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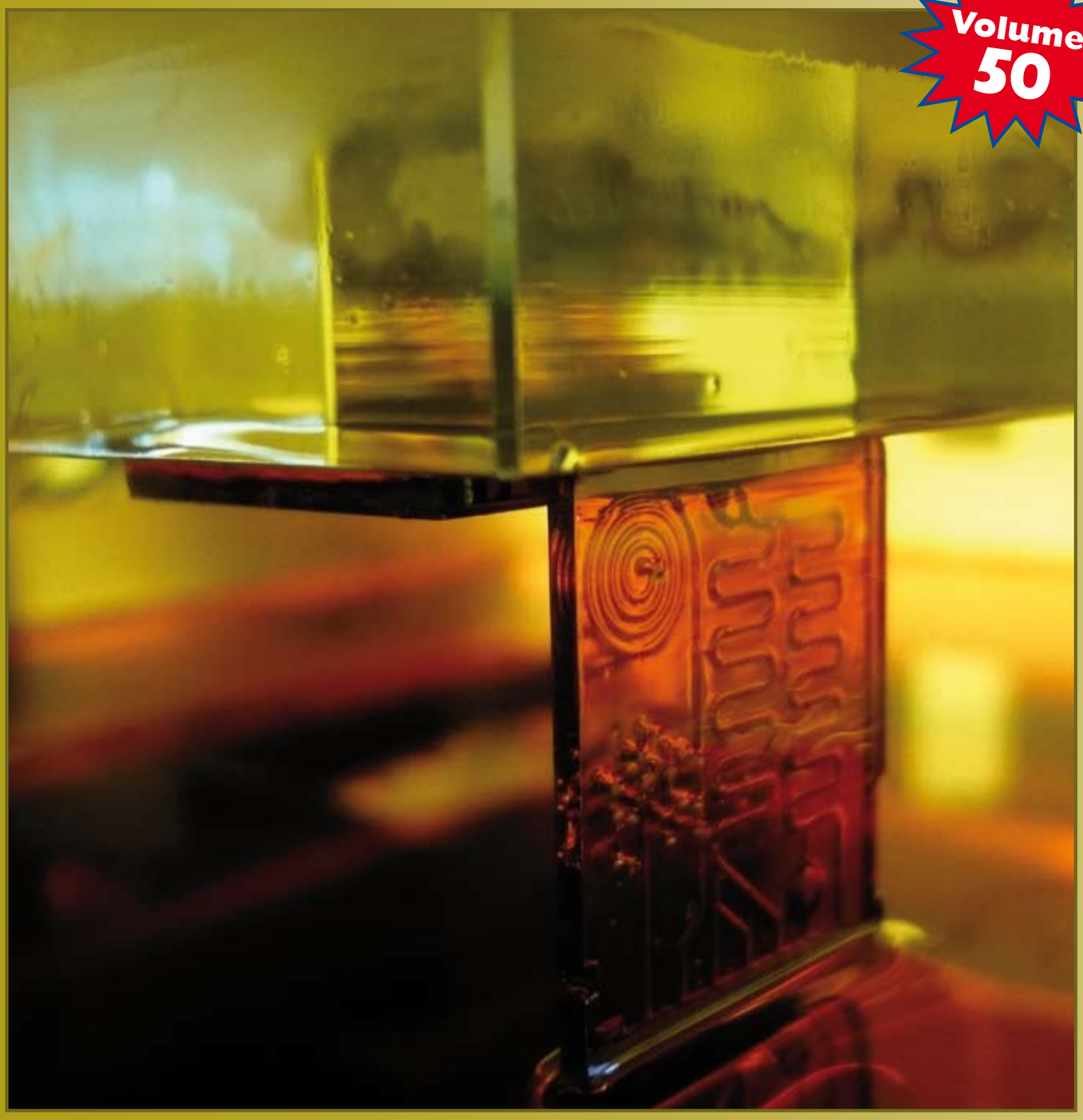

Variable stiffness actuators • Aspheres and freeforms • Dynamic error budgeting
Selective Laser Melting • Microstereolithography • Rapid, lightweight precision
Mechatronic design for harsh environments • Thermo-mechanical stability
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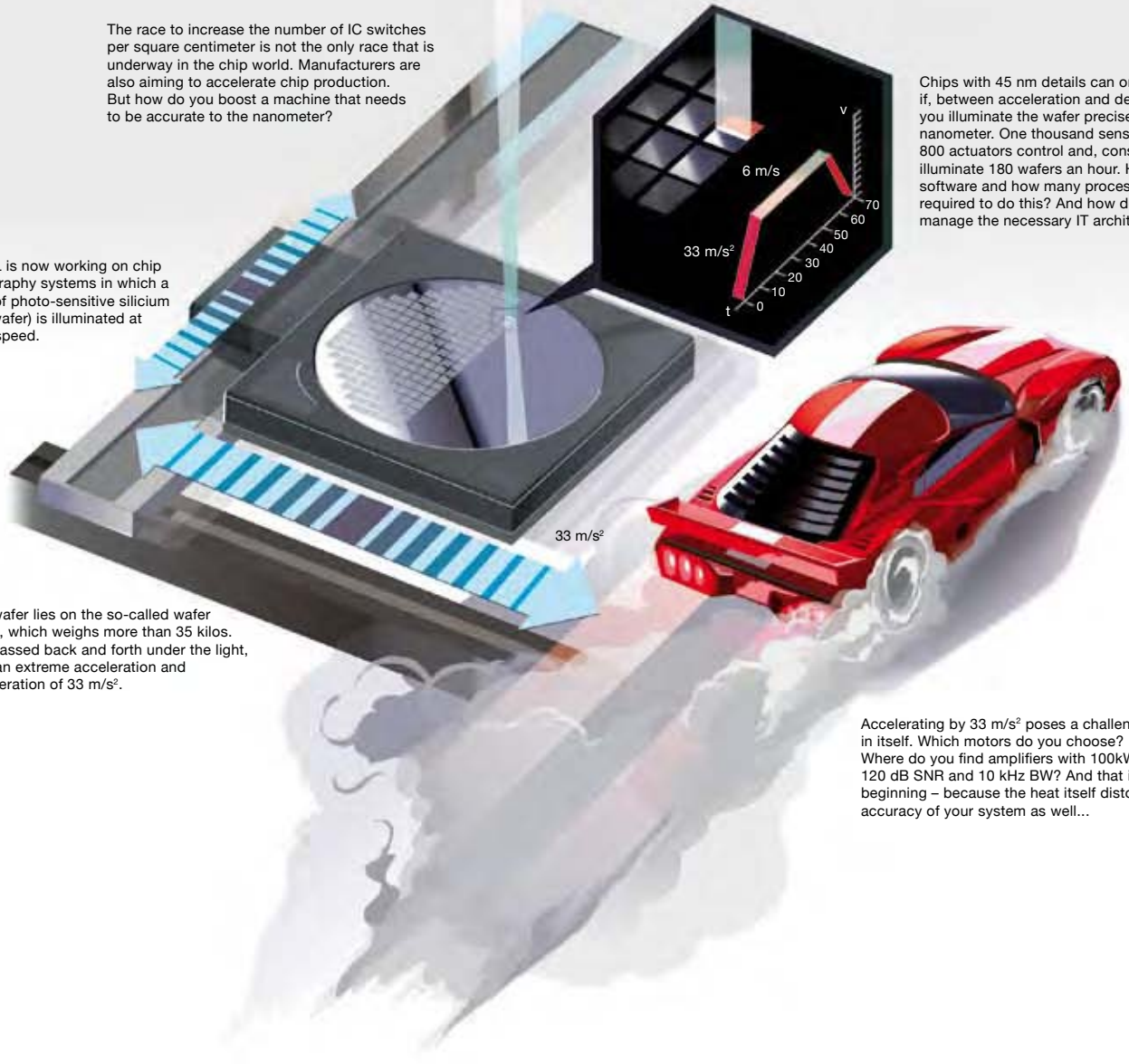

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The cover photo (Microstereolithographic building process of a microfluidic chip) is courtesy TNO Science and Industry.

editorial

‘High-tech’ equals ‘outgoing’

The more high-tech your company is, the more you have to broaden your horizon when it comes to doing business. People keep referring to your markets and activities as niches. So, the search for business partners has to be very specific and precise. Also, more and more you have to search for relevant cooperation partners. Often, the first step towards a new market – and therefore a new field of application – is to find additional expertise and knowledge to adapt your own technology to this (niche) market’s specific needs. Having access to relevant networks could be very helpful. Visiting fairs and participating in international matchmaking events is a must. Not only to keep up with the latest developments within your field of expertise, but also to get to know who-is-who in your own and adjacent fields.

