable events are given odd and even numbers, respectively, and states are numbered 0, 1, etc., with 0 being the initial state. Table 4 shows the event numbers. For instance *DRH* is assigned 106. The TCT model of a process can simply be obtained by replacing the events and states of the process with numbers. For example, the TCT model of *REQ2* is shown in Figure 7.

Table 4 *Event numbers.*

Event name	Event number	Event name	Event number
Start	302	Start	302
RDH	101	RDS	201
RFH	102	RFS	202
RO	303	RO	303
DDH	107	DDS	207
LFH	104	LFS	204
LPH	109	LPS	209
DRH	106	DRS	206
GP	311	GP	311



7 TCT model of REQ2.



8 Designed process. It meets the requirements automatically, hence needs no after-design verification.

After creating *HW*, *SW*, *REQ1*, and *REQ2* in TCT, we need to build the uncontrolled process and its requirement from their components. The uncontrolled process, called *PLANT*, is obtained from *HW* and *SW*, and the requirement, called *REQ*, is obtained from *REQ1* and *REQ2*, all using the *Sync* command of TCT as follows:

PLANT = Sync(HW,SW); REQ = Sync(REQ1,REQ2)

Having the models of the uncontrolled process and its requirement, we can verify whether the design is feasible using the following TCT commands:

CONT = Condat(PLANT,REQ) Controllable.

True = Nonconflict(PLANT,REQ)

The terms '*Controllable*' and '*True*' above confirm that a supervisor can be synthesised to enforce the *REQ* on *PLANT*. TCT computes this supervisor, called *SUP*, and the closed-loop process, called *CL*, as follows:

SUP = Supcon(PLANT,REQ); CL = Sync(PLANT, SUP)

Figure 8 shows the model of *SUP*, which is by coincidence the same as the model of the desired process, *CL*. It has 13 states and 31 transitions. Observe that after *Start* the HW and SW requirements are derived (*RDH*, *RDS*) and bug-fixed (*RFH*, *RFS*) in any order at states 1 to 4. A joint agreement (*RO*) leads the development to state 5. At states 5, 6, 7, and 9, HW and SW designs are made (*DDH*, *DDS*) and locally bug-fixed (*LFH*, *LFS*) in any order. However, local acceptance of SW design (*LPS*) may happen at state 10 where local acceptance of HW (*LPH*) has already occurred. Note that SW design can be delayed to state 8, i.e. after HW local acceptance. (Note: SCT-design is maximally permissive. This implies that all the different orders of executing events in the plant's behaviour remain in the closed-loop behaviour, except those which violate the requirement.)

Global verification is done next at states 10 and 11. Global verification of HW can be started at state 10, i.e. before SW is locally accepted, or after that at state 11, an instance of maximal permissiveness of SCT. Any found SW error (*DRS*) redirects the development to state 8 to repeat SW design without doing HW-related activities. A found HW error (*DRH*), however, redirects the development to state 7 to repeat HW design (*DDH*) and HW and SW local verifications. State 12 is marked to designate the job completion.

Conclusions and remarks

On a mechatronics development use case we showed how a process can be designed automatically right in a model-based fashion. This approach shifts the efforts in guess-verify activities of process design to modelling, hence eliminating the vague interpretations, and unnecessary human intervention. In practice, deriving the models from descriptions is a challenging task, on which we are working now. The work will be extended in future to include time, distributed processes, and adaptation to project changes and market fluctuations. ■

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REPORT ON THE PRECISION-IN-BUSINESS DAY: DEMCON

On 12 June 2014, over 60 people attended the Precision-in-Business day that DSPE had organised in Enschede, the Netherlands. The day comprised a company visit to the headquarters of Demcon, the mechatronic engineering spin-off from the University of Twente, which in just 20 years has grown into a high-end technology supplier with 200+ employees and a turnover of €25 million. Participants were given an overview of the challenging projects being tackled in the High-Tech Systems and Medical Systems business units and also enjoyed a tour of the premises, which featured project showcases and included a visit to production facilities and sister company Focal Vision & Optics.

CEO and co-founder Dennis Schipper kicked off with a short introduction on Demcon, highlighting its R&D business activities and its role as a system supplier in the fields of high-tech systems and medical systems. Demcon activities include mechatronic development and production (i.e. assembly and qualification). Demcon is also involved in OEM medical device companies and has a number of investments (e.g. minority interests in companies operating in complementary fields such as vision & optics, MEMS, simulations and metal injection moulding).

Demcon's headquarters are in Enschede, with regional offices in Amsterdam, Eindhoven, Oldenzaal and Münster (Germany). The ambition is to grow to 300+ employees within the next few years and to extend the international scope with a clear focus on Germany, where the large high-tech OEMs are ready to outsource R&D activities and production to system suppliers such as Demcon.

High-Tech Systems

Business unit manager Henkjan van der Pol introduced the High-Tech Systems business unit, which serves the semiconductor industry, the analytical and laboratory markets, the defence & aerospace sectors and the general equipment and machine industries. The central discipline in high-tech projects is mechatronic systems engineering, complemented by the mechanical, electrical and software engineering disciplines, as well as industrial design and quality and project management. Van der Pol focused on the so-called V-model for development projects, in which the seven stages of the V can be covered three times, i.e. for the concept phase, the prototype phase and the proof-of-principle phase. These stages run from functional specification/system concept right down to design and technical product documentation/module implementation and up to system integration and testing & debugging.

The showcases included a short-stroke stage for Mapper Lithography, a Coriolis flow sensor for Bronkhorst High-Tech, a wafer stage qualification tool for ASML and a direct electron detector camera for FEI.

Demcon headquarters in Enschede (the former R&D site of the Swedish telecom giant, Ericsson), located on the Business & Science Park, near the University of Twente. (In the background, the FC Twente football stadium, Ed.)

Design of the Vector Installation Tool.

To conclude, Henkjan van der Pol elaborated on VECTOR, a Seventh Framework Programme funded by the European Union, for which Demcon develops a compact, mechatronic handheld tool for making optical fibre connections. At the moment, this time-consuming precision job requires craftsmanship. Automation is required to accelerate fibre-to-the-home deployment. Demcon automated the six steps of this process (i.e. stripping, cleaning, cleaving, plasma treatment, inspection and connector placement), which involved disciplines such as optics, plasma technology and microfluidics. DEMCON handled everything from concept to prototype, invested a lot in validation and six-sigma proofing of the tool, and assists TE Connectivity in the industrialisation for large-scale production.

Medical Systems

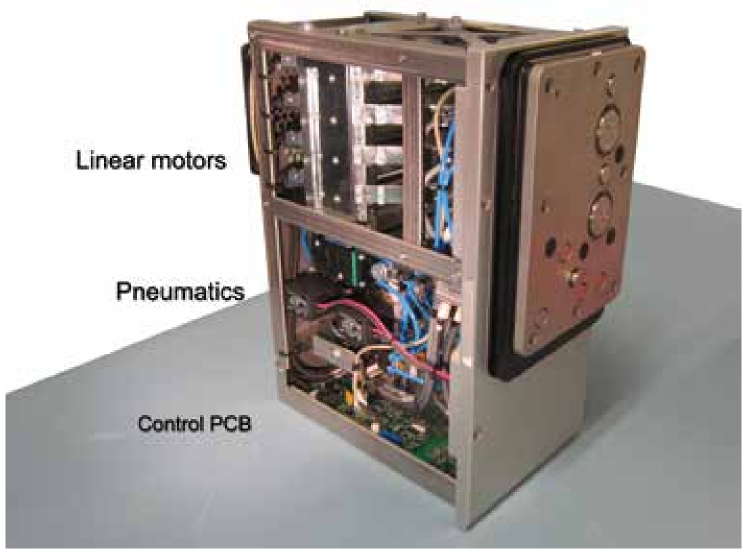
Although most medical systems can be regarded as high-tech, Demcon decided to create a separate business unit to accommodate medical product development, featuring long project lead times, close user involvement and a certification trajectory due to strict safety regulations. Manager Michiel Jannink introduced his business unit and presented a quick overview of projects, from the Fluido unit for the controlled heating of blood and infusion fluids to an HME (heat and moisture exchanger) booster for ventilation equipment. The presentation also included projects for Demcon's own medical OEM subsidiaries, Finapres Medical Systems (non-invasive hemodynamic monitoring) and Macawi Medical Systems (high-performance ventilators).

Jannink then presented some details of the advanced eye surgery activities the company is involved in, i.e. the development of an innovative eye surgery system for D.O.R.C. Demcon handled the system integration and developed the heart of the system, a new fluid control system called Vacuflow VTi (valve timing intelligence), which eliminates the risk of unwanted pulsation or unwanted flow. The smart pump design, which is based on the use of linear motors and is well known from semiconductor equipment applications, means that it can instantly deliver the exact flow and fast vacuum required by surgeons. As such, the project is a great example of a technology crossover from high-tech to medical systems.

Jannink concluded with a few slides on the development of an image-guided needle positioning system as part of a project within the Center for Medical Imaging North East Netherlands. This system is in line with the trend towards image-guided intervention and therapy, which is expected to cut costs and increase quality because of its minimally invasive character. Demcon's mechatronic design automatically positions and guides existing intervention needles, using well-known 3D imaging techniques. This approach reduces procedure time as well as complications, enhances usability and allows more complex procedures.

Focal Vision & Optics

The final presentation of the day was given by Gerard van den Eijkel, CTO of Demcon sister company Focal Vision & Optics, which designs and delivers optical measurement systems for a variety of industrial applications, including quality precision inspection and in-line optical measurement. He discussed the trends in precision optics and vision engineering, such as the integration of imaging and image recognition, and the increasingly tighter specifications on the required optics for industrial measurement systems (e.g. 2,5 μm optical resolution, 10 μm depth of field, 3 μm field curvature and 3 μm astigmatism). These trends require the design of smart vision algorithms as well as high-end simulations of optical designs, and this places high demands



Design of the pump unit for the new D.O.R.C. eye surgery system.

on mechanical construction and assembly tolerances for mounting lenses for instance.

Tour

The company tour that concluded the day included the above showcases, while also taking in Demcon's production facilities and Focal's optical laboratory. The successful Precision-in-Business Day underlined that, after Eindhoven, the Enschede (Twente) area is the second most important high-tech systems region in the Netherlands. ■

WWW.DEMCON.NL WWW.FOCAL.NL

■ *Production facilities at Demcon include a cleanroom (still under construction at the time of the Precision-in-Business day) and additional facilities for 'clean' assembly.*

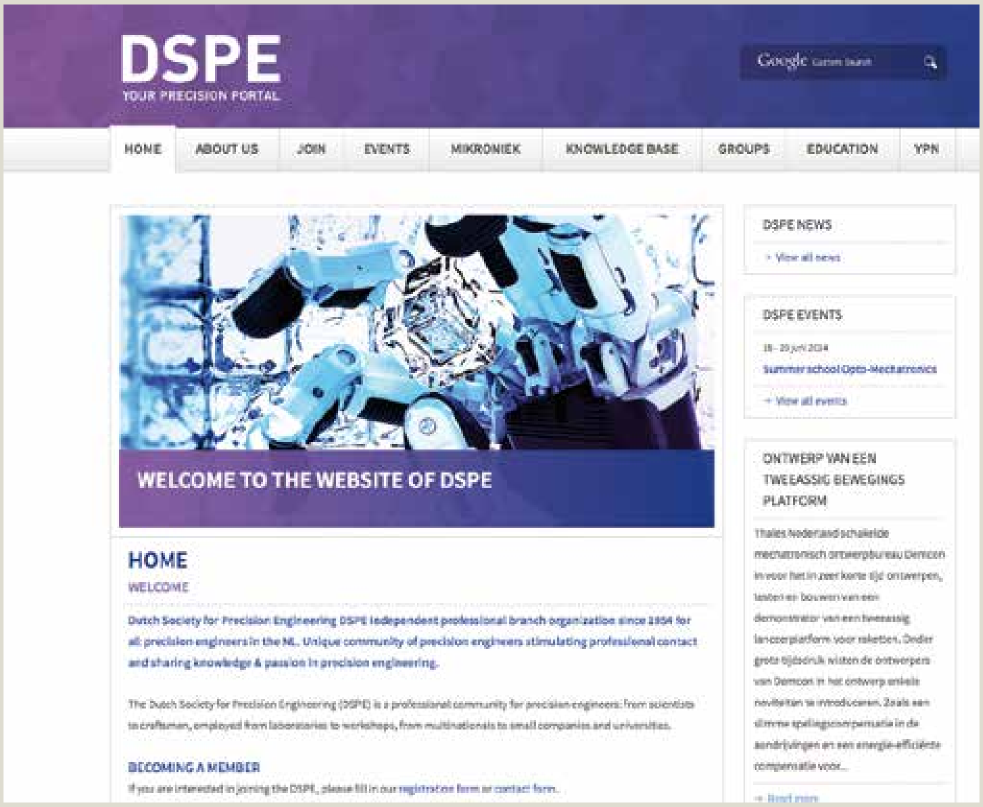
DSPE 60 years

This year, DSPE is celebrating its 60th anniversary as an independent professional trade organisation for all precision engineers in the Netherlands (and increasingly abroad). At 60, DSPE is alive and kicking, rolling out all kinds of new initiatives with a variety of partners. Recent examples include the Special Interest Groups, a new summer school, the DSPE Conference, etc. Check out the brand new website as well for a comprehensive overview of DSPE activities.