Last June, with a couple of companies I visited the German Thuringia region. This region is renowned for its expertise in optics (Zeiss!), sensorics and direct-drive technologies. The Dutch participants were not only surprised by the good infrastructure (modern ‘Autobahnen’) and the beautifully renovated towns, but also by the professionalism of the companies visited and their creativity, which can be ascribed to the situation in former DDR (German Democratic Republic) times, when there was a strong embargo on almost anything. “Okay, we are not allowed to import cars, so let’s engineer and build a car ourselves.” Here, car can be replaced by radio, tv, computer, etc….

It appeared that most companies had been founded in 1991, two years after the Berlin Wall had come down. Before that, entrepreneurship was not being encouraged. So a lot of future entrepreneurs waited for the situation to settle and for their initiatives to be supported by public funds, which took some two years. Now these companies are literally located in the heart of Germany and open to the world.

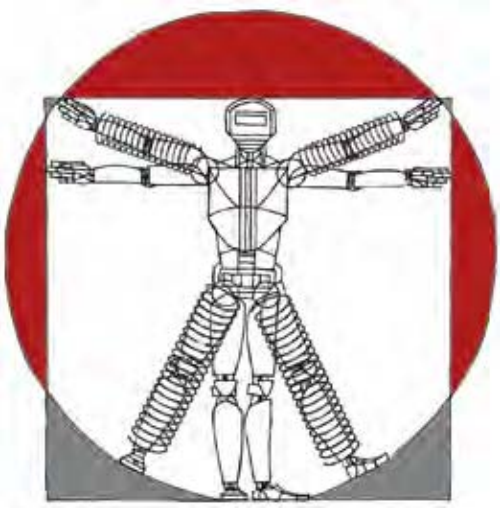
Last month, with other Dutch companies I visited the Jura, the border region between France and Switzerland, known for centuries of watchmaking and now one of Europe’s hotspots for precision technology. For next year I am planning a company mission to Israel, just like the one to Japan three years ago. This kind of missions broadens our horizon. Companies are able to establish new contacts, not only in the group they are travelling in, but primarily in the target region or country.

Try to find Europe’s hotspot for your company! And please, let our network be of support to you.

Rim H.M. Stroeks
Innovation consultant for Syntens, technology transfer consultant
for the Enterprise Europe Network

Towards a new generation of robots

The concept of variable stiffness actuators is of relevance to emerging robotics applications. In particular, the intrinsic compliance of the actuator can ensure safe human-robot and robot-environment interaction, even in unexpected collisions. From the analysis of two elementary design classes, lying at the basis of the majority of variable stiffness actuator designs, it is concluded that they are not energy efficient in changing the apparent output stiffness. This can be an issue in mobile applications, where the available energy is limited. Therefore, a new class of energy-efficient variable stiffness actuators is introduced. The conceptual design has been validated by means of simulations and experiments with a prototype realisation.



VIACTORS

• *Ludo C. Visser, Raffaella Carloni and Stefano Stramigioli* •

The advancements in robotics have caused major revolutions in the industrial world. In fact, thanks to robots, repetitive manufacturing processes can be performed endlessly with high repeatability and precision. This has resulted in lower costs and high quality of products. In order to achieve the required precision, the robots are mechanically stiff and are actuated by high-gain controllers, resulting in accurate motion. Moreover, to increase productivity, the robots are generally moving fast. The combination of high-speed motion with stiff actuation makes these systems potentially very dangerous, which explains why they are operating in environments where humans are not allowed.

Authors

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Their work as described in this article was funded by the European Commission's Seventh Framework Programme as part of the project VIACTORS under grant no. 231554.

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Compliant behaviour

In new emerging robotics applications, such as prosthetics, rehabilitation devices, and service robotics, human-robot and robot-environment interactions are an integral part. In such applications, the robotic system should show a compliant behaviour to prevent instability, damage or injuries. This approach is very similar to how humans perform tasks in unstructured environments: by pretension of the muscles, humans vary the stiffness of their joints to a specific level, appropriate for the task and the environment.

In robots, the compliant behaviour can be achieved by proper control action [6], but to guarantee intrinsic safety, a mechanical compliance should be introduced into the joints of the system. Ideally, the compliance should be variable, so to adapt it to the requirements of the task, and thus a trade-off between precision of motion and limited impact/interaction forces has to be found. For example, when moving slowly, the stiffness can be increased to achieve more accurate motion and it should be lower when the robot is moving fast, to ensure safe interaction in the case of a collision.

The requirement of mechanically variable stiffness joints is fulfilled by a new generation of actuators, called variable stiffness actuators [1], [2]. This class of actuators is characterised by the property that their apparent output stiffness, and thus the apparent stiffness of the joint they are connected to, can be controlled independently of the actuator output position, and thus the joint position. This can be achieved in many ways.
For example, the 'Jack Spring'™ achieves a variable stiffness by changing the number of active coils in a spring in series with the actuator output [4]. The actuator presented in [3] uses a variable configuration of permanent magnets to emulate a variable stiffness at the actuator output. However, most variable stiffness actuator designs present a number of internal elastic elements, usually springs, and some internally actuated degrees of freedom. The intrinsic properties of the elastic elements and the configuration of the internal degrees of freedom define the apparent output stiffness [5], [8], [12], [13].

In this article, some commonly encountered working principles for variable stiffness actuators are presented, and particular advantages and disadvantages of the principles are highlighted. In particular, it is shown how to design energy-efficient variable stiffness actuators, in which the internal elastic elements can be used for storage of potential energy, reducing the required control energy. Energy efficiency is especially an advantage in the actuation of mobile systems, in which the available energy supply is limited, e.g., walking systems or prosthetics.

Variable stiffness actuator designs

In this section, some variable stiffness actuator designs are presented. The discussion is restricted to the class of actuators that internally have a number of elastic elements and a number of internal degrees of freedom that can be actuated. In particular, two elementary design classes are considered, which encompass the majority of variable stiffness actuator designs presented in the literature.

To focus on the working principle, the following assumptions are made:
- the elastic elements can be represented by ideal springs, either linear or nonlinear;
- the internal degrees of freedom are purely kinematic, i.e., they have no mass or internal friction;
- other internal inertias and friction of the actuator can be neglected.

Moreover, it is assumed that the state s of the springs, i.e. their elongation or compression, is completely determined by the configuration of the internal degrees of freedom, denoted by q, and by the output position r. Formally, this means that there exists a map $\lambda : (q,r) \mapsto s$ such that $s = \lambda(q,r)$. The energy stored in the springs is a function of the state of the spring, i.e., $H(s)$, and thus either by changing the configuration q or the output position r, the energy stored in the springs can be changed. In particular, it follows:

$$\begin{aligned} \frac{\mathrm{d}H}{\mathrm{d}t} &= \frac{\partial H}{\partial s}\frac{\mathrm{d}s}{\mathrm{d}t} \\ &= \frac{\partial H}{\partial s}\left(\frac{\partial \lambda}{\partial q}\frac{\mathrm{d}q}{\mathrm{d}t} + \frac{\partial \lambda}{\partial r}\frac{\mathrm{d}r}{\mathrm{d}t}\right) \end{aligned} \tag{1}$$

This relation is used to investigate how efficient a particular actuator design is in terms of energy consumption in changing the apparent output stiffness, which is defined as:

$$K := \frac{\delta F}{\delta r} \tag{2}$$

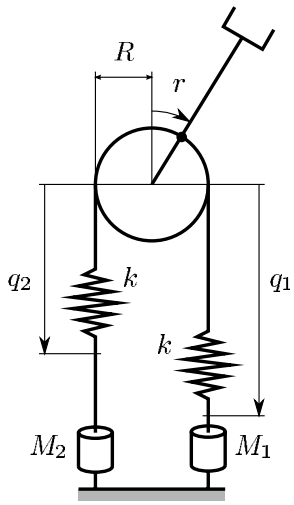

Figure 1. Design I - Variable stiffness actuator based on an antagonistic spring setup.

i.e., the infinitesimal change in the force F felt at the output, due to an infinitesimal change of output position r.