This milestone provides the perfect opportunity to connect a historical perspective of the ongoing developments in the field of precision engineering (including mechatronics and related disciplines) to the current roadmaps in the high-tech systems area. In its 60 years, DSPE has seen the high-tech industry become an important part of the Dutch economy, with the Dutch regarded as world-class players in mechatronics.

The forthcoming issue of Mikroniek will in part be devoted to 60 years of DSPE. A small 'party' is also planned at the Precision Fair, the event of Mikrocentrum (this year on 12 and 13 November, once again in Veldhoven, the Netherlands) that is so closely connected with DSPE. For more announcements, please go to the DSPE website. ■

WWW.DSPE.NL



■ *Check out the brand new DSPE website.*

SHINY METAL IN THE PICTURE

Aluminium is the material of choice in numerous industrial applications because of its high strength-to-weight ratio and other attractive characteristics, such as its resistance to corrosion, low density, malleability and ductility. Its relatively high conductivity is also an advantage, but causes significant problems during machining. Especially when using one of the most precise and cost-effective machining processes (photochemical etching), it leads to significant issues in terms of etching accuracy and repeatability. This article examines the issues and presents solutions.

ALBERT TSANG

Despite the fact that photochemical etching has been a machining technology for over fifty years, it is still a relatively low-profile process, and its practical use in a variety of manufacturing scenarios with an ever broadening number of materials is one of industry's best kept secrets. Commonly misrepresented as a prototyping technology, photochemical etching (see Figure 1) is in fact a versatile and increasingly sophisticated metal machining technology, with an ability to mass manufacture complex and feature-rich metal parts and components.

Using photo-resist and etchants to chemically machine selected areas accurately, the process is characterised by retention of material properties, burr-free and stress-free parts with clean profiles, and no heat-affected zones. Coupled with the fact that photochemical etching uses easily re-iterated and low-cost digital tooling, it provides a cost-effective, highly accurate, and speedy manufacturing alternative to traditional machining technologies such as stamping, pressing, punching, and laser and water-jet cutting.

However, for any machining technology to remain viable and relevant in modern and innovative manufacturing projects and environments, it must adapt to the needs of industry. Specifically, machining technologies these days must be able to work to extremely high tolerances, and on

1 *Photochemical etching starts with applying a photoresist layer and imaging (under cleanroom conditions) of the pattern to be etched.*

AUTHOR'S NOTE

Albert Tsang is the Technical Manager at Precision Micro, Birmingham, UK. For over fifty years, Precision Micro has pioneered photochemical etching, a manufacturing technology using subtractive chemical erosion to produce burr- and stress-free precision metal components. The company creates highly innovative solutions to a wide range of engineering challenges using a 2D process to create 3D components that cannot be created with other technologies.

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2 *Example of a photochemically etched aluminium product.*

more ‘modern’ metals which are sought after in various industrial applications.

As such, companies such as Precision Micro that have invested in research and development in the field of photochemical etching, have focussed huge amounts of time and money refining the process for use on aluminium, a metal that is used more and more due to its inherent characteristics, but which is notoriously difficult to work. Many companies that have used traditional manufacturing processes on aluminium, for example, will be familiar with issues such as the reflective nature of aluminium (which makes laser cutting problematic), and the fact that aluminium coats dies which makes punching unreliable.

This article analyses developments in the area of aluminium machining via photochemical etching, and looks at the opportunities that are therefore opened up for product designers in various industry sectors; see Figure 2.

A versatile material

Aluminium alloy is the material of choice in a number of industrial applications due to the fact that it is corrosion-resistant, light, and strong. In this way, it exhibits many of the attributes of titanium, the strength-to-weight ratios of each metal being a key attribute. However, aluminium is significantly cheaper than titanium, this lower cost not so much being a product of its abundance and ease of production (it is in fact quite expensive to extract from the ore bauxite) as of its recyclability. It is in fact suggested that within twenty years there will be no need to mine for more aluminium as enough will have been mined and will be continually recycled to meet demand.

Aluminium is also considerably less dense than titanium. Whereas titanium is stronger and more corrosion-resistant than aluminium, it has a relatively low fatigue limit, which makes aluminium the material of choice in numerous aerospace applications, and the automotive, transportation, and building sectors. Its low density is the key, coupled with another characteristic, the fact that it is an excellent conductor of heat and electricity making it a preferred material for cabling and heat exchangers.

But this characteristic is also its Achilles heel when it comes to working the metal. For example, aluminium in the photochemical etching process reacts with the corrosive chemistry and becomes exothermic, releasing heat energy. This has a knock-on effect to the efficiency and accuracy of the photochemical etching process..

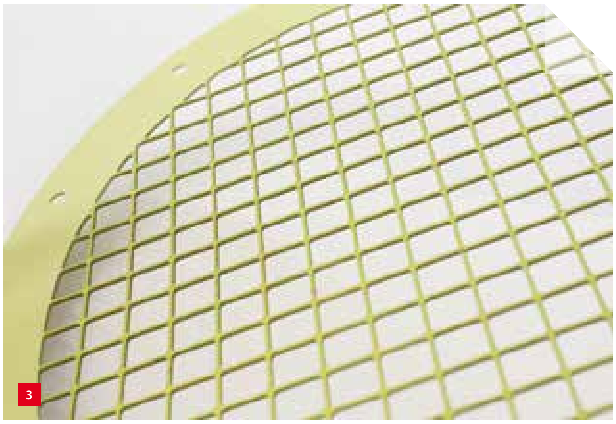
Working with aluminium

So it is its exothermic nature that introduces hurdles for the efficient application of photochemical etching processes to aluminium, as well as the fact that aluminium is a corrosion-resistant metal, and photochemical etching is a machining process based around selective corrosion. Aluminium is amphoteric in nature, meaning that it will react with acids or alkalines. As such it can be photochemically machined using either acidic or alkaline etchants, but use of either presents challenges.

The highly exothermic reaction of aluminium to the etching process can in some instances destroy the phototool, and creates a rough etch. Effectively, the exothermic reaction causes the resist to pull away from the aluminium sheet, allowing the etchant to seep under the resist and compromising the etch. This leads to a rough, jagged, granular edge, a long way away from the smooth and straight-etched profiles typical of the photochemical etching process. The key to successful photochemical etching is strict process controls. Some research into the efficient etching of aluminium has focused on the etchants used, some on temperature control, and still more on the cleaning and preparation of the metal.

Due to the exceptional demand for aluminium in a variety of industrial applications, and the requirement for a machining process that is both repeatable and consistent, and overcomes such issues as already highlighted with laser cutting and punching, Precision Micro has invested considerable resource (some £500,000) on lamination equipment to improve the adhesion of the resist to the aluminium.

In addition, the company has utilised its 5-decade long experience of photochemical etching to refine and adjust



the concentrations of the corrosive chemistry used on aluminium to overcome some of the inherent issues involved with etching an amphoteric material. Such adaptations of chemistry have proved satisfactory for numerous projects with additional emphasis on a range of other factors including process speed adjustment and temperature control. All these factors are inter-related, and one can have a negative impact upon the other. For example, adjusting speed of etching can lead to resist lift, so the optimisation of the process is a balancing act.

3 *Etched aluminium air intake grille.*
4 *20-µm aluminium etched from a 40-µm kapton backing.*

Practical applications

Through the reconfiguration of machines, chemistry, and process parameters, Precision Micro has been involved in countless projects involving photochemical etching of aluminium. One such was work undertaken for a leading helicopter manufacturer that involved the etching of aluminium air intake grilles; see Figure 3. This was a not a mass volume project by any means, and the parts were certainly not as feature-rich as in many other projects (photochemical etching typically being associated with high-volume runs of complex parts). However, etching was the chosen manufacturing process as alternative technologies introduced stress into the components. As this was an aerospace application, weight was a key factor, so the client demanded the use of aluminium due to inherent weight savings.

In another aerospace application, similar techniques were applied to the manufacture of numerous different aluminium parts that made up a dehumidifier used in aircraft cabins. For this application, aluminium was used for a variety of reasons, key among which was its low weight, but also its thermal characteristics.
Etched channels and precision apertures were produced in many of these parts, photochemical etching being the manufacturing process of choice as use of stamping would have been prohibitively expensive due to the need for 36 different stamping tools. In addition, stamping would not have been able to achieve the necessary cross section of the profiles which were essential to achieve the flow and thermal profile specified. Also, photo-chemical etching meant that there were no re-cast layers which are typical of some machining processes such as EDM.

One final application was for an audio equipment manufacturer that required planar ribbon tweeters for high-end recording studio speakers. On this project, 20-µm aluminium was etched from a 40-µm kapton backing which needed to be kept intact; see Figure 4. This material would have been too thin to stamp successfully, and stamping would also have compromised the kapton backing.

Conclusion

The fact that across industry, aluminium is now so often the material of choice requires that any metal manufacturing process is able to efficiently and precisely work the material. Photochemical etching is one of today's most cost-effective and accurate manufacturing technologies, especially for the high volume manufacture of complex and feature-rich products and components. The inherent accuracy of the process, the fact that it induces no stress in worked materials, and the fact that use of the process provides massive tooling costs savings, means that OEMs are clamouring for the process in a variety of metals.

The nature of aluminium is such that it has until recently provided significant challenges for photochemical etching practitioners. However, Precision Micro has developed and successfully applied photochemical etching to aluminium in a variety of real industrial applications. ■

SEECUBIC PROVIDES "ULTRA-D INSIDE"

Until now, adding a third dimension to your TV enjoyment required the cumbersome use of an extra pair of glasses. That's why 3D TV wasn't the success people had hoped it would be. Therefore, many companies are now trying to develop a glassless 3D TV system, one such company being SeeCubic in Eindhoven, the Netherlands, which is part of US-based StreamTV Networks. A demonstration of its 3D system produces admiration of its performance and comfort, but it also becomes clear that the system needs the application of sophisticated optical and precision-mechanical technology, as well as advanced dedicated software.

AUTHOR'S NOTE

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

FRANS ZUURVEEN

The history of the SeeCubic glassless 3D system starts in the nineties at Philips Electronics Research Laboratories. In 2009, the global company decides to stop these activities. Walther Roelen and Hans Zuidema, who were involved in the project at an earlier stage, then start SeeCubic (see Figure 1), with the mission to further develop this 3D technology, which is already covered by a series of basic patents. The optics and software of the system, which is currently called Ultra-D, have now been perfected thanks to fresh insights, making them ready for use in commercial products. SeeCubic doesn't want to be a TV hardware provider however. Its vision is to provide the innovative technology to third parties. It won't be long before there are TV sets with the logo "Ultra-D inside" displayed on the outside.

1 *The SeeCubic assembly and testing room. The cleanroom is visible at the back.*

Experiencing the third dimension

The human brain is able to construct a 3D image from two stereoscopic images provided by the eyes of a viewer (see Figure 2). This phenomenon is called stereopsis. Common 3D technologies work with two separate images transmitted to the brain of the viewer by periodically switching the transmission factors of two glasses on and off. Ultra-D doesn't need these separate glasses because the light of the individual pixels of the LCD screen is directed into space and merges to provide a complete view, different for each of the viewer's eyes.

The Ultra-D software is able to handle different formats of TV signals with integrated information for the third viewing dimension. From these signals, Ultra-D generates a dedicated digital signal in real time. Here, these software procedures will not be dealt with further.

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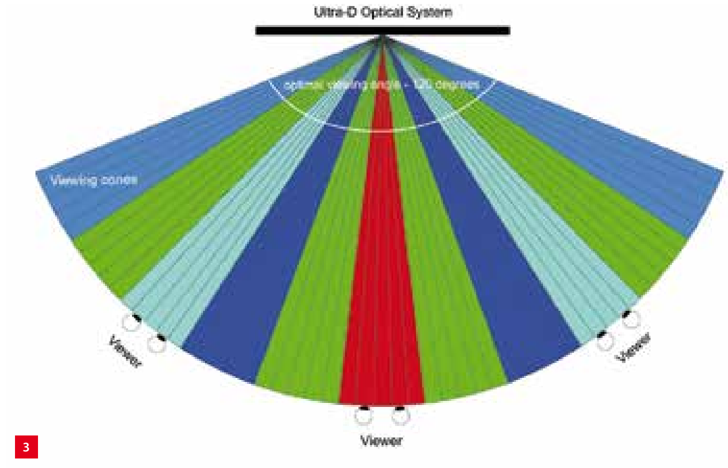


3

2 *Artist impression of experiencing 3D.*
3 *The sectors in the 120° field of view, each of which provides an ideal 3D sensation.*

It is interesting to note that Ultra-D can also add information about the third dimension to 'simple' 2D signals. This non-stereoscopic procedure is based on the fact that a 2D image contains information about the depth of individual image parts, called monocular cues. One example of this is the image of a road leading into the distance with a vanishing point. Another example is the decreasing of the size of an object with further depths. Also, colour can be used to distinguish depth: white, yellow and red for near objects, grey and blue for objects further away. One final monocular cue is motion parallax. When a viewer moves, the background moves with respect to the object, making clear that the background is further away.

The software built into Ultra-D can transfer 2D signals into semi-three-dimensional signals by using these monocular cues. One notable example is the addition of a 3D sensation to historic 2D movies.

Ultra-D optics

The essential component of the Ultra-D optical system is a square array of small lenses positioned at a well-defined distance in front of the LCD screen. When observing LCD pixels through one of the lenticular lenses, one of the eyes sees different LCD pixels than the other eye because of the difference of the viewing angles for both eyes. Thus, the eyes receive different viewing information, resulting in the intended stereoscopic 3D effect.

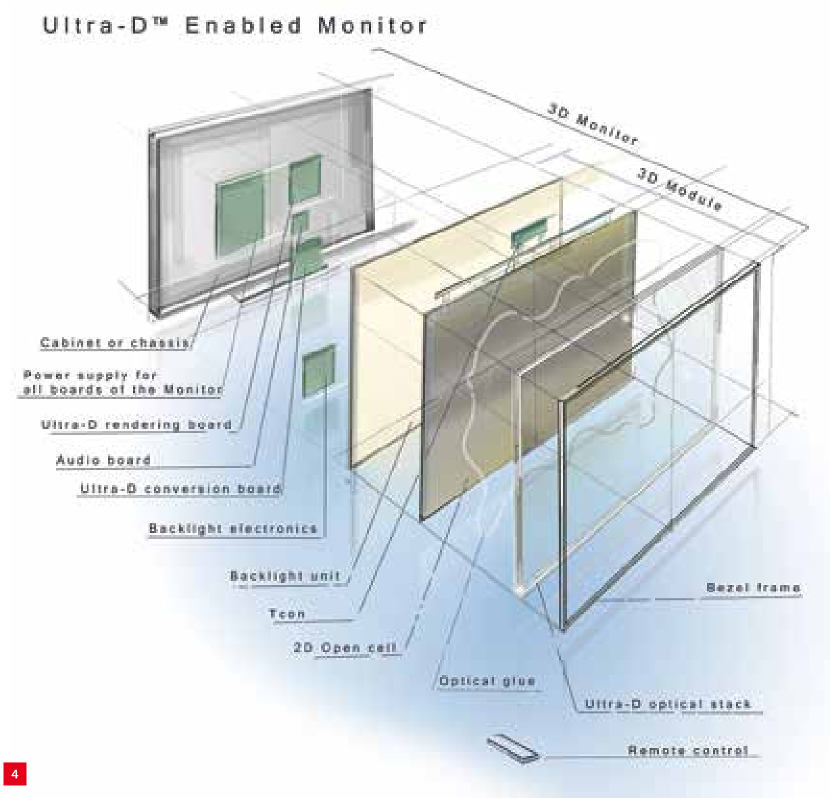
To acquire a spatial image with sufficient resolution, Ultra-D uses the best possible LCD screen: QFHD, Quad Full HD, with 3840 x 2160 pixels. Each LCD pixel consists of three subpixels, for the colour components red, green and blue, which merge into one colour for the viewer. The pitch of the QFHD pixels depends on the screen size diagonal, of course. For the 50" TV set used by SeeCubic for demonstrations, the resulting pixel pitch is about 300 µm, providing a subpixel pitch of 100 µm, corresponding with the dimensions of 100 x 300 µm for one set of subpixels. The pitch of the lenses in the lenticular stack is 3-10 times larger than the LCD pixel pitch.

The resolution of a spatial viewing system cannot be expressed as a number of pixels, as is the case for 2D systems. For Ultra-D, the resolution is expressed in spatial units called voxels. An Ultra-D system presents a viewer with about 500 million voxels in their viewing space.

The total field of view for the viewer of a SeeCubic screen is about 120° in a horizontal plane. When moving through this angular range, the viewer's eyes then see different LCD pixel sets through one individual lenticular lens. This is why a viewer then moves through subsequent sectors, which each provide an ideal 3D sensation (see Figure 3). The most important challenge when designing Ultra-D was to make the transitions from sector to sector as smooth as possible, making them invisible for the viewer. SeeCubic succeeded in solving this problem by introducing a small angle between the LCD screen and the lenticular stack: 0.1 mrad, about 20 arcsec.

Precision technology

As mentioned before, the Ultra-D system is based on two cornerstones: dedicated software and precision technology (see Figure 4). Taking a closer look at this last cornerstone, we note that it can be subdivided into two challenges: firstly, to produce a faultless lenticular stack, and, secondly, to precisely position the stack in relation to the LCD screen. An extra factor complicating these challenges is the limited space on the outside of the LCD-lenticular combination. Because consumers demand a 'rimless' screen for their TV sets, the available space on the outside is no wider than



4 *Exploded view with all the hardware components of the Ultra-D system.*
5 *The SeeCubic positioning and bonding machine.*
6 *Detail of the mechanism for the accurate positioning of the optical stack.*

1-2 mm, which means that the 'manoeuvring free space' for positioning the lenticular stack in relation to the LCD is very 'cramped'.

Tolerances for the position of individual lenticular lenses with respect to the LCD pixels amount to ±20 μm in the X and Y directions and ±100 μm in the Z direction perpendicular to the (X,Y) screen plane (see Figure 5). The specified Z distance between the lenticular lens and the LCD arrays is acquired by depositing the individual tiny plastic lenses onto an accurately plane-parallel glass plate with a thickness of about 10 mm. The problems arising when manufacturing such a lenticular stack are more or less comparable with the problems when making large HD LCD screens with not a single subpixel missing. For this, LCD manufacturers in the Far East have been contacted. They have succeeded in delivering lenticular stacks according to the specifications formulated by SeeCubic.

To connect the lenticular stack to the LCD screen, UV-hardening glue is being used. However, air bubbles and other defects are not allowed in this procedure with a glue sheet thickness of about 0.2 mm. SeeCubic applies one dot of glue in the central area, which spreads by way of capillary action between the two surfaces. Needless to say, this is a challenging procedure that has caused numerous initial difficulties.

INFORMATION
WWW.SEECUBIC.COM

In this gluing procedure, the accurate positioning of the lenticular stack in relation to the LCD screen is of vital importance, especially in connection with the required angular positioning of 0.1 mrad (see Figure 6). A manipulating mechanism has been designed with a functional adjusting criterion, namely that the LCD screen is switched on. The operator is then able to read off the angular deviation from the LCD patterns observed.

To conclude

Ultra-D is an excellent example of the fruitful combination of advanced software with precision technology. Not only can a microprocessor perform highly complicated calculations in such a short space of time that a TV viewer can see the result in real time. Also, it is almost impossible to believe that subminiature pixels and lenses can be mutually positioned so accurately that the viewer can see a continuous spatial image with a wide angle of 120°. It is worth bearing in mind that many innovative ideas behind the future glassless 3D TV screen with "Ultra-D inside" come from Brainport Region Eindhoven. ■

Dutch successes at the RoboCup 2014 in Brazil

The Tech United robot football team of Eindhoven University of Technology (TU/e) won the RoboCup in the Middle Size League (MSL), the 'premier league' of robot soccer, in Brazil this July. In the MSL league, each team consists of four field players on wheels and one goalkeeper with special arms to stop the ball. Completely independently, without any human control, the robots play two fifteen-minute games. In the 2014 final, the Dutch robots beat the Chinese Water team from the University of Beijing three goals to two, thanks to their combination play and excellent goalkeeper.

The Eindhoven team had already faced the Beijing team twice in a RoboCup final, but lost both the 2011 and 2013 matches. The Chinese robots are known for their speed and strength, as well as their rough play. The Dutch team, on the other hand, is focused on technical combination play, and has made it to the finals for seven years straight. This was only the second time since 2012, however, that the team actually won the cup.

In the RoboCup @Home league for service robots, Eindhoven robot AMIGO took second place. The @Home team demonstrated that, using a tablet, the operator can give AMIGO instructions, and that the care robot is able to explore its surroundings and familiarise itself with objects. The winning team in Brazil was from China.

WWW.TECHUNITED.NL

WWW.ROBOCUP2014.ORG

FLICKR.COM/TECHUNITED

5k€ football robot

Just before the RoboCup 2014 tournament kicked off in Brazil, the TURTLE-5k football robot was launched at home in Eindhoven. Its design was based on the TURTLE robot used by the Tech United team that became world champion in the MSL league in 2012. The TURTLE-5k has the same performance capabilities as the 2012 MSL robot, but was fully redesigned to develop a platform that can be available to everyone. Where possible, this new platform recapitulates hardware knowledge gained over the past 15 years of the RoboCup MSL.

It is now possible to make this robot for around €5,000 a piece. Originally, these robots cost about €25,000 to make. This huge cost reduction was achieved by a consortium of ACE, Frencken, VEDS and TU/e. Drawing on their experience in the high-tech industry, the companies were able to reduce the cost price by 80%.

The idea, according to a press release, was to make the robot easily adjustable and extensible to maintain the innovative character of the MSL in terms of hardware. Teams focussing on a specific part of the robot, e.g. vision, are encouraged to add their own equipment or to replace existing units with their own. TURTLE-5k is not meant to be a standard platform for the MSL. Instead, it gives teams that are already able to play football but require extensions in order to stay competitive the opportunity to buy an affordable base. This, therefore, makes it easier for new teams to join the RoboCup MSL competitions, while also allowing current MSL participants to focus on cutting-edge research on a particular component instead of having to design the entire robot from scratch.

ASML was the first to buy a team of TURTLE-5k robots. The design has been released for other interested parties through www.roboticopenplatform.org/wiki/TURTLE-5K.

WWW.TURTLE5K.ORG

Europe invests in robotics

At Automatica 2014 in Munich, Germany, on 3 June, the European Commission and euRobotics AISBL have launched the world's largest civilian research and innovation programme in robotics. The PPP in Robotics initiative is to maintain and extend Europe's leading position in this strategic area, whose overall market volume could reach more than €60 billion by 2020, and is expected to create over 240,000 jobs in Europe. The European Commission will invest €700 million in the PPP in Robotics under its new research and innovation programme Horizon 2020. The European industry's overall investment will amount to €2.1 billion. This public-private partnership (PPP) will increase Europe's competitiveness in the production and use of robotics in industry, agriculture, health, transport, civil security and households.

The programme is run by SPARC, a contractual partnership between the European Commission and euRobotics AISBL, the Brussels-based international non-profit association for all stakeholders in European robotics.

WWW.SPARC-ROBOTICS.NET

WWW.EU-ROBOTICS.NET

Multilayer actuators with improved heat dissipation

In extreme operating conditions, where oil, splash water or continuously high humidity prevail, PI Ceramic's PICMA® stainless steel encapsulated multilayer piezo actuators ensure the required reliability and lifetime. But if these actuators are to be used for dynamic applications at the same time, the self-heating of the actuator can be a limiting factor. Therefore, PI Ceramic (located in the city of Lederhose, Thuringia, Germany) now offers encapsulated actuators with improved heat dissipation properties. A casting compound that does not impair the actuator displacement replaces the inert gas in the hollow space between metal bellow and piezo actuator.

An additional cooling of the stainless steel casing, e.g. with compressed air or water, can support to dissipate the heat generated by the dynamically operating actuator. This allows to achieve working frequencies that are ten times higher than with an actuator without casting compound, for example, up to 3.5 kHz with the P-885.95 actuator over the full travel range of 36 µm.