In this article, an intuitive analysis and discussion of the designs is presented. For a thorough mathematical treatment, the reader is referred to [9], [11], [12].

Design I - Antagonistic spring setup

The first design, schematically shown in Figure 1, is biologically inspired. Similar to the human muscular system, the design employs two springs in an antagonistic setup. The springs are nonlinear, to enable the independent control of output position and stiffness. Intuitively, by actuating the motors M_1 and M_2 in common mode, the pretension of the spring is increased and, therefore, the output is kept fixed but it becomes stiffer. While moving the motors in differential mode, the output position is changed. An example of an actuator of this type is the VSA [7], [8].

In this design, the springs are quadratic and, therefore, the force they exert is quadratic in the state, i.e., $f = ks^2$, with k the elastic constant of the springs. By investigation, it follows that the states of the two nonlinear springs are, respectively:

$$s_1 = q_1 - Rr, \quad s_2 = q_2 + Rr \tag{3}$$

The force F at the output is then derived:

$$\begin{aligned} F &= f_1 - f_2 \\ &= R\left(ks_1^2\right) - R\left(ks_2^2\right) \\ &= Rk\left(q_1 - Rr\right)^2 - Rk\left(q_2 + Rr\right)^2 \\ &= kR\left(q_1^2 - q_2^2 - 2R\left(q_1 + q_2\right)r\right) \end{aligned} \tag{4}$$

Using the definition (2), from (4), the apparent output stiffness K is given by:

$$K = 2kR^2\left(q_1 + q_2\right)$$

Observe that by changing q_1 and q_2 in common mode, i.e., $\dot{q}_1 = \dot{q}_2$, the stiffness is changed. In differential mode, i.e., $\dot{q}_1 = -\dot{q}_2$, the stiffness remains constant, while the output position changes.

The time derivative of (3) in matrix form is given by:

$$\begin{bmatrix} \dot{s}_1 \\ \dot{s}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}}_{A} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} -R \\ R \end{bmatrix} \dot{r}$$

The matrix A is a full-rank matrix, and, thus, regardless of the choice for $\dot{q}_1$ and $\dot{q}_2$, there is always a change of energy in the springs, i.e., using (1), $\dot{H} \neq 0$ for all $\dot{q} \neq 0$. In particular, when changing the stiffness, energy is put in the springs and internally stored, and therefore not usable for doing work on the load. Intuitively, by pretensioning the springs, the energy level in the springs increases, but since both springs are equally elongated, the forces on the output balance and hence the output position do not change. Therefore, this design is not energy efficient in the change of its apparent output stiffness.

Design II - Decoupled stiffness and position change

In the previous design, the springs have to be pretensioned simultaneously to change the stiffness, while a differential motion of the internal degrees of freedom leads to a change

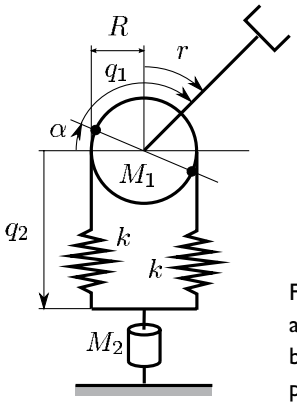

Figure 2. Design II - Variable stiffness actuator with complete decoupling between the change of the output position and the output stiffness.

of the output position. This observation has led to designs in which these two operations are decoupled and controlled by separate actuators. The design is schematically depicted in Figure 2. The linear motor M_2 changes the degree of freedom q_2, which realises a change of stiffness, while the rotational degree of freedom q_1, actuated by the rotational motor M_1, changes the output of the actuator with respect to the equilibrium position of the pulley. The VS-Joint [13] is an example of this type of design.

The analysis of this design is nearly identical to that of the previous design. Let the springs be quadratic, and by investigation of the kinematics, it follows that:

$$s_1 = q_2 - R\alpha, \quad s_2 = q_2 + R\alpha \tag{5}$$

with $\alpha = r - q_1 + \frac{\pi}{2}$. The output force is:

$$\begin{aligned} F &= f_1 - f_2 \\ &= R\left(ks_1^2\right) - R\left(ks_2^2\right) \\ &= Rk\left(q_2 - R\alpha\right)^2 - Rk\left(q_2 + R\alpha\right)^2 \\ &= -4kR^2\alpha\, q_2 \end{aligned} \tag{6}$$

Using the definition (2), from (6), the apparent output stiffness K is given by:

$$K = 4kR^2 q_2$$

which confirms that the change of the stiffness only depends on the degree of freedom q_2 and, therefore, is decoupled from the control of the output position, which depends on the degree of freedom q_1.

By differentiating (5) to time, it follows:

$$\begin{bmatrix} \dot{s}_1 \\ \dot{s}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} R & 1 \\ -R & 1 \end{bmatrix}}_{A} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} -R \\ R \end{bmatrix} \dot{r}$$

Observe that the matrix A is full rank, and thus that, in order to increase the apparent output stiffness, energy has to be stored in the springs, i.e., $\dot{H} \neq 0$ for all $\dot{q} \neq 0$.

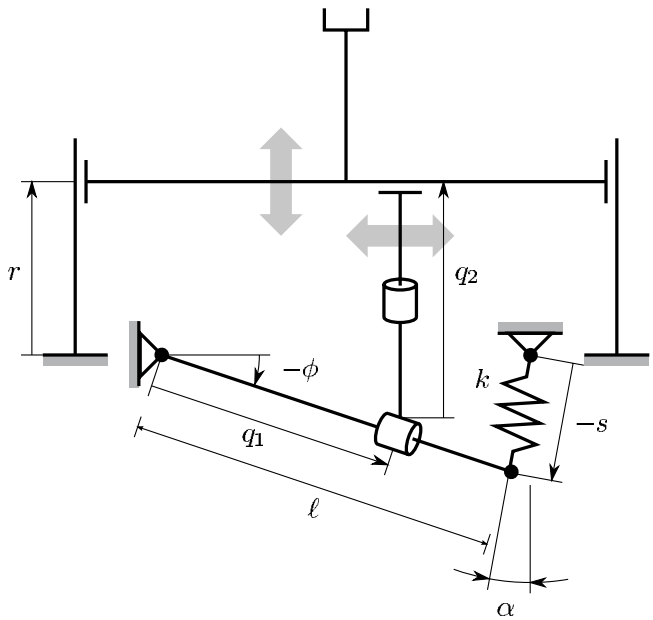

Figure 3. Conceptual drawing of vsaUT, a new energy-efficient variable stiffness actuator design.

Intuitively, in this design, increasing q_2 indeed increases the energy level in the springs, but the output position does not change. Therefore, this design is not energy efficient in the change of the apparent output stiffness.

A novel energy-efficient design

The observations made in analysing the previous two designs, regarding inefficient use of energy in changing the stiffness, gave the motivation to derive a new energy-efficient concept. In particular, the concept is such that the kinematics allows a change of stiffness without any change in the energy stored in the springs.

The concept, named vsaUT, is shown in Figure 3, and is extensively described in [12]. The working principle is based on a linear zero-free-length spring, connected to the output via a lever arm of variable length. How the spring is sensed at the output depends on the transmission ratio implemented by the lever arm. The effective length of the lever arm, and thus of the output stiffness, is determined by the linear degree of freedom q_1, while the linear degree of freedom q_2 controls the output position. Also AwAS [5] is based on this concept, but it realises a rotational implementation.

Assuming that the base length ℓ is large compared to the elongation of the spring, and thus $\alpha = 0$, from analysing the kinematics, the length of the spring is given by:

$$s = \ell \sin\phi = \ell \frac{r - q_2}{q_1} \tag{7}$$

Since the spring is linear, the force it exerts is given by $f = ks$. The lever arm introduces a transmission ratio $\frac{\ell}{q_1}$

between the spring and the output, and thus the force at the actuator output is given by:

$$F = \frac{\ell}{q_1} f = \frac{\ell}{q_1} ks = \left(\frac{\ell}{q_1}\right)^2 k(r - q_2) \tag{8}$$

Using the definition (2), from (8), the apparent output stiffness K is given by:

$$K = k\left(\frac{\ell}{q_1}\right)^2$$

and, therefore, the stiffness is uniquely determined by q_1.