WWW.PI.WS

maxon systems to boost innovation

maxon motor benelux has started a new business unit, maxon systems, based in Enschede, the Netherlands, to meet the increasing demand for development capacity. Developing systems is a logical addition to the in-house product development capacity, with Enschede being the third site besides maxon's R&D capacity in Sachseln, Switzerland, and Sexau, Germany.

maxon motor is a worldwide leading provider of high-precision drive systems up to 500 W. For the past 50 years, their modular product range has constantly been expanded and now includes brushless and brushed DC motors with ironless winding up to 500 W; brushless flat motors with iron core up to 90 W; planetary, spur and special gearheads; sensors, servo amplifiers and position controllers; etc.

WWW.MAXONSYSTEMS.NL

WWW.MAXONMOTOR.COM

CPE COURSE CALENDAR

COURSE (content partner)	CPE points	Provider	Starting date (location, if not Eindhoven)
BASIC			
Mechatronic System Design - part 1 (MA)	5	HTI	29 September 2014
Mechatronic System Design - part 2 (MA)	5	HTI	15 December 2014
Construction Principles	3	MC	18 November 2014 28 October 2014 (Utrecht)
System Architecting (Sioux)	5	HTI	10 November 2014
Design Principles Basic (SSvA)	5	HTI	to be planned
Motion Control Tuning (MA)	6	HTI	19 November 2014
DEEPENING			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	1 December 2014
Actuation and Power Electronics (MA)	3	HTI	22 September 2014
Thermal Effects in Mechatronic Systems (MA)	3	HTI	5 November 2014
Summer school Opto-Mechatronics (DSPE/MA)	5	HTI	to be planned
Dynamics and Modelling (MA)	3	HTI	28 October 2014
Summer School Manufacturability	5	LiS	to be planned
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	28 October 2014
Applied Optics	6.5	MC	11 September 2014
Machine Vision for Mechatronic Systems (MA)	2	HTI	25 September 2014
Electronics for Non-Electronic Engineers (T2Prof)	10	HTI	13 January 2015
Modern Optics for Optical Designers (T2Prof)	10	HTI	12 September 2014
Tribology	4	MC	21 April 2015 28 October 2014 (Utrecht)
Introduction in Ultra High and Ultra Clean Vacuum (SSvA)	4	HTI	27 October 2014
Experimental Techniques in Mechatronics (MA)	3	HTI	to be planned
Design for Ultra High and Ultra Clean Vacuum (SSvA)	3	HTI	to be planned
Advanced Motion Control (MA)	5	HTI	6 October 2014
Iterative Learning Control (MA)	2	HTI	3 November 2014
Advanced Mechatronic System Design (MA)	6	HTI	to be planned
Finite Element Method	5	ENG	30 October 2014

DSPE Certification Program

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

WWW.DSPE.NL/EDUCATION/LIST-OF-CERTIFIED-COURSES

Course providers

- Engenia (ENG)
  WWW.ENGENIA.NL
- The High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- LiS Academy (LiS)
  WWW.LISACADEMY.NL

Content Partners

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

Alten Mechatronics – "providing personalised solutions that meet client objectives"

Alten Mechatronics is a leading technology consulting and engineering company in which all activities revolve around technology, especially mechatronics and robotics. Alten conducts research and development activities and works for leading technology-oriented companies. Alten's mission is "to support clients in deploying their industrial strategy by providing personalised solutions that meet their specific objectives."

With highly qualified staff Alten works on innovative technical developments. The services of Alten Mechatronics vary from short-term consulting assignments to full-time design and development in the client's project team or taking over full responsibility of his project.

Robotics

Within the area of mechatronics, the integral approach to optimally (re)design a mechanical system and its control system, is central. Alten also specialises in system integration and robotics, dealing with the theoretical implications and practical applications of robots in the broadest sense of the word. Robotics in the Netherlands is still in development and Alten Mechatronics is strongly involved in this technological development. For example, Alten organises training courses in robotics and in ROS-Industrial specifically. The Robot Operating System (ROS) is an open source cross-platform framework for robot-specific software development. With ROS-Industrial the application of ROS can be realised within industrial robotics.

One of Alten's expertises is system integration and robotics.

Multidisciplinary approach

An integrated approach to the optimal (re)design of mechanical systems, together with the associated control system, is central to the field of mechatronics. Projects on the cutting edge of control technology, measurement, mechanical engineering and electronics require a multidisciplinary approach. Such projects appear in all market sectors and the engineers of Alten Mechatronics have the knowledge and experience to operate in this multidisciplinary environment.

International presence

In the Netherlands, Alten is located in Eindhoven, Capelle a/d IJssel and Apeldoorn. Internationally, the Alten Group counts over 14,000 engineers and is active in 16 countries, and, therefore, is one of the leading suppliers of technical consultancy in Europe, having the international presence to take responsibility for large projects. At the same time, the decentralised organisation ensures that Alten can offer local and customised solutions to specific customer requests. ■

INFORMATION

INFO@ALTEN.NL
WWW.ALTEN.NL

"Revolution vs. Evolution"

The second edition of the DSPE Conference on Precision Mechatronics will be held in conference hotel De Ruwenberg in Sint Michielsgestel, the Netherlands, on 2-3 September 2012. This year's theme is "Revolution vs. Evolution", because progress is always a mix of evolution (optimisation) and revolution (disruptive technologies).

The DSPE Conference 2014 will be held at the inspiring location of conference hotel De Ruwenberg in Sint Michielsgestel.

The target group of the DSPE Conference includes technologists, designers and architects in precision mechatronics, who, through their respective organisations, are connected to DSPE, the mechatronics contact groups MCG and MSKE, or selected companies and research/educational institutes. In addition to paper and poster presentations and demos, the conference will provide the ideal setting for networking, technical discussion and sharing the enthusiasm of working in this challenging field.

The programme is outlined below and the following pages feature the abstracts of the papers and the posters and demos. ■

INFO@DSPE-CONFERENCE.NL
WWW.DSPE-CONFERENCE.NL

Tuesday 2 September 2014

Invited speaker

Nanopatterning Steppers and Large Area Patterning Tools Based on Jet and Flash Imprint Lithography
Prof. Dr. S.V. Sreenivasan (Professor of Mechanical Engineering & Computer Engineering, and Co-Director of NSF NASCENT Center, University of Texas at Austin; Chief technologist, Canon Nanotechnologies, Austin, TX, USA)

SESSION 1: SYSTEM DESIGN 1

TEM Piezo short-stroke stage – a design based on error budgetting
Jeroen de Boeij, Twan van den Oetelaar (FEI)

Conceptual design of high-performance motion systems using topology optimization
Gijs van der Veen, Matthijs Langelaar, Fred van Keulen (Delft University of Technology)

Inside the EUV Source, design to specification and costs
Cor Ottens (ASML)

SESSION 2: THERMAL / CRYO

Let's move in cryo
Maurice Teuwen, Maarten Dekker (Janssen Precision Engineering)

Accurate cryogenic opto-mechanical system for MATISSE
Felix Bettonvil (Astron, Leiden Observatory), Gabby Kroes, Lars Venema, Ramon Navarro (Astron)

From evolutions in motion control to revolution in thermal control
Marco Koevoets, Marc van de Wal, Wouter Aangenent (ASML)

SESSION 3: ROBOTICS

Flexible industrial robotics through imitation learning
Jacco van der Spek, Simon Jansen, Heico Sandee (Alten Mechatronics)

A CT-compatible transmission for a needle placement system
Maarten Arnolli, Klaas-Jan Gunnink, Derio Gelink, Martijn Buijze, Michel Franken (Demcon advanced mechatronics)

Low cost hexapod platform for consumer robot applications
Bart Dirkx (WittyWorX)

Wednesday 3 September 2014

Invited speaker

Planar Stage 2.0
Dr. Xiaodong Lu (Head of Precision Mechatronics Lab, University of British Columbia, Canada)

SESSION 4: ADVANCED APPLICATIONS

Sensorised Wheel Bearing
Henk Mol (SKF Engineering and Research Centre)

Nanometer precision Six Degrees of Freedom Planar Motion Stage with Ferrofluid Bearings
Max Café, Jo Spronck (Delft University of Technology)

High-Performance Web Handling for Flexible Electronics
Ben van den Elshout, An Prenen, Raymond Knaapen (VDL FLOW)

SESSION 5: METROLOGY

Ultra-high precision metrology of 3D surfaces with wavelength scanning interferometry
Ivo Hamersma (IBS Precision Engineering), Haydn Martin, Hussam Muhamedsalih (University of Huddersfield)

Model-Based Calibrations for Medical 3D Reconstructions
Rick van der Maas (Eindhoven University of Technology – TU/e), Johan Dries (Philips Healthcare), Maarten Steinbuch (TU/e)

Parallel scanning probe microscopy comes of age
Hamed Sadeghian (TNO, Delft University of Technology), Teun van den Dool, R.W. Herfst, J. Winters, W.E. Crowcombe, G.F.I.J. Kramer (TNO)

SESSION 6: CONTROL

Iterative Learning Control as part of an industrial motion framework
Tom Kok, Abhishek Bareja, Frank Boeren, Tom Oomen (ITEC / NXP Semiconductors)

High performance control of mirror segment actuators for the European Extremely Large Telescope
Gert Witvoet, Remco den Breeje, Jan Nijenhuis (TNO)

A numerical and experimental study of passive damping of a 3D structure using viscoelastic materials
M.W.L.M. Rijnen (Eindhoven University of Technology – TU/e), F. Pasteuning (Philips Innovation Services), R.H.B. Fey (TU/e), G. van Schothorst (Philips Innovation Services), H. Nijmeijer (TU/e)

SESSION 7: SYSTEM DESIGN 2

Revolutionary evolution in the isolation of a Turbo Molecular Pump on an Electron Microscope
Ab Visscher (FEI)

Mechatronic Approach "Project Velocity" (ColorWave 900)
Ivan Smits (Océ-Technologies)

Autonomous Fast Tool Servo on a standard turning lathe
Peter van der Krieken (TMC), Jeroen Brom (Brom Mechatronica)

Both days

POSTER SESSIONS AND DEMONSTRATIONS

DSPE CONFERENCE 2014 – PAPERS (abstracts)

SESSION 1: SYSTEM DESIGN 1 - 1

TEM Piezo short-stroke stage – a design based on error budgetting

Jeroen de Boeij, Twan van den Oetelaar (FEI)

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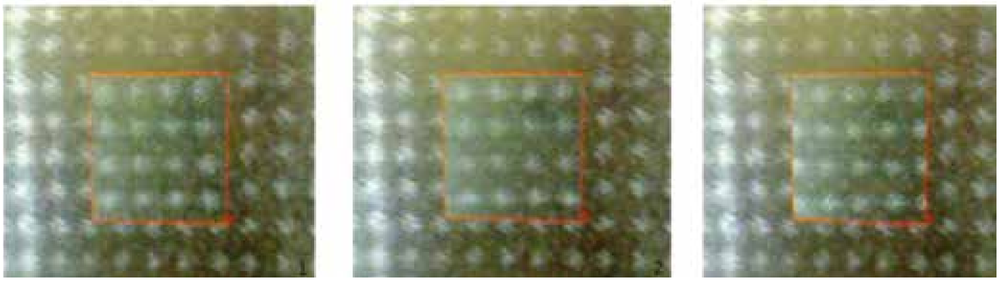
In the last decade, FEI put a lot of effort in improving the resolution of the Titan transmission electron microscope (TEM), resulting in a record-breaking 50 pm resolution. The existing stage has excellent stability and can achieve nm steps using a special gearbox that combines high stiffness with a large gear ratio (1:500). However, it is not suitable for sub-Ångström (< 0.1 nm) steps required for positioning atomic structures.

Recently, short-stroke piezo actuators have been added to the existing stage, capable of making 20-pm steps in the image. The image is very sensitive to a large frequency range of vibrations. With a total resolution of up to 50 pm, the total error budget of the piezo actuator vibrations is a fraction of the total resolution of the microscope. This requires extremely stable sensor signals and an very quiet amplifier output. Initially, the system was deteriorating the optical resolution, but using dynamic error budgetting the system has been redesigned to reduce noise and improve dynamics. This resulted in an improved noise level of the piezo amplifier and smooth movement at the atomic level.

The noise measurements, dynamics identification, error budgetting and design choices will be discussed, and movies will show the behaviour of the piezo short-stroke stage in the microscope. ■



Smooth movement at the atomic level.

SESSION 1: SYSTEM DESIGN 1 - 2

Conceptual design of high-performance motion systems using topology optimization

Gijs van der Veen, Matthijs Langelaar, Fred van Keulen (Delft University of Technology)

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The development of motion systems in the semiconductor industry is driven by a desire for higher throughput, better accuracy and larger wafers, e.g. from 300 mm to 450 mm. A simple scaling of existing designs by this factor of 1.5 implies a near threefold increase in mass, leading to prohibitive increases in actuator demands and heat dissipation. Furthermore, designs of motion systems are multi-objective and multidisciplinary in nature, and aspects such as bandwidth, mass, control performance, stiffness and thermal expansion all play important roles and depend upon each other. This makes design by traditional iterative procedures involving several teams of specialists time-consuming.

An integrated optimisation method is described for designing structural components of motion systems for optimal closed-loop performance. The structural design is performed using topology optimisation, which permits a very large design freedom. For the example of a positioning stage this is shown to lead to a nontrivial structural design which performs significantly better than a solid design. This integrated design approach leads to rather intricate structural designs, which are unlikely to be obtained by traditional manual design methods. However, combined with the rapid developments in additive manufacturing which will allow such complex designs to be realised, this provides a powerful approach to support future mechatronic device development.

Many aspects deserve further investigation, such as the issue of designing 3D parts and the associated computational complexity, the design of complete 6-DoF motion systems, and the use of Additive Manufacturing techniques. ■

SESSION 1: SYSTEM DESIGN 1 - 3

Inside the EUV Source, design to specification and costs

Cor Ottens (ASML)

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Two important business drivers of ASML are "Performance Specifications" and "Cost of Goods". During the initial development of the EUV Source, the main focus was on the "Performance Specifications", but to make a profitable machine the "Cost of Goods" is getting more attention now. ASML is continuously developing machines for the production of faster micro-chips. One of the key parameters is the Critical Dimension (CD). ASML developed an Extreme Ultra Violet (EUV) light source that is generating 13.5 nm light. The current Deep Ultra Violet light source is generating 193 nm light. Decreasing the wavelength to 13.5 nm is a big step in decreasing the CD.

The EUV light is generated by a CO_2 laser beam hitting a liquid tin droplet, by which a plasma is created that typically emits 13.5 nm light. The key module in the Beam Transport System is the Mirror Bending Block with a damping system for environmental dynamic disturbances. The CO_2 beam is actively adjusted with actuated mirrors in the Final Focus Assembly to target the beam on the droplet in the source. The EUV light is collected and sent to the scanner; correct pointing and positioning is realised by the Source Support Frame with which the source vessel is adjusted in six DoFs with respect to the scanner.

To develop machines with a cost-effective design, ASML more and more is using Value Engineering. This involves methods to determine in an efficient way the main cost drivers in a design or process. Methods like Cost Modelling, Function Analysis and Concept Scoping are used to obtain insight in the cost drivers of the EUV-source hardware. Architects and designers within ASML are trained in the Value Engineering methods. Together with the suppliers of ASML the cost reduction will be achieved. ■

SESSION 2: THERMAL / CRYO 1

Let's move in cryo

Maurice Teuwen, Maarten Dekker (Janssen Precision Engineering)

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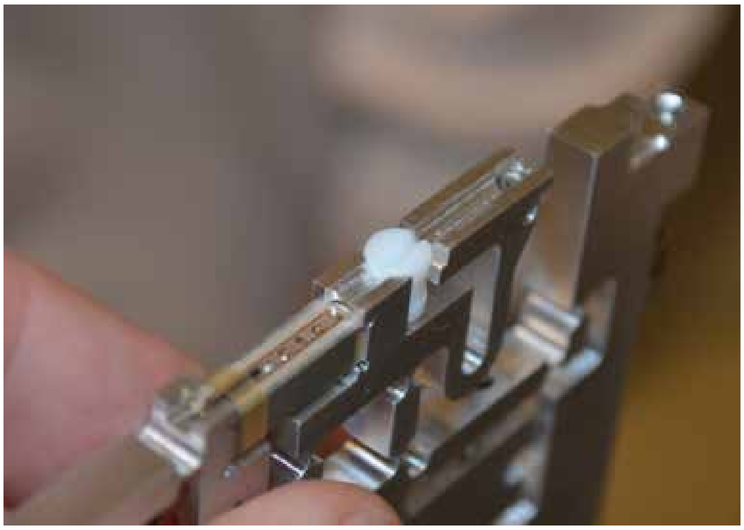
Some types of dedicated research, such as space and quantum physics, often involve experiments in cryogenic environments, i.e. environments with temperatures below –150 °C and sometimes even very close to the absolute zero (µK range). To maintain these temperatures, the 'cryostats' are as small as possible with an internal vacuum to prevent convection. On top of this, several other phenomena, such as cold-welding, dissipation, thermal expansion, superconductivity, etc., can compromise trivial solutions for mechanisms to be used for experiments.

Experimenting in cryogenic environments poses special positioning challenges. JPE has developed and realised several piezo- and voice-coil-based actuation principles to overcome these challenges in different ways for all sorts of applications, such as a linear actuator with µm resolution and 'infinite' stroke, a fast 3-DoF chopping mirror device and JPE's PiezoKnob Actuation. The latter consists of stick-slip-inertia actuators that are built in several translational and rotational stages with nanometer resolution and sub-nanometer stability proven to operate down to 1 K. ■



A cryogenic linear actuator with 'infinite' stroke.

SESSION 2: THERMAL / CRYO 2

Accurate cryogenic opto-mechanical system for MATISSE

Felix Bettonvil (Astron, Leiden Observatory), Gabby Kroes, Lars Venema, Ramon Navarro (Astron)

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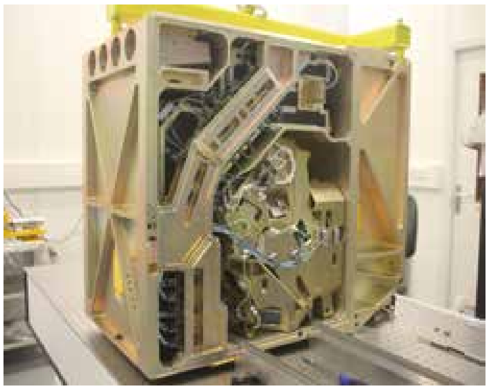
The NOVA Optical-Infrared Instrumentation Group at ASTRON is currently building the Cold Optical Benches for MATISSE, a mid-infrared interferometric spectrograph and imager for ESO's VLT interferometer (VLTI) at ESO's observatory at Paranal, Chile. This instrument will be able to combine the light of all four eight-meter VLT telescopes coherently, which enables imaging at spatial resolutions of ~6 milli-arcsec in the 2.8-5 (LM-band) and 8-12 (N-band) µm wavelength ranges.

The Cold Optical Bench (COB) receives the four telescope light beams, applies spatial filtering, splits the beams up in interferometric and photometric parts, creates anamorphism between spatial and spectral directions, and directs the light through a selectable spectral filter, polariser and disperser. Finally, a camera combines all beams on the detector, where the interference occurs.

To make interferometric detection feasible, stringent requirements exist for both image (wavefront) and pupil quality and inter-beam relationships (overlap accuracy). The design was based on 'alignment by design' with only a single arcsecond-resolution tip-tilt device per beam for achieving the co-pointing requirements. The final design consists of two COB sister parts, one for the N-band, the other for the LM-band, with each assembly accommodating 26 m optical path length and over 100 optical components. Nine cryogenic precision mechanisms provide user-selectable operational modes. ■



COB completely assembled.

SESSION 2: THERMAL / CRYO 3

From evolutions in motion control to revolution in thermal control

Marco Koevoets, Marc van de Wal, Wouter Aangenent (ASML)

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An important performance parameter in wafer scanners used in the semi-conductor industry is the so-called 'overlay' error, which is desirably small (order one nanometer) for the accurate stacking of multiple electrical layers. Important parts of the wafer scanner are the reticle and wafer stage and the lenses and mirrors in the optical column between the two stages. To reduce overlay error, advanced servo (or position) control of these high-accuracy electro-mechanical devices is a long-standing and well developed competence at ASML.

However, overlay in wafer scanners is not only determined by problems in the domain of the structural dynamics of mechanical physics and its position control, but also by problems in the domain of the dynamics of thermal physics and its control. Over time, this thermal contribution to overlay has increased from negligible (early systems) to a level comparable to the structural contribution (current systems). However, compared to modelling and control for positioning problems, advanced thermal modelling and control for high-precision mechatronic systems has received considerably less attention so far.

This presentation will discuss the development of such advanced thermal control concepts within ASML. It will be shown that many of the concepts developed in the rich history of advanced servo position control can be re-used and tailor-made to advanced thermal modelling and control. In other words, the basic system theory is available to a great extent, but must be re-considered and modified to thermal problems. This is not trivial, due to fundamental differences in the physics of dynamics of mechanical vs. thermal systems, e.g. the differences in time scales and the differences between the combination of spectral contents of the disturbances and the relevant frequency range of the plant dynamics.

From the presentation it may be concluded that recent evolutions in the field of motion control could result in a revolution in the thermal control domain. ■

SESSION 3: ROBOTICS 1

Flexible industrial robotics through imitation learning

Jacco van der Spek, Simon Jansen, Heico Sandee (Alten Mechatronics)

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In the industrial environment, robots are used for various tasks. However, it is not feasible for companies to deploy robots for productions with a limited size or fast-changing products. The current generation of robots is highly inflexible, and many repetitive tasks are still performed by humans. Current robots essentially have an insufficient level of intelligence; they are programmed at controller level and not at task level, typically a fixed sequence of actions is programmed, and the robots do not learn from their mistakes or optimise their behaviour over time. Furthermore, a robot expert is still needed to program the robot. A solution to these challenges would be a new generation of robots and software that can adapt quickly to new situations and learn from their mistakes while being programmable without needing an expert.

The concept proposed here as enabler for more flexible robotics is the combination of imitation learning and reinforcement learning. Imitation learning is a method "by which a robot learns new skills through human guidance and imitation". The purpose of imitation learning is to perform a task by generalising from observations. The power of imitation learning is that the robot is programmed in an intuitive way while the insight of the teacher is incorporated in the execution of the task.

A combination of imitation and reinforcement learning is applied to a grasping application in an industrial setting. The robot generalises movements from observations of human operators and optimises these for energy-efficiency and time using reinforcement learning. This optimisation is important, because the demonstrations and observations cannot be assumed to be perfect. The novelty of the work in this paper is that a computational and data-efficient reinforcement learning algorithm, TEXPLORE, is applied. With this, the number of trials for learning is kept to a minimum while the needed computation time is also kept low. ■

SESSION 3: ROBOTICS 2

A CT-compatible transmission for a needle placement system

Maarten Arnolli, Klaas-Jan Gunnink, Derio Gelink, Martijn Buijze, Michel Franken (DEMCON advanced mechatronics)

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The development of an automated medical system for CT-guided percutaneous needle placement raises technical challenges for which no standard mechatronic solutions are available. The need for CT compatibility, which requires obstacles to be sufficiently radiolucent to avoid image distortion, disqualifies the use of common construction materials such as steel, copper and many more. Standard automation components such as electrical motors or copper-wired encoders that are to be used must therefore remain outside the field of view of a CT scanner.

To automate the manipulation of a needle guide inside this field of view, a cable drive has been developed that transfers the motion of a motor through a number of joints to a worm gear transmission. To adjust for inaccuracies caused by slippage of the cable drive, an encoder is required at the worm gear. This inherently requires the encoder to be radiolucent. For this purpose, the design of a standard incremental encoder has been adjusted by creating distance between (1) the radio-opaque electrical part including LEDs and photodiodes, and (2) the sufficiently radiolucent rotational code disc that is mounted onto the worm gear. The distance is bridged by using flexible plastic optical fibres.

This paper presents the design considerations and achieved performance of the developed CT-compatible transmission. ■

SESSION 3: ROBOTICS 3

Low cost hexapod platform for consumer robot applications

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Research on robotic technology for personal use has been subject of many programmes, with encouraging results. Yet, the technology has not made it to the mass market despite attempts such as Sony's AIBO and Aldebaran's NAO. The main reason for this is that advanced robots are too expensive even when produced in large quantities. Toy manufacturers produce affordable robots, but they use cheap gearboxes to allow their tiny motors to deliver the needed torque, resulting in a noisy solution with bad dynamics, which negatively influences user experience. This issue also holds for homebrew solutions with hobby servo motors. This paper proposes an integrated motion module based on design principles.

Instead of stacking motion modules, it is proposed to use a Gough Stewart Platform (GSP). In this system all six motors rest on the fixed world, so they do not have to carry each other. Moreover, because all six motors work together, the system has six times the force of a single system. Furthermore, the GSP is a decoupled mechanism, so all movements are independent. The big disadvantage is the complex kinematics, but with modern electronics the inverse kinematics can be solved on the fly.