Differentiating (7) with respect to time yields, in matrix form:

$$\dot{s} = \underbrace{-\frac{\ell}{q_1}\begin{bmatrix}\sin\phi & 1\end{bmatrix}}_{A}\begin{bmatrix}\dot{q}_1 \\ \dot{q}_2\end{bmatrix} + \frac{\ell}{q_1}\dot{r}$$

Observe that A is not a full-rank matrix, which implies that there exist $\dot{q} \neq 0$ such that $\dot{H} = 0$, i.e., the configuration q, and thus the apparent output stiffness, can be changed without changing the energy in the spring.

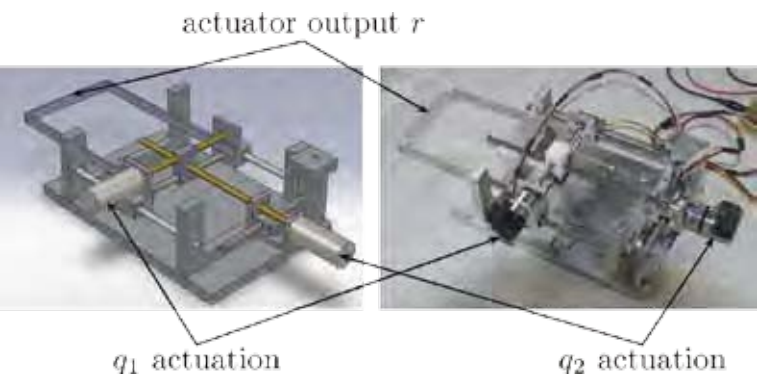

Figure 4. CAD drawing and photograph of the vsaUT prototype.

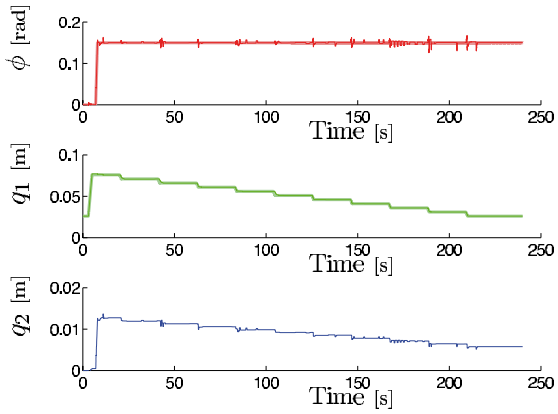

Figure 5. Experiment for determining the apparent output stiffness in the vsaUT prototype.

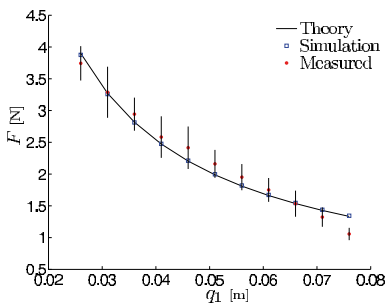

Figure 6. Evaluation of the apparent output stiffness by force measurements in the vsaUT prototype in theory, in simulations and in the experimental measurements.

Experimental validation

To validate that the concept indeed works as described in the theory, a simulation model and a prototype were built, as shown in Figure 4 and presented in [10].

The following experiment was conducted: the degree of freedom q_1 is preset to its maximum value, and the spring is preloaded by constraining the output motion r and by setting q_2 to some desired value. Using a force sensor, the force exerted at the output is measured, which is a direct measure of the stiffness, as follows from (2). Then, in equal steps, q_1 is moved to its minimum position, while q_2 is actuated such that $A\dot{q} = 0$, i.e., the spring length remains the same. At each step change of q_1, the force is measured. This experiment is shown in Figure 5, where the thick lines indicate the setpoint values. The above experiment was done both with the simulation model and the prototype. The results are shown in Figure 6. The theoretical curve is described by $F = \gamma \cdot q_1^{-1} = 0.101 \cdot q_1^{-1}$, where γ is obtained from the design parameters. The experimental data can be accurately represented by the curve $F = 0.107 \cdot q_1^{-0.99}$, showing that the concept is indeed working as predicted by theory.

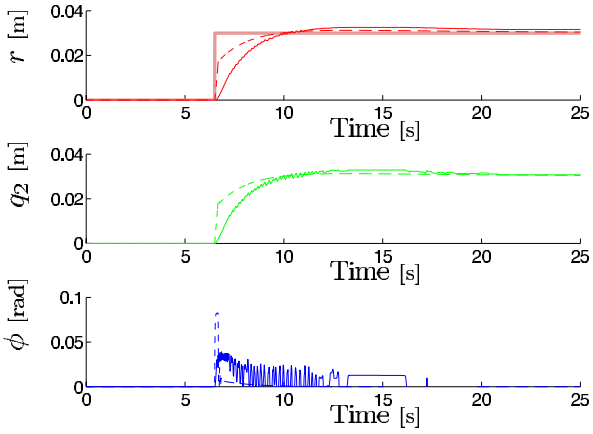

Figure 7. Actuation of a load with the vsaUT. Both simulation (dashed) and experimental (solid) results indicate that no energy is internally stored in the actuator.

A second experiment, presented in Figure 7, shows that in this concept no energy is stored in the spring that cannot be used to do work at the output. In particular, a step setpoint (thick line) for the output position, connected to a load, has been used. Due to the inertial properties of the load, the spring is initially compressed, but all energy stored due to this effect is eventually used for actuation, since the spring is not loaded at the end of the experiment.

Conclusion

The concept of variable stiffness actuators and their relevance to new emerging robotics applications have been presented. In particular, the intrinsic compliance of the actuator ensures safe human-robot and robot-environment interaction, even in unexpected collisions.

Two elementary design classes were presented and analysed. The working principles of these designs lie at the basis of the majority of variable stiffness actuator designs, proposed in the literature. From the analysis, it has been concluded that these designs are not energy efficient in changing the apparent output stiffness, which can be an issue in mobile applications, where the available energy is limited.

Triggered by this observation, a new class of energy-efficient variable stiffness actuators has been introduced. The conceptual design has been validated by means of simulations and experiments with a prototype realisation. The results show that the concept works as predicted by theory, and thus will form a new category of energy-efficient actuator designs.

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Aspheres and freeforms

Historically, the disadvantages of poor manufacturability and metrology determined the choice of using classical optics for opto-mechanical instrumentation. Worldwide however, a lot of time and effort is invested in manufacturing aspheres and freeforms, e.g. in advanced manufacturing and metrology machines and also in the improvement of optical design packages. This paper describes the state-of-the-art manufacturing technologies that TNO Science and Industry is using to manufacture these complex optics.

• *Guido Gubbels* •

TNO Science and Industry develops opto-mechanical instrumentation, important markets for which include the semiconductor industry and space and science applications. Besides providing valuable design work on these systems, TNO can also manufacture the optical components for the high-precision instruments involved. An ongoing trend in optical manufacturing is the manufacture of aspherical and freeform optics.

Author

Guido Gubbels earned his Ph.D. from Eindhoven University of Technology on the subject of the diamond turning of glassy polymers. Currently seconded through TMC Physics to the High Precision Equipment business unit at TNO Science and Industry, he works as a researcher in optical fabrication technology.

This paper is an updated version of [1].

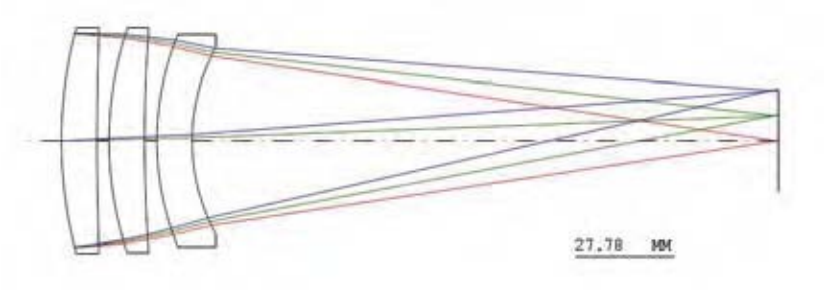

Figure 1. Fraunhofer triplet. The light comes from the left (far field) and is imaged on the right plane.

Aspheres and freeforms

Why?
This is an important question because aspheres and freeforms are difficult to manufacture. The benefits of aspheres and freeforms are as follows:

- Less optics are used in the opto-mechanical system, resulting in a decrease in the number of optical surfaces. Since every surface means a reduction in light intensity (e.g. by scattering), this results in a higher throughput of the optical system.
- Less optics also means a reduction in mass and size.
- An improvement in optical quality (e.g. spherical aberration, coma, distortion).
- A more favourable positioning of the optical components is possible.
- They facilitate chromatic aberration-free optics. When aspherical or freeform mirrors are used, chromatic aberration does not occur.

Optical designers have recognised these advantages for many years. However, for the single production of high-accuracy optics, which are generally needed in the aforementioned markets, the following disadvantages are also very important:

- Optical tolerance analyses are not standard practice yet in optical design packages.
- Aspheres and freeforms are difficult to manufacture with classical production technologies.
- It is difficult to validate the surface shape.
- They are more difficult to align because they have more degrees of freedom.
- They are more expensive because of the above reasons.

Aspheres and freeforms may be an interesting option for mass production because of the major benefits. This is evident from their increasing use in mobile phones and camera objectives, for example. Many of these optics are manufactured using moulding techniques, indicating that one good mould can produce many optics, thus decreasing the cost per element. However, for prototyping and small batch optics, the disadvantages generally result in a choice in favour of classical optics (spheres and flats).

Optical designing
The optimisation of a Fraunhofer objective with an aspherical surface will be shown as a design example. In this case, optimisation was only performed on lens shape and not on lens material. The classical Fraunhofer objective is a triplet as shown in Figure 1. When reducing the number of elements and letting the left surface become aspherical, the transmitted wavefront error of the lens system diminishes from 3.26λ to 0.89λ. This example shows the power of aspheres, i.e. less optical elements and higher accuracy.

The application of aspherical and freeform optics involves new design methodologies. Although a nominal freeform optical design can be made relatively easily these days, the optical tolerance analysis of such a system is more complex. Performing a good tolerance analysis and distributing the error budgets to an opto-mechanical system requires a good knowledge of available machining and metrology capabilities.

Freeform manufacturing

Deterministic machining
Freeform (and asphere) manufacturing is a bit different from classical production technologies in that manufacturing is performed using a so-called sub-aperture tool. This is a tool that is significantly smaller than the area to be machined. Examples of deterministic machining processes include diamond turning, computer-controlled polishing (CCP), ion-beam figuring, plasma jet etching and fluid jet polishing.

In deterministic machining, the workpiece is pre-machined to the rough shape with typical surface shape deviations of 5 µm peak-to-valley (PV). After that, a first precision machining step is applied to decrease the surface roughness. This can be diamond turning or pre-polishing. After this, an iterative process of metrology and corrective machining is applied, as shown in Figure 2. Two techniques are available at TNO, i.e. diamond turning and computer-controlled polishing.

Diamond turning
Diamond turning is a precision machining process that is commonly used in optics manufacturing nowadays. Typical materials for diamond turning include non-ferrous metals such as aluminium and copper, some crystalline materials

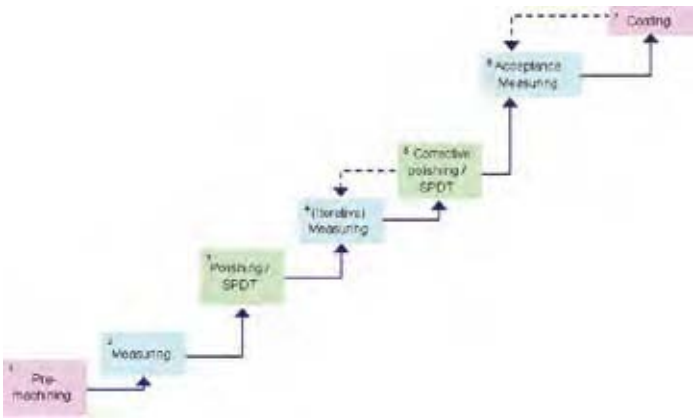

Figure 2. Value chain for freeform machining and metrology.

Figure 4. Diamond turning of a cylindrical mirror, which is a freeform surface, using the machine's slow tool servo.

such as germanium, silicon and calcium fluoride, and some polymeric materials such as polymethylmethacrylate (PMMA). At TNO, most diamond turning is performed on aluminium AA6061. The application of rapidly solidified aluminium grades [2] that have smaller grain sizes and reach better surface roughness values is a new development.
Generally, diamond turnable nickel platings have to be applied to reach 1 nanometer surface roughness levels. However, nickel platings require additional manufacturing steps and post-polishing to remove the diamond turning grooves. In an ESA study, TNO recently improved the achievable results for the rapidly solidified aluminium RSA6061. Figure 3 shows a diamond-turned surface of RSA6061. Diamond turning to 1 nm R_q surface roughness is now possible using this special material. Additional manufacturing steps, such as nickel plating, are no longer needed.

Today's diamond turning machines are very accurate and, as a rule of thumb, an accuracy of 100 nm PV can be achieved with a 100 mm diameter. The accuracy of the

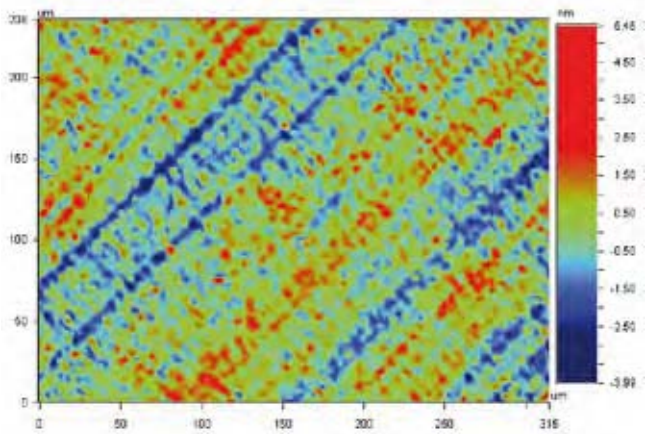

Figure 3. Diamond-turned rapidly solidified aluminium. Surface roughness value as good as diamond-turned nickel plated surfaces.

final product depends on interfacing, balancing and tooling. For freeform optics, the PV is slightly higher, but TNO is proactively working on decreasing the surface shape error to attain values similar to those for on-axis optics.

The reason that the PV error is higher in freeform machining is due to the diamond turning machine's slow-tool-servo action. An example of a freeform optic production is shown in Figure 4, where a cylindrical surface is cut using the slow tool servo. The tool needs to move to and fro per revolution to cut the cylindrical surface. This results in subsequent errors, which directly lead to additional surface errors.

TNO has two diamond-turning machines, a Precitech Nanoform 350 and a recently purchased Precitech 700A. The former is a three-axis machine that can apply slow-tool-servo turning (XZC mode) and the latter is a five-axis machine, not only capable of slow tool servoing, but also capable of fly-cutting (grid) in XYZ mode. Furthermore, this machine has a B-axis that facilitates tool normal machining, for example. It is not only optical components, but also precise mechanical components that can be made on these machines. Both machines can be fitted with a grinding spindle as well, which means that precision grinding aspheres and freeforms is then possible.

Computer-controlled polishing

TNO is able to apply deterministic polishing for producing non-diamond-turnable optics. Computer-controlled polishing (CCP) can produce freeforms and aspheres with high accuracy. Figure 5 shows an example of an asphere being polished using TNO's Zeeko robot polisher (FJP600). Zeeko technology uses an inflatable membrane called the bonnet, which has a spherical surface to which a polishing cloth is glued. As can be seen from Figure 5, polishing slurry is added to the polishing zone.
In contrast to magneto-rheological finishing (MRF), Zeeko technology enables the application of any kind of polishing

cloth to the bonnet. This makes it possible to machine various materials and carry out quick testing with different polishing cloths to optimise the polishing process. This is very important since TNO makes optics from different glasses and many other materials, like stainless steel, molybdenum and silicon carbide.

All deterministic processes use the same principle: they measure the deviation from the theoretical surface and use this error map to calculate the dwell times needed to remove this error. Typical accuracies that can be reached using deterministic polishing techniques are 60 nm PV over 100 mm diameter, but this is largely influenced by mounting, bonnet size and metrology. The difficulty in deterministic polishing of high-accuracy optics is accurately determining the removal function created by the bonnet and the error after each polishing step.

Figure 5. An aspherical surface on TNO's polishing robot.