Instead of using linear actuators, a crankshaft architecture is chosen to achieve the right transmission ratio, which increases towards the outer ends. By adding end strokes to the system, the mechanism is protected against external forces. All parts are designed so that they can be either injection molded or cheaply manufactured otherwise. Connection of the pushrods is a combination of hinges and bend and torsion flexures to minimise play at low cost. The system is actuated using compact piezo motors, pretensioned by springs. This not only helps to achieve manufacturing tolerances and prevent wear, also their friction coupling allows them to slip when external forces are too high. ■

SESSION 4: ADVANCED APPLICATIONS 1

Sensorised Wheel Bearing

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The Sensorised Wheel Bearing will show the progress made with a so-called load-sensing bearing of the second generation. The principle of these bearings is based on measurement of the elastic deformation of the stationary ring with the help of strain gauges. This is not ideal due to the modifications of the bearing ring to be made before such gauges can be attached, but it demonstrates what precisely can be expected from these measurements.

The elastic response of the bearing, however, is a sum of forces and moments from the mechanical load on one hand and the deformation due to the thermal gradient on the other hand. The problem is enlarged by the elastic environment of the bearing, which then requires an in-situ calibration that is not always possible. Experiments on a 5-degree-of-freedom test rig showed that strain responses vary up to 120% depending on the compliance of the 'housing', represented by the knuckle, on the load-sensing bearing. Additional measurements were then considered for deriving a response in a fundamentally different way than the strain method, which is also sensitive to environment and running conditions.

The bearing can also be considered a 'spring nest', where the Hertzian contacts between balls and rings are (non-linear) springs. The rigid-body displacements in translational and rotational direction can in principle be measured using non-contact displacement sensors. This is demonstrated by correlating the measured tilt movement of the rotating seal in an example wheel bearing with the cornering forces exerted on this bearing. Then, it is also demonstrated that such sensors need not be exotic; actually ordinary Hall sensors commonly used for wheel ABS sensing may already qualify for measuring a crude but realistic estimate of the load on the wheel bearing and thus the cornering force, for instance.

The method in principle allows a sensing fusion between ABS (safety) and load sensing (comfort, safety, handling) and ultimately the performance of the tire-to-road contact without very high additional costs. ■

SESSION 4: ADVANCED APPLICATIONS 2

Nanometer precision Six Degrees of Freedom Planar Motion Stage with Ferrofluid Bearings

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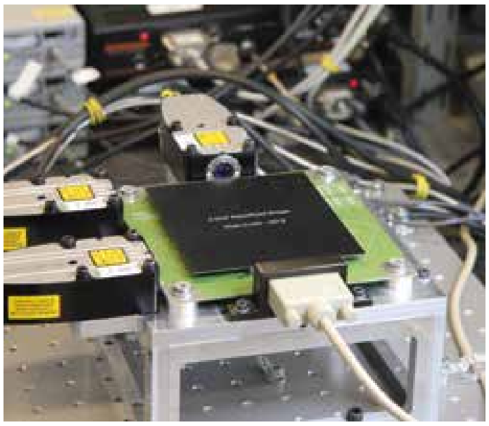
For biological microscopic research or diagnosis a planar stage of 10 mm x 10 mm may be used for imaging a specimen fast and with high resolution. This is commonly achieved by stitching multiple images together to one full image. For application as a white-light interferometric microscope an out-of-plane range of 0.2 mm is also required, preferably with nm resolution.

The planar ferrofluid bearing applied here is a type of hydrostatic bearing, containing a magnetisable fluid which is pressurised and held in place by a magnetic field. The magnetic pressure is used to carry loads and allows planar motions together with relatively small vertical motions. Advantages of these bearings over other high-precision bearings are their compactness, the absence of stick-slip, the increased damping and the absence of pumps and seals, which are required in hydrodynamic bearings with an air or oil film.



Demonstrator stage.

The low-cost 6-DoF precision stage consists of a steel top plate, three permanent magnets and a support frame to align the magnets and interferometry mirrors. The magnets hold the ferrofluid and simultaneously provide the magnetic field for the six Lorentz actuators that position the stage. The actuator coils are located on a custom-made multi-layer printed circuit board, which also acts as the base plate on which the stage moves. A capacitive/interferometric measurement system was used for position feedback. Results show a precision of 4 nm 1σ and a rise time of 0.42 ms for a planar step of 100 nm. ■

SESSION 4: ADVANCED APPLICATIONS 3

High-Performance Web Handling for Flexible Electronics

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Roll-to-roll (R2R) processes have the potential of manufacturing flexible electronics in a cost-effective way. Organic Photo Voltaics (OPV) and Organic Light Emitting Diodes (OLED) are examples of flexible electronics, typically produced by subsequent application of highly uniform coatings of functional layers on a flexible substrate (web). For these applications, very accurate coating thickness is required, because the smallest variation in layer thickness has direct consequences for device efficiency and performance.

For high-quality coating processes in general, the web speed and positioning need to be controlled accurately. In the case of flexible substrates, there is an additional requirement on web tension variation, because tension variation can result in layer inhomogeneities due to strain differences within the web. Additionally, in order to ensure high yield, the web shall not be touched on the functional side, which is not self-evident in conventional R2R web handling systems.

A model-based approach is used to design an R2R machine that is capable of combining the mentioned accuracy and tension requirements. A tool set is developed based on physical models to enable quick machine design evaluation and to develop advanced control strategies that are required for high web handling accuracies.

This paper will present the design of the so-called Canopus-1 Pilot OPV Line with web handling simulation results and actual measurement data for model verification. The line has the following main web handling specifications:

- web speed accuracy better that 0.1 % of the speed set point;
- web tension variation during processing less than 2.5 N;
- lateral web position within 50 micrometer accuracy. ■

SESSION 5: METROLOGY 1

Ultra-high precision metrology of 3D surfaces with wavelength scanning interferometry

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A wavelength scanning interferometer (WSI) for fast areal surface measurements of micro- and nanoscale structures is introduced. A broad-band light source combined with an acousto-optic tunable filtering technique is used to generate a sequence of filtered wavelengths, from which a sequence of interferograms is measured. By using this set of interferograms, a height map of (discontinuous) areal surfaces can be produced by using the known phase shifts. Excluding the need for a mechanical scanning process makes the system more suitable for integration.

An active servo system is used to control the optical path length difference between the object and reference. This serves as a phase-compensating mechanism to eliminate the effects of environmental noise. Using this vibration compensation, the requirements on construction and environ-mental conditions can be relaxed. This makes it possible to use a high-end system for online or in-process measurements on a shopfloor.

Measuring traceable step height specimens, the system achieves uncertainty within the nanometer range. The measurements, under mechanical disturbance, show that the system can compensate for environmental noise. ■

Prototype of WSI measurement head.

SESSION 5: METROLOGY 2

Model-Based Calibrations for Medical 3D Reconstructions

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Obtaining high-quality 3D reconstructions of the interior of the human body is of increasing importance to the medical society. A 3D reconstruction is obtained by a mapping of various 2D images, each acquired from a different orientation with respect to the object of interest. The quality of the obtained 3D reconstruction is directly dependent on the accuracy of the knowledge of position and orientation of the X-ray detector and source corresponding to each acquired 2D image.

Current calibration methods are based on a single external measurement using a specifically designed object (phantom), which leads to an estimation of the deviations from the ideal trajectory based on obtained X-ray images. As a result, many of these calibrations are required for each variation in the reconstruction scan (e.g., number of images or scan velocity). There is a desire to reduce the required number of calibrations while maintaining a sufficient 3D reconstruction quality. The problem can be considered from a control point of view where the detector and X-ray source are forced to follow a desired trajectory within small error bounds. A second approach is a model-based estimation of calibration parameters based on a limited set of calibration measurements by exploiting system properties.

Dynamical disturbances in the system typically lead to a blurred effect in the obtained 3D reconstructions, whereas quasi-static disturbances typically lead to artifacts. The proposed solution consists of a linear model for which the parameters are identified based on a limited calibration set. The predictive properties of the model are exploited to predict calibration parameters for various scan types. The resulting quasi-static model is combined with a parametric, position-dependent dynamical model, based on frequency response measurements. By combining the obtained models, a prediction can be made of the calibration values that lead to sufficient 3D quality while reducing the calibration time drastically. ■

SESSION 5: METROLOGY 3

Parallel scanning probe microscopy comes of age

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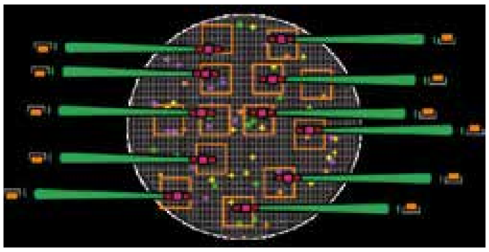
Scanning probe microscopy (SPM) is emerging as an essential nano-instrument in many applications where nanometer resolution imaging and characterisation are required. The ability to accurately measure critical dimensions in nanometer scale, has made it an important instrument in several industrial applications, such as semiconductor, solar and data storage. Examples of applications are surface roughness, channel height and width measurement, defect inspection in wafers, masks and flat-panel displays. In most of these applications, the target area is very large, and, therefore, the throughput of the measurement plays an important role in the final production cost.

Single SPM has never been able to compete with other inspection systems in throughput, thus has not fulfilled the industry needs in throughput and cost. Further increase of the speed of the single SPM helps, but it still is far from the required throughput and, therefore, insufficient for high-volume manufacturing. Over the past three years, a revolutionary concept was developed for a multiple miniaturised SPM (MSPM) heads system, which can inspect and measure many sites in parallel. The very high speed of miniaturised SPM heads allows the user to scan many areas, each with the size of tens of micrometers, in a few seconds. Recent experimental results demonstrate that the time for a parallel SPM has arrived.


Schematic illustration of the principle of parallel MSPM to image several locations on a wafer or mask.

This paper presents an overview of the demonstration, the technical developments and experimental results of the parallel SPM system currently being developed at TNO. ■

SESSION 6: CONTROL 1

Iterative Learning Control as part of an industrial motion framework

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Extensive research has been done on how to improve servo performance using the repetitive nature of trajectories in feedforward design. Although the methods developed in this field show very good results in lab environment or in special applications, it has turned out to be much harder to use them in a general motion environment. This is due to a number of factors, e.g. small variations in trajectories, limitations of industrial controllers, feedforward design methodology, fear of robustness problems, etc.

This research focuses on how to overcome these problems and use the already developed methods in a general motion framework. The first part of the research has focussed mainly on the performance of the algorithms under small variations in trajectories. Several methods were tested. The next part of the research will be the applicability to the current motion control hardware and the effort with respect to implementation of the algorithms. For instance, the current design of the motion framework will only support change in the feedforward signal during the trajectory.

The last part of the research will focus on the tuning of the feedforward controller. In practice, the control engineer who designs the feedforward controller will not always have the in-depth knowledge of the used feedforward algorithms. The implementation should be such that it is possible for a control engineer to tune the feedforward controller without in-depth knowledge. ■

SESSION 6: CONTROL 2

High performance control of mirror segment actuators for the European Extremely Large Telescope

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Future extremely large telescopes, such as the E-ELT, require segmented primary mirrors. To achieve optimal optical performance, each individual mirror segment should be actively controlled in piston-tip-tilt via three dedicated single-DoF actuators. These actuators should combine high accuracy (1.7 nm rms) with large stroke (15 mm), to compensate for the rotation with respect to the gravitational field (loads up to 900 N), while being exposed to non-stationary structural vibrations and wind loads.

In collaboration with VDL ETG, TNO has developed a prototype for E-ELT piston-tip-tilt actuators. The actuator set-up assembly has been accurately modelled based on first principles and mass and stiffness calculations from CAD drawings. Experimental frequency response measurements of the actuator, using the internal on-axis sensor, are in very good agreement with this model up to about 300 Hz. This has enabled the design of high-bandwidth robust controllers on the fine stage, with a bandwidth of about 80 Hz on the internal sensor. Next, a controller was derived for the coarse stage of the actuator, which essentially off-loads the force of the high-accuracy fine stage during tracking.

The TNO actuator prototype.

In the presence of simulated wind disturbances and actual ground and frame vibrations, the piston-tip-tilt actuator and corresponding controllers have been extensively tested. The actuator achieves 1.4 nm rms positioning accuracy over the full 15 mm stroke, while tracking with speeds between 0 and 1.2 µm/s. This is all well within the requirements. ■

SESSION 6: CONTROL 3

A numerical and experimental study of passive damping of a 3D structure using viscoelastic materials

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Structural vibrations often have unwanted consequences. They can result in noise, decreased performance, and control limitations in high-precision instruments. One way to reduce the effects of these vibrations is to create a lighter and stiffer structure, which increases the natural frequencies. However, this has its limitations. Another approach is to introduce active or passive damping to the structure. Since active damping methods require power and are generally more complex and costly, passive approaches are preferred. Passive damping can be introduced in many ways. This paper focusses on passive damping through the application of viscoelastic engineering materials (VEM). First, the effectiveness of several VEM application methods is compared for a simple structure.
Subsequently, two methods are selected and used to efficiently damp a more complex 3D structure: an open aluminum box representing a structural component of a high-precision instrument. Discrete damping elements and the constrained layer configuration are found to be most effective, and are considered.
The dynamics of the box structure including VEM components is simulated with a finite-element (FE) model that incorporates the VEM's frequency-dependent complex Young's modulus. The VEM model is obtained for several materials through a Dynamic Mechanical Thermal Analysis (DMTA). The FE model is used together with the findings of the initial effectiveness study to find a damping solution that optimises damping of the box while taking into account design constraints on mass and volume.

Validation of the simulation results is done by comparison of both modal parameters and transfer functions with results obtained from experiments on the real structure. A good resemblance is found, even without a model updating step or fine-tuning. In conclusion, for effective machine performance improvement through the reduction of vibrations, an experimentally validated FE model has been developed for evaluating viscoelastic damping design. ■

SESSION 7: SYSTEM DESIGN 2 - 1

Revolutionary evolution in the isolation of a Turbo Molecular Pump on an Electron Microscope

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The application of rotating machinery like turbo-molecular pumps (TMPs) on electron microscopes is in strong conflict with the user needs of pm-stability of this instrument. The machine specs for these pumps are challenging already. Moving the pump far away via several meters length of bellow leads to unacceptable pumping times. Traditionally, the pump is connected via a short isolation bellow provided by the pump supplier, or even two in series. The steel bellows used are typically distributed mass-stiffness elements, exhibiting numerous badly damped internal vibration modes that restrict the dynamic stiffness at higher frequencies. The massive rubber to carry the 600 N vacuum force leads to force transfer at the higher frequencies by viscous damping. Two other transmission paths connected to TMPs are acoustics and electromagnetic interference, but these are tackled in other ways.

The case is intrinsically three-dimensional. In radial direction at the pump flange typically the main rotor rotation is a stationary harmonic spike. In axial direction there are also some stationary random peaks, likely from resonance, far below the rotation frequency. For the user, image vibrations of steady harmonic nature are extremely critical, visible already at a magnitude smaller than the size of a pixel, being 10 pm in a high-resolution image. Random resonant disturbances are less critical and may be a few pixels large. Via basic dynamic models it is found that the bellow dynamic stiffness is desirably smaller than $1.6 \cdot 10^5$ N/m, axially as well radially for both types of vibration.

The current standard solution of the supplier cannot fulfill these stiffness demands, so FEI started a development for a SuperCompliBellow. This bellow combines three existing design principles: a built-in pre-load force against the vacuum force, a strong restriction on the use of rubber with viscous damping, and introduction of a solid intermediate mass giving a second-order effect to the dynamic stiffness characteristic. ■

SESSION 7: SYSTEM DESIGN 2 - 2

Mechatronic Approach "Project Velocity" (ColorWave 900)

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Project Velocity was the project realising the 'Velocity' concept demonstrator at the Drupa fair in 2013 (www7.oce.com/velocity/us/). The Velocity is the world's most productive wide-format colour printer. The concept demonstrator was realised within only eight months from start of project to demonstration at Drupa.

The approach to realise Project Velocity built both on evolution as well as revolution on different levels:

- Project approach: V-gates, a revolution within Océ.
- Product-market combination: a revolutionary technology in a new market segment.
- Product architecture: a combination of existing modules (evolution) with a revolutionary new technology.
- Flexible control architecture anticipating on:
  - changing requirements;
  - fast time to early market confrontation;
  - fast time to lead customer market.

After an overview of the product and project, this paper focuses on the flexible control architecture for the concept demonstrator at Drupa and its evolution into a flexible embedded control platform for the lead customer products.

The flexible control architecture is based on OSCAT (Océ Simulink Control Architecture & Toolbox). OSCAT is an architecture and toolbox in Simulink which supports the complete model-based control design cycle: from rapid prototyping to production code generation. Its objectives are to:

- give a jump start;
- apply best practices;
- share knowledge;
- reuse components and scripts;
- connect project phases.

It offers both flexibility and extensive diagnosability during development. This approach enabled a way of scaling R&D investments with product-market potential while accelerating time-to-market. ■

SESSION 7: SYSTEM DESIGN 2 - 3

Autonomous Fast Tool Servo on a standard turning lathe

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High-end pistons (used in motor racing) have oval shapes and local deviations from the nominal diameter. These shapes are needed to make the piston round at operating temperature. To be able to make these high-end pistons, new production techniques were needed.

In the market several solutions are available that enable oval piston turning. Most of these machines are optimised for high-volume piston production, which is not applicable here. Some suppliers do offer a dedicated machine with an additional X-axis stacked on the normal x-axis, that can make high-dynamic movements. This axis is light weight and driven by a linear motor. The oval shape can be programmed at the machine interface. Disadvantages of these solutions are high investment cost and unknown programming language of the machine.

Other solutions to make freeforms is using fast-tool servos (FTS). These are well known in diamond turning. Optical moulds for contact lenses are manufactured by these kind of FTS systems. Actuated tools are available, but also have limitations in stroke and robustness of the tool.

For the case at hand, only two production steps are allowed, first milling and finishing on the turning lathe. Also, the programming/design of the oval shapes should not be done on the machine by the operator, but by an expert, with knowledge of the pistons. The solution has to fit in an existing production machine, and should be robust, i.e. withstand collisions due to programming errors or other operator faults.

Using all standard components, linear glass encoders for feedback, piezo technology for actuation, synchronised set-point generation and smart mechanical and mechatronic design, makes a normal production lathe evolve into a high-end piston turner by implementing an autonomous FTS. Possible applications outside piston manufacturing that could benefit from this technology, are being explored. ■

System evolution by module revolution

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Evolutionary improvement of a mature system is getting harder while asymptotically approaching natural limits. "System evolution by module revolution" can present a way out. The required breakthroughs can be found in abundance on subsystem or module level, each executed with limited resources at acceptable risk. Derived from this approach, development of the first version of a new system may not require revolutionary solutions for the basic modules. After market launch, module revolutions can be planned and funded. This approach for a new system in a new market was tested in the development of the "Inpassion ALD" system from SoLayTec, intended for high-volume solar cell production. The "system evolution by module revolution" approach is elaborated and examples are presented. ■

Automatic 6DOF vacuum connection for an ASML EUV Scanner

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For ASML EUV systems the light source is a heavy and large system that is build up apart from the rest of the machine. During integration and service the Source needs to be (de-)coupled towards the Scanner system. A connection module has been developed that is able to automatically create a vacuum connection while allowing positional freedom between Source and Scanner. The working principle of this module and the alignment and coupling strategy is presented. ■

Additive Manufacturing for High Tech systems

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In order to keep up with customers' roadmaps, ASML needs to continuously improve the overlay and focus performance of their systems. One of the main contributors to these performance specifications is the high-precision waferstage. Parts designed for Additive Manufacturing (lightweight construction, more efficient cooling geometry) can help improve stage performance, but advances need to be made on a number of materials and technologies. A roadmap with R&D work packages is presented. ■

In the quest for nm improvements, ASML needs to explore new physical effects

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With the increasing demand of tighter system overlay and focus specifications, the stage accuracy specifications also become tighter. The overall accuracy is decomposed in many individual budget items, each having a sub-nanometer requirement. By going to sub-nanometer specifications, relatively new physical phenomena are becoming an important part of the budget. The challenge is to identify these disturbances in an early phase of the project, understand the physics, and implement solutions to the stage and machine design. Various types of new effects encountered in ASML machines are discussed. ■

Revolutionary piezo strain sensor with sub 100 pε resolution

Iwan Akkermans, Jeroen de Best, Teis Coenen, Peter van der Krieken, George Leenknegt, Hans Vermeulen (ASML), Maikel Heeren, Bo Lensen, Hein Schellens (Heinmade)

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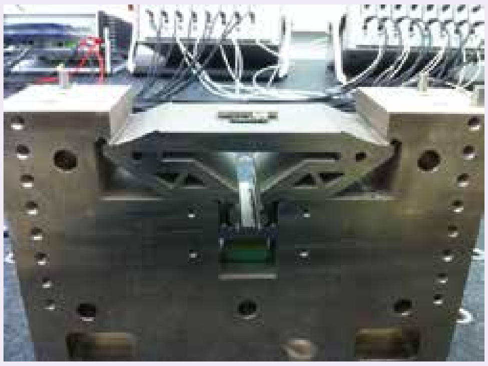
The internal deformation of wafer stage chucks becomes a significant contributor to the overlay and focus performance of the current positioning modules in lithography scanners. Therefore, a strain sensor is being developed that can measure these deformations of about 10 to 100 pε. Piezo strain sensors are attractive because of their high sensitivity. A prototype piezo-based strain sensor with integrated charge amplifier electronics is discussed. Topics include hysteresis compensation, development of a qualification measurement set-up, EMC-robust design, and temperature effects in the sensor. In a demo, sensor readings with pε resolution levels are shown. ■



Test set-up for qualification of strain sensor performance

DSPE CONFERENCE – POSTERS AND DEMOS (abstracts)

Point of interest control for flexible stages

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For position control of wafer and reticle stages in ASML scanners, the Point Of Interest (POI) is the actual location on the stage structure that is subject to light exposure. This POI cannot be measured directly; instead the measurement system (using encoders or interferometers) gives an estimate, called the Point Of Control (POC). The servo error is defined as the difference between the setpoint and the POC. While the ambition of accurately controlling an immeasurable location on a flexible structure is quite revolutionary, the actual development of the advanced position control design methods is done in a more evolutionary fashion. An overview is given of the methods being developed at ASML Research Mechatronics. ■

From PC-based to PC-less – the next step in Industrial Motion Control

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High-end mechatronic systems are becoming increasingly complex, up to the point where traditional, centralised PC-based control reaches its limits. In addition, motion performance requirements demand an architecture that "keeps the local things local", and the decreasing availability of consumer PCs inevitably will have a negative impact on the availability and cost price of industrial PCs. Therefore, the trend is towards open, intelligent and distributed motion control systems. In this architecture the role of the PC may diminish from a central real-time motion director to an optional component. The concept of PC-less control as opposed to PC-based control may be called a revolution. Here, it is discussed how this can be implemented by means of piece-wise evolution. ■

Controlled Pre-sliding for Precision Positioning

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Delicate tasks, such as alignment of optical elements or high-precision sensors, often require motions in the millimeter range with sub-micrometer precision. The alignment function must, however, be combined with a good position stability after alignment. As disturbances should be minimised, it is preferred to achieve this stability passively, i.e. without active control, and with a high stiffness. These demands make friction clamping a preferred way to achieve stability, but stick-slip effects might lead to problems with precision positioning. It is shown experimentally how a simple control structure can be used for precise positioning in the pre-sliding regime. ■

Advances in Optimization-Based Feedforward Tuning

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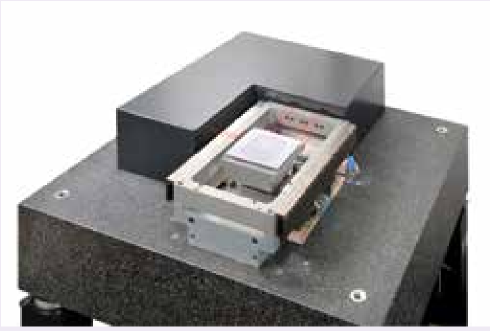
Feedforward control is the key method to improve the servo performance of high-precision motion systems. In typical applications of motion control, a low-order feedforward controller is designed that approximates the inverse of the system. For example, the servo performance of systems with dominant rigid-body dynamics can be effectively enhanced by acceleration feedforward. Two new contributions to feedforward control are presented and their value is confirmed by experimental results from the NForcer set-up. ■



NForcer experimental set-up.