Metrology

Metrology is very important in the above techniques, since a very accurate 3D error map is needed as input for deterministic machining. In fact, until now only few metrology instruments are available to measure aspheres and freeforms as 3D objects. In industry, a lot of metrology is performed by 2D profilometers (e.g. from Taylor Hobson, Mahr and Mitutoyo). An extra stage has been added to these instruments to enable 3D measurement, but this has a lower accuracy than 2D measurement. For 3D measurements, coordinate measuring machines (CMM) can be used. But high accuracy is only reached for CMMs with small measurement volumes (e.g. ISARA, Zeiss F25, Panasonic UA3P). The disadvantage of these CMMs is that they work in contact mode, which means that optics can be damaged during measurement. An interesting technique that is available commercially and that is non-contact is QED's stitching interferometer. Although stitching may yield high accuracy, its long measurement time is a disadvantage.

The required surface shape errors for infrared applications are less critical (can be a few micrometers), but for visual applications in the high-tech industry shape accuracies better than 150 nm over 100 mm are not uncommon. When dealing with aspheres and freeforms this is an enormous task for metrology instruments. It can therefore be said that the real breakthrough in freeform optics will come when metrology catches up with the current capabilities of machines for manufacturing optics.

TNO has two techniques that can be used in the production of aspheres and freeforms. The first is on-machine metrology, typically suited for infrared optics or optics with less stringent accuracy requirements. The second is the latest development in freeform metrology technology, an instrument called NANOMEFOS.

On-machine metrology

Infrared applications require less stringent surface shape accuracies. It is therefore interesting to apply an on-machine metrology tool. Contact probes are available on current diamond-turning machines, as can be seen in Figure 6. This is not standard technology for polishing machines, although investments are being made for them to become standard. The difficulty with polishing robots is that these machines are not as accurate as diamond turning

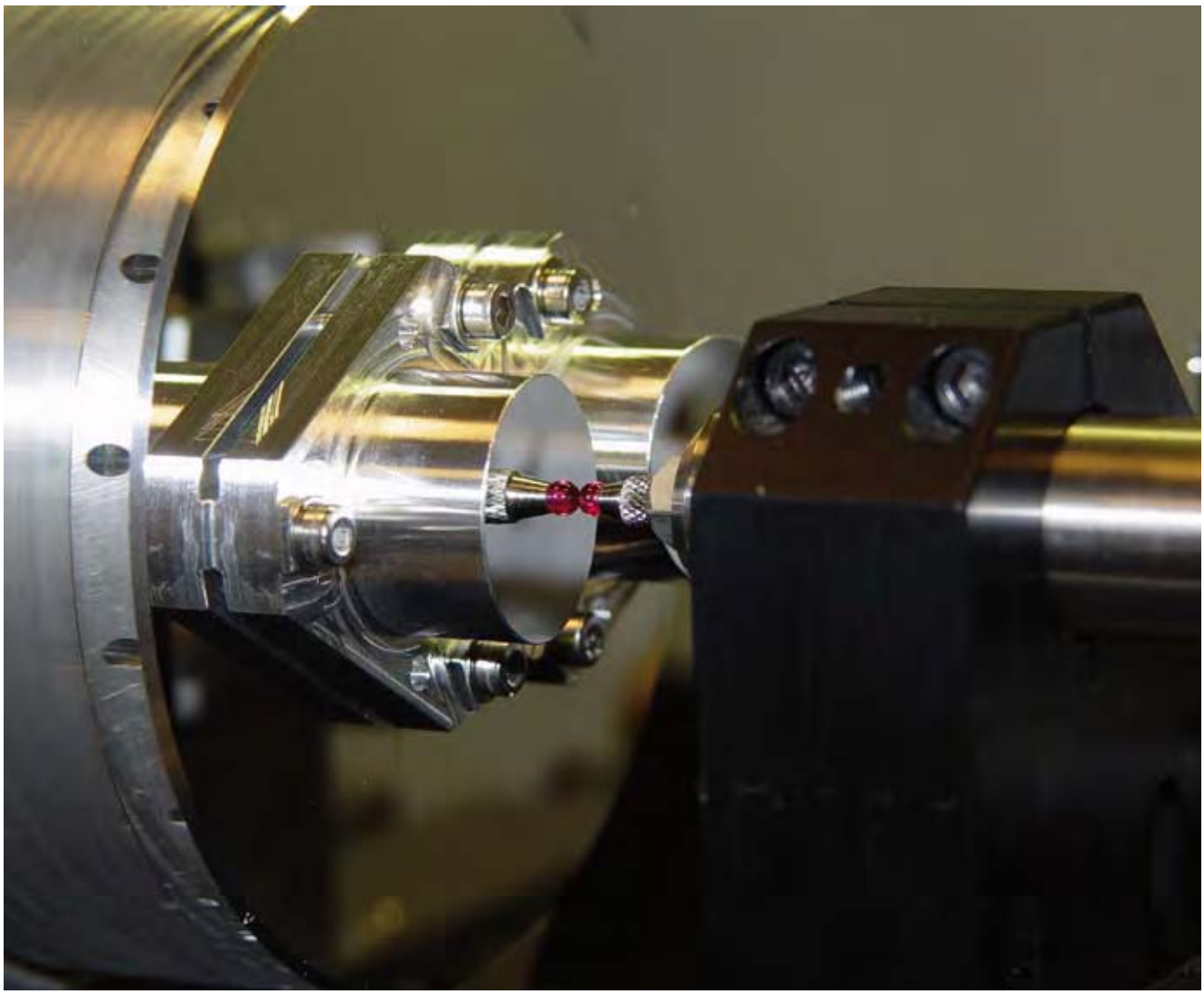

Figure 6. On-machine metrology (the Precitech Nanoform 350's Ultracomp system) to measure an off-axis parabola.

machines, meaning that an on-machine metrology system can only measure to micrometer uncertainty, whereas with a diamond-turning machine this can be well below one micrometer.

Non-contact freeform metrology instrument

When on-machine metrology is not enough to measure an aspherical or freeform optic (which is often the case), TNO employs a new and very promising instrument called NANOMEFOS [3]. This instrument is a non-contact measuring machine for freeform (and aspherical) optics up to 500 mm diameter. It has been developed by TNO Science and Industry, Eindhoven University of Technology and the Dutch metrology institute VSL as part of SenterNovem's Dutch Innovation-oriented Research Programme (IOP). This machine can be used as a measurement machine during deterministic machining processes, and it can be used as an acceptance measuring machine (see also the value chain in Figure 2).

When using NANOMEFOS, the surface to be measured is placed on a continuously rotating air-bearing spindle, while a specially developed optical probe is positioned over it by a motion system (see Figure 7). The optical probe facilitates high scanning speeds (up to 1.5 m/s), and its 5 mm measurement range captures the non-rotational symmetry of the surface. This allows for the stages to be stationary during the measurement of a circular track, reducing the dynamically moving mass to 45 g. This way, a circular track is measured several times to acquire sufficient data for averaging. The position of the probe is measured interferometrically relative to a silicon carbide metrology frame. Capacitive probes measure the product position, also relative to this reference frame. Static as well as dynamic position errors from this short metrology loop are compensated for in data processing.

Reproducibility tests on tilted flats, which are traceable freeforms, have shown that a reproducibility of

Figure 7. Measurement of a strongly curved convex asphere on NANOMEFOS.

approximately 3 nm can be reached. NANOMEFOS has a measurement uncertainty of approximately 30 nm.

The major advantage of NANOMEFOS is its flexibility. Measuring an asphere is difficult and generally requires the use of a computer-generated hologram. However, with NANOMEFOS every asphere can be programmed and measured easily. Custom-made (if at all possible) computer-generated holograms are no longer required. Although high-accuracy freeform measurements are very difficult, NANOMEFOS is very flexible and can be programmed for many freeforms. Another major advantage is the measurement of convex optics. Typically, a highly curved convex optic of > 50 mm diameter cannot be measured on most 4” interferometers (most standard versions) and requires large-aperture interferometers, which is why convex aspheres are frequently not applied. NANOMEFOS can therefore be considered to facilitate convex aspheres.

Conclusions

Historically, the disadvantages of poor manufacturability and metrology determined the choice of using classical optics for opto-mechanical instrumentation. Worldwide however, a lot of time and effort is invested in manufacturing aspheres and freeforms, e.g. in advanced manufacturing and metrology machines and also in improvement of optical design packages. Aspheres are being used, but cheap and high-quality aspheres are still difficult to come by. Freeforms are emerging, but still relatively far off, which is primarily due to difficult metrology.

TNO is actively working on improving freeform optical designing and tolerancing freeform optics. In combination with its advanced manufacturing and metrology technology, TNO will be ready for future optics and optical instruments.

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Handling units for

Technobis Mechatronics has developed and manufactured three mechatronic handling units for harsh environments. These units are part of breakthrough technological development operated by RGS Development, a company founded by Dutch energy research centre ECN, Deutsche Solar and Sunergy Investco, to come to a direct silicon wafer casting process (called Ribbon-Growth-on-Substrate (RGS) wafer casting). As part of this process development a prototype/test machine had to be developed and built in co-operation with technology partners, to find solutions to the challenges that had to be overcome in the translation of the RGS process from the batch-type laboratory-scale towards continuous operation. On the downstream side of the process, Technobis Mechatronics contributed its expertise on high-accuracy, high-speed mechatronics solutions that can be applied in harsh environments.

• *Ruud Bons and Alex de Leth* •

In general, silicon wafers are used as starting product for the production of solar modules. The wafer manufacturing today contributes to about 50% of the module production costs. By the RGS casting process the manufacturing costs can be reduced by 50% due to higher silicon material yield and more efficient high-speed production of the wafers. However, to enable this technology, a proven laboratory-scale process had to be translated into a continuously operating production process. To enable this, new solutions for silicon supply towards the casting process and wafer and tool handling after the casting process had to be developed. Technobis Mechatronics developed the handling units that are used to take the cast wafers out of the process environment, and to exchange worn or damaged cassettes on which the wafers are cast. The unit responsible for collecting the wafers is called the Wafer Outfeed (WO), and the units that exchange the cassettes are called the Cassette Infeed & Cassette Outfeed (CICO); see Figure 1.

Authors

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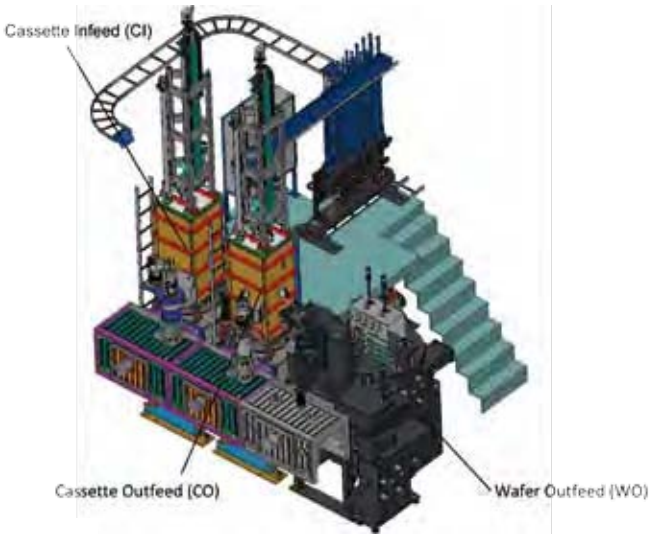


Figure 1. Three handling units attached to the RGS production line.

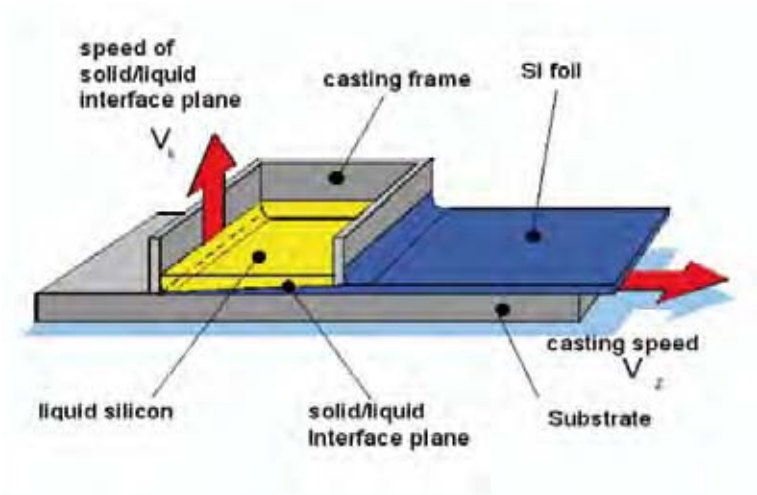


Figure 2. The Ribbon-Growth-on-Substrate (RGS) process.

RGS process

The casting of RGS wafers is a continuous process; see Figure 2. Silicon is melted in a casting frame. As bottom of the casting frame a relatively cold substrate band is used that extracts the crystallisation heat from the melt. During the pass of the substrate underneath the casting frame, the silicon wafer (Si foil) is grown. After the casting process, the wafer can be removed from the substrate and the substrates are re-used in the process; see Figure 3.

Challenges

Due to the special properties of silicon (melt temperature at about 1,410 °C, sensible to oxygen and metal contaminations), the wafers are cast in a vacuum/argon environment at temperatures far above 1,000 °C, which immediately states the challenges of this project. All three handling units are partially exposed to temperatures of around 1,000 °C, and have to operate in a vacuum environment without contaminating the process by e.g. metal evaporation. The handled wafers and substrates will have to be brought to an atmospheric environment without compromising the vacuum/argon environment by loadlocking units. Allowing oxygen to enter the process chamber, would result in the contamination of the silicon wafers and the oxidation of constructive elements (graphite burning).

Requirements

The requirements for the handling units can be divided in functional and environmental requirements. Functional requirements have reference to the handling of the products, such as picking up wafers or substrates without damaging the products, the sequence of functions which will have to be performed by the handling units, and the interface with the transport unit which moves the substrates in the vacuum furnace to create an “endless” flow of substrates to cast on.

Figure 3. RGS wafers (156 mm x 156 mm), substrate side on the left, and free crystallising top surface on the right.

The main environmental challenges for the handling systems are:

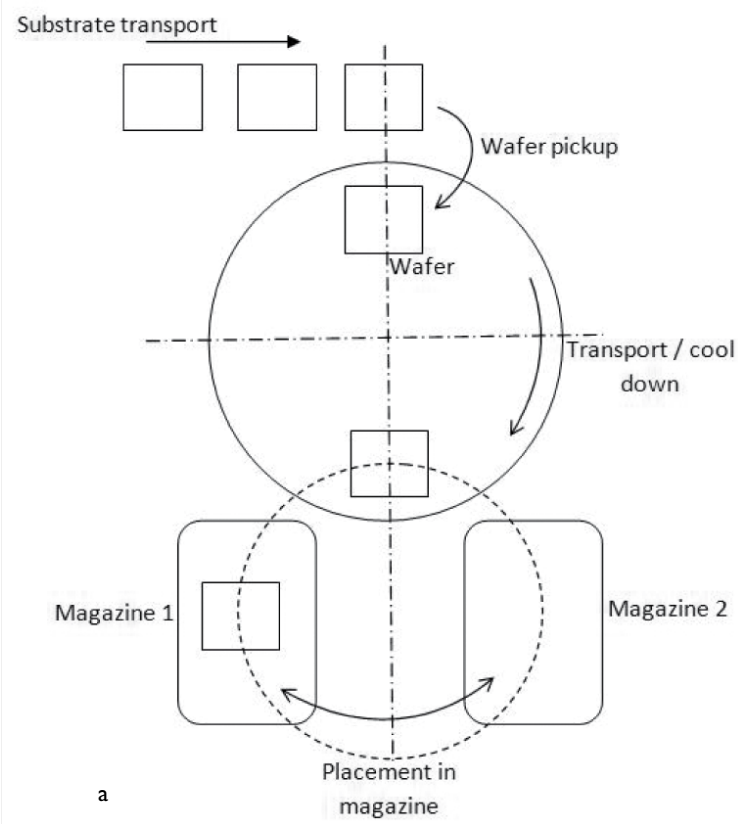
- The systems will have to be able to operate under vacuum conditions as well as ambient conditions while meeting the requirements for handling accuracy.
- The systems will have to operate in a high-temperature (> 1,000 °C) environment.
- The systems will have to handle products which have temperatures of more than 1,000 °C.
- The systems may not contaminate the shielded environment (metal outgassing, leakage, oxidation).
- The systems may not contaminate the handled silicon wafers and substrates (contact contamination).