A Novel Master-Slave System for Reconstructive Microsurgery

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A novel robotic system is demonstrated, able to assist during reconstructive microsurgery. An extensive analysis of conventional methodologies, combined with a review of currently available alternative solutions, has led to the design of a new 7-DoF master-slave system. The modular design concept is focused on precision, safety, ease-of-use, and cost-effectiveness. A proof-of-concept has been realised, whereas preliminary results indicate a bidirectional precision at the slave end-effector down to 30-40 μm. ■

Intelligent feedforward: increasing performance and extrapolation capabilities with iterative learning control

Joost Bolder, Jurgen van Zundert, Tom Oomen, Sjirk Koekebakker, Maarten Steinbuch (Eindhoven University of Technology)

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Motion stages are the key components that often determine the throughput and production accuracy. Examples include robotic arms, printing systems, pick and place machines, electron microscopes, wafer stages, and additive manufacturing machines. To enhance the performance of these systems, the development of intelligent control techniques that automatically optimise the performance per system is highly promising. A new iterative learning control algorithm is presented that possesses extrapolation capabilities with respect to the task. Significantly improved performance with respect to pre-existing techniques is demonstrated for a medium-loading drive of an Océ large-format printer. ■

Integration and Mechatronics

Tom Gierstberg (EMCMCC)

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Similar to mechanical integration issues, issues occur in electronic system design. Simple things are the power and signal connector fittings, pin assignments (both more electro-mechanical issues), the electric and electronic signalling involved, the coding of digital words, bitrates, carrier frequencies, channels, etc. All these basic electric boundary issues that come with mechatronic system integration shall be dealt with from an initial architectural approach. Here, the most common pitfalls and the measures to overcome and/or detect these shortcomings before mechatronic system integration are elucidated. ■

Design of a TEM lamella lift out manipulator

Ron van den Boogaard (FEI)

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Dual-beam systems have both an electron and an ion column. Besides for viewing purposes, the ion column can also be used to remove material at a microscopic scale. A typical use case for this milling technique is the so-called TEM lamella prep process. In the past, FEI used a third-party, 3-DoF manipulator to perform the lift-out step in this process. With technology moving forward, this solution was proven not to be satisfactory anymore and FEI decided to develop its own solution, yielding improved performance and better integration. ■

Robust Design in Product Creation Process

Henk van Haren (Holland Innovative)

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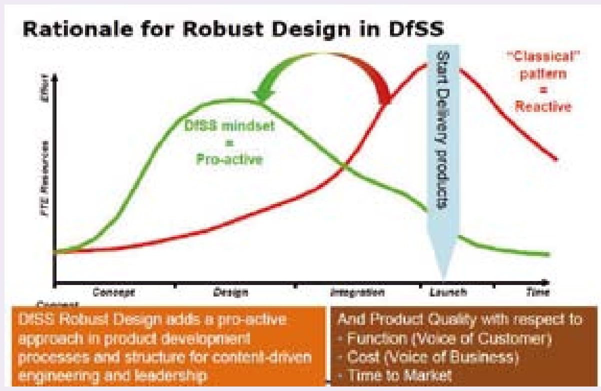
The presentation focusses on the use of a balanced mix of tools in the product creation process and on the rationale for this "balance". In more detail the HI PRP (Holland Innovative Project Reliability Plan) is discussed. ■



The Rasnik 3-Point Alignment Monitoring System

H. van der Graaf (Nikhef, Delft University of Technology, Sensiflex)

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The Rasnik system has been developed, since 1983, for the monitoring of the geometry of large particle detector systems at CERN. Since then, new applications have been realised, based on a set of standard low-cost components, such as webcams.
Rasnik is applied as a deformation monitor; application examples include relative displacement of tunnel sections, monitoring displacement of piles, measuring the sag of a bridge, or the sag of roof beams (e.g. in a warning system for snow overloads). The high precision allows the registration of small changes like rainfall and persons passing. The 3-point Rasnik system includes an illuminated coded mask, of which an image is projected, by means of a lens, onto a pixel image sensor. A displacement of the lens, relative to the mask and sensor, results in a displacement of the image on the sensor, which can be recorded on a processor. ■

Measurement of Acoustic Vibration Sensitivity of Precision Machinery

Asma Qadir, Pieter Nuij (NTS-Group)

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Precision engineering equipment, with its micro/nanometer-precision specifications, is sensitive to internal and external disturbances. External disturbances can be floor vibrations, magnetic field interference, temperature variations and pressure surges in the environment due to sound. High-level air pressure variation produces sound or acoustic disturbances, which leads to a displacement in flexible systems. The acoustic error budget for precision machinery can well be in the order of nanometers. Here, the measurement of acoustic vibration sensitivity of precision machinery is discussed. ■

How to make an active vibration isolation system cheaper and better

Chenyang Ding (NTS System Development)

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A new system design and a new control design approach have been developed, and subsequently realised and validated on an active vibration isolation system (AVIS): a 6-DoF contactless electro-magnetic suspension system. Control has been designed by a recently developed approach, sliding surface control. A control bandwidth of 150 Hz was achieved for all 6-DoF motions. Closed-loop performance, compliance (disturbance force to payload displacement) and transmissibility (floor displacement to payload displacement), have been validated by comparing the measured and predicted curves. ■

Combining repetitive and iterative learning control

Ronald Winarto (Océ-Technologies)

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A printing system containing multiple imaging devices and a conveyor belt for sheet transport may exhibit recurring disturbances. A distinction can be made between event-triggered (or trial-based) disturbances and constantly repeating disturbances. Repetitive controllers (RCs) are designed to handle constantly repeating disturbances, while iterative learning controllers (ILCs) can handle event-triggered (specifically task-based) disturbances. They both rely on learning from previous experiences though. A cascading control structure has been worked out to allow combining different types of controllers, including ILC and RC. This structure has been analysed using a theoretical approach as well as simulation. ■

Drive model and collision detection

Eric Smeets (Philips Healthcare)

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Medical equipment like interventional X-ray equipment used for treating patients must be safe for patient and personnel. Medical market trends are towards cost cut-down, so equipment BOM costs must be kept to a minimum. The required additional safety features should be software-only, preferably. Collision detection is a way to limit the impact of collisions on humans and equipment. Motor current and servo position both are available as input signal for collision detection. Provided drive train and motor behaviour is somewhat predictable, a model can be made that predicts the required motor current. Deviations between the predicted and measured current can then be used as a measure to signal collision. ■

Towards an automated model order reduction toolbox

Walter Aarden (Philips Innovation Services)

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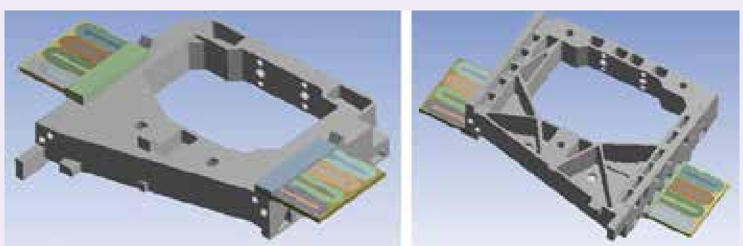
Current computational methods for reducing the complexity of Finite Element (FE) structural models in ANSYS are mainly based on modal analysis. An alternative method is moment-matching approximation (Krylov subspace), which for larger systems is computationally more efficient. Another advantage over currently used methods is that the FE damping matrix can be taken into account, for incorporating the effects of frequency- and location-dependent damping. An ANSYS/MATLAB toolbox has been developed to interface with ANSYS output and efficiently compute Multiple Input Multiple Output (MIMO) reduced-order models using a Krylov subspace method. ■



Test case for the Krylov subspace method: model of a frame used in a high-accuracy measurement system.

Advanced modelling and simulation of non-linear cable slab dynamics in high precision systems

Toon Hardeman (Philips Innovation Services), Ashwin Sridhar (Delft University of Technology – TUD), Stijn Boere (Philips Innovation Services), Paolo Tiso (TUD)

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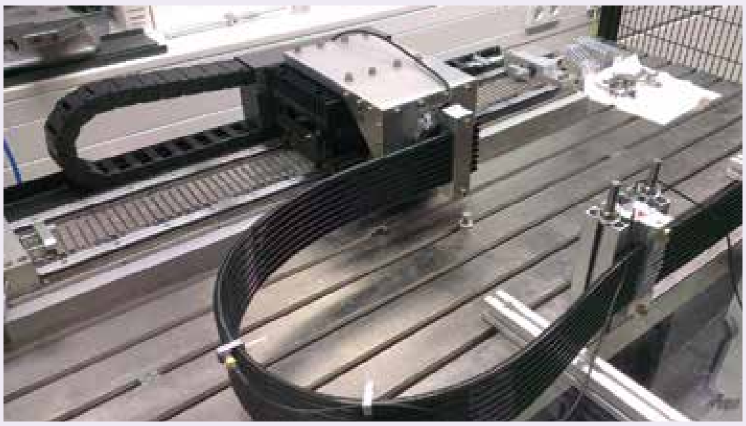
In high-precision motion systems, the positioning accuracy is defined by the disturbance forces acting on the moving stage. One of the dominant disturbances for large-range stages is the cable slab. Dynamic modelling of these cable slabs is essential for accurate and reliable designs, especially in case of a multi-DoF floating stage architecture with high acceleration levels. Here, methods are presented to estimate the disturbance forces on a moving stage due to cable slab dynamics. ■



Set-up for experimental validation.

Model-based development of die-bonding machine at SEGULA Technologies Nederland

Dragan Kostić, Patrick Smulders (SEGULA Technologies Nederland)

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To facilitate realisation of challenging requirements on positioning accuracy, contact force and temperature control, while strictly accommodating specifications on the environmental conditions and isolation of external vibrations, SEGULA utilises a systematic product development which incorporates different model-based design and analysis techniques, including CAD, FEM, model-based control, dynamical and servo-control simulations, etc. Here, the model-based framework is described and its practical application is illustrated for the development of a die-bonding machine. ■

PRODUZO: back-end interconnection for thin-film PV cells is here!

Dimitri Eijkman (CCM), Jac Jamar (TNO), Johan Bosman (ECN), Sjoerd van de Geijn (SPGPrints), Ivo Hamersma (IBS Precision Engineering)

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PRODUZO ("PROcesstation voor serieschakeling van DUnne-film Zonnecellen") is a demonstrator system designed to investigate and validate technical and economic improvements related to making the serial interconnections on thin-film PV modules as the very last process step. The PRODUZO manufacturing philosophy places all the separation and integration steps at the back end of the line. The back-end interconnection concept was implemented in a demonstrator, compatible with roll-to-roll processing of flexible substrates. Photographs and movies of the system in operation are shown, and results of the interconnection quality are presented. ■

Intermittent slot-die coater

Jeroen Smeltink, Bas de Kruif, Ike de Vries (TNO), Maarten van Lent (Heidenhain Numeric)

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Flexible electronics allow for free-form low-cost Organic Photovoltaics and displays. One of the production steps for flexible electronics the Holst Centre is working on, is to create patterned layers of coating. These coatings have to be thin and very uniform in thickness. The intermittent coating can be made by stopping the liquid flow and moving the slot-die away from the coated area and vice versa while the foil keeps moving. Conflicting requirements demand for a mechatronic system approach in which predictive modeling has a crucial role. The design choices are explained and preliminary results are shown. ■

Additive Manufacturing enabled Mechatronics: Freeform for performance and first results

Gregor van Baars, Jeroen Smeltink, Marco Barink, Maurice Limpens, John van der Werff, Jan de Vreugd (TNO)

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Additive Manufacturing (AM) is a rapidly developing technology, with increasing relevance for high-precision systems development. Particularly, the inherent freeform nature of AM offers new design possibilities for system engineering. Typical system requirements include extremely accurate motion and positioning of a substrate, combined with substrate (thermal) stability. The question is addressed how AM-enabled freeform design can provide precision mechatronic solutions, and pave the way for breakthroughs in system performance. First results are presented, probing various mechatronic research directions. ■

Evolving thermal control for semiconductor wafers

Paul Blom, Meltem Ciftci, John Vogels, Ton Peijnenburg (VDL ETG)

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Thermal control of semiconductor wafers in patterning becomes more critical as overlay requirements further tighten up. Being considered non-core, wafer handling modules typically evolve in small incremental steps. Here, a larger incremental step is taken to secure thermal performance for new equipment generations, covering additional requirements from design-for-manufacturing, testability, serviceability, availability, etc. Current cooling plate designs suffer from limitations of conventional manufacturing techniques for making embedded channels that introduce the need for soldering or brazing, O-rings, etc. This impacts both thermal performance as well as reliability. Novel designs enabled by Additive Manufacturing can address these limitations.

Multi-sensor metrology for microparts in innovative industrial products

Rob Bergmans, Gertjan Kok, Henk Nieuwenkamp, Petro Sonin (VSL)

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A project under the European Metrology Research Program addresses the need for improved metrological capabilities regarding industrial microparts with complex geometry. Multi-sensor coordinate metrology has the potential to fulfil the requirements to measure complex microparts. It combines the speed of optical measurements with the accuracy and 3D capability of tactile measurements and, more recently, the ability to measure interior features using computed tomography (CT) with X-rays. An overview of the project is given, with a focus on the activities at the Dutch metrology institute, VSL. ■

Tactile and optical probing with the VSL 3D Micro Coordinate Measuring Machine.

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