Design and implementation

Wafer Outfeed

The design of the Wafer Outfeed consists of a large vacuum housing in which the functions pick-up, transport/cooling, inspection and placement in storage are carried out; see Figure 4. The Wafer Outfeed vacuum housing is connected to the vacuum furnace, which contains the transport for substrates.

After the wafer is taken out of the transport line, it is rapidly cooled down to almost room temperature. At that point the wafer is picked up by a second handler, which places it in one of the storage bins. When one storage bin is full, it is closed with a custom-made loadlock valve. After pressurising the storage bin, an operator can take out the wafers. Meanwhile the handling unit fills the other storage bin, enabling the Wafer Outfeed to have a continuous work cycle. When an operator has emptied the storage bin, all oxygen needs to be removed, before opening the loadlock valve. This is done by evacuating the storage bin to a pressure below 0.1 mbar, and filling it with argon in a



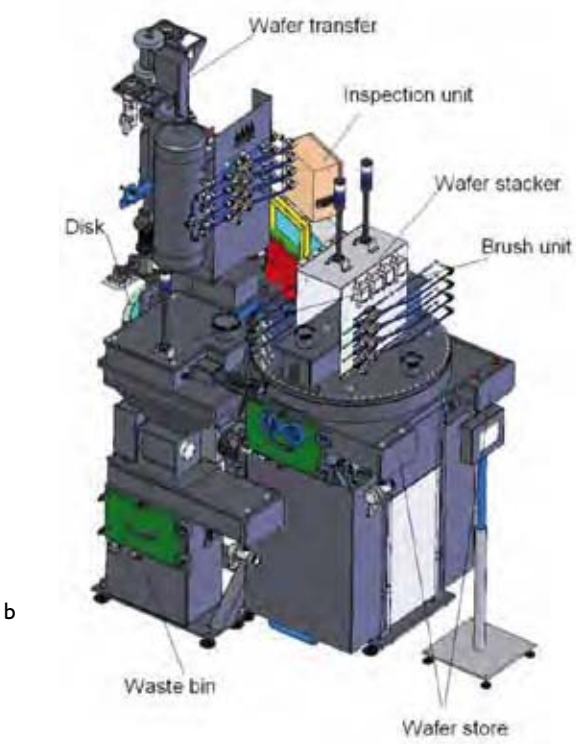
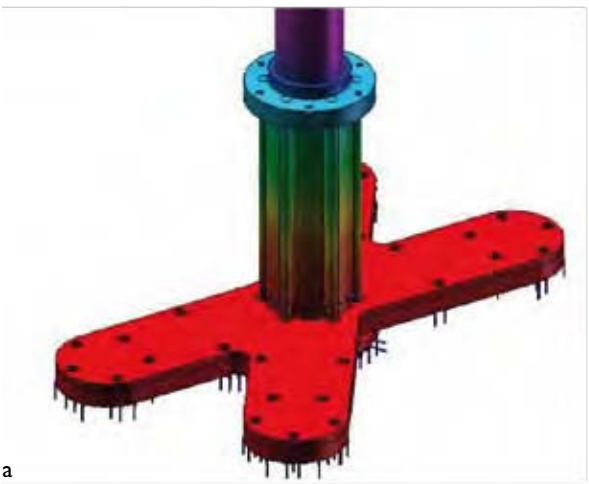


Figure 4. Wafer Outfeed (WO).
(a) Schematic of the process.
(b) Design.



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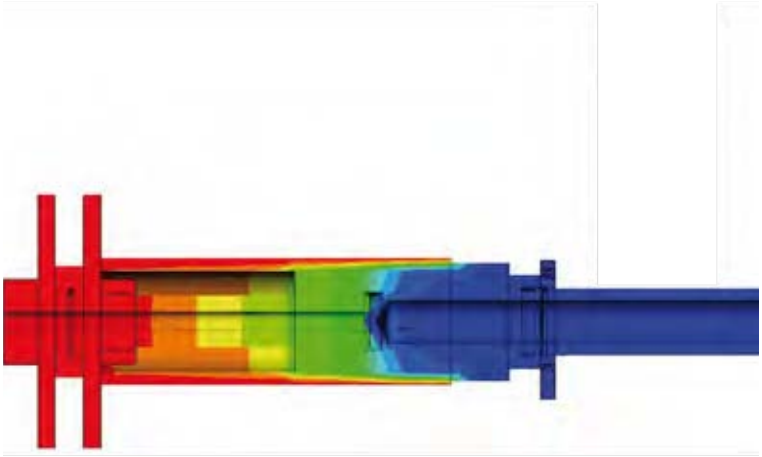

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Figure 5. Examples of finite-element design calculations to examine the temperature of the materials in the wafer pick-up; the range is from room temperature (blue/purple) to 1,000 °C (red). The components studied are introduced below.
(a) Carrier of vacuum chucks with central rotation axis.
(b) The pusher unit.

well-controlled way to ensure a low oxygen level in the process environment.

Harsh environments and WO

One of the critical functions of the Wafer Outfeed is the pick-up of wafers from the transport at high temperatures with high yield. High wafer breakages would be critical for machine uptime and must be avoided. The main challenges were:

1. Wafers that are picked up can have a temperature of more than 1,000 °C, the pick-up construction has to be able to withstand this.
2. Wafers can only be accessed from the top for a pick-up.
3. As a result of casting process disturbances, wafers are not always completely flat when they are picked up.
4. The pick-up forces may not break the wafer.
5. The materials used for the pick-up must not contaminate the wafer.

In order to meet the requirements, a pick-up unit was designed using high-temperature ceramics such as graphite and reinforced carbon. Several thermal analyses have been carried out to ensure that all materials used remain below a process design temperature in order to avoid the contamination of the product; see Figure 5.

Vacuum chuck

To be able to pick up the wafers at the top surface, a special vacuum chuck was designed; see Figure 6. In a test set-up the different chuck designs were built and tested to optimise the design regarding sufficient force for reliable picking without wafer breakage. During these tests, the challenge was to find high-temperature ceramics with sufficient lifetime to allow long-time operation of the chuck under hot conditions and to find a shape-adapting high-temperature material to compensate for the non-flatness of the produced wafer.

The pick-up unit has two pairs of vacuum chucks. While one pair picks up the wafers from the transport line, the other pair lays down the wafers on the cooling disk. After that, the unit lifts up, rotates 180° and moves down, and the cycle repeats itself. The movements of the unit are powered by two servo actuators connected to a special spindle unit that can move in a linear, rotational and spiral-shaped way.

Each vacuum chuck can be individually pressurised and depressurised. The central axle was designed to allow the individual pressure and vacuum supply to be combined

Figure 6. One of the metal prototypes of the vacuum chucks used in the test system.

with the water cooling that is needed for temperature control. To allow a rotational movement, the axle is sealed with a ferrofluidic rotational seal.

When the wafers are lowered on the cooling disk, they enter a unit that allows rapid wafer cooling down by a combination of gas treatment, vacuum sucking and individual water cooling. Due to these measures the wafer can undergo a large temperature drop in a short period of time. After that treatment, the wafer is “cold” enough for further handling.

Cassette Infeed & Cassette Outfeed

The Cassette Infeed (CI) and Cassette Outfeed (CO) are two almost identical units, both responsible for the exchange of worn or damaged cassettes with clean new ones; see Figure 7. The wafers are cast on graphite-based cassettes. Continuous casting on these cassettes results in wear, pollution and sometimes damaging of the cassettes. For this purpose, units had to be designed that can replace cassettes under hot operational conditions in the machine. When the CO takes a cassette out of the process line, the CI fills the gap with a new cassette at process temperature. Due to the continuous casting principle, no gaps are allowed between cassettes at the casting process. The bottom part of the units consists of a cassette storage unit, which in the CI case is supplied with an additional heating unit. The upper part is a loadlock compartment divided by a large gate valve that allows the exchange of cassettes via a loadlock procedure. A pusher or puller unit and a Cassette Transfer Module (CTM) were built to transport the cassette from the storage to the track and vice versa. The loadlocking procedure and all materials in the units were designed in a way that the casting process will not be contaminated by material evaporation or leakage to the oxygen-containing atmosphere.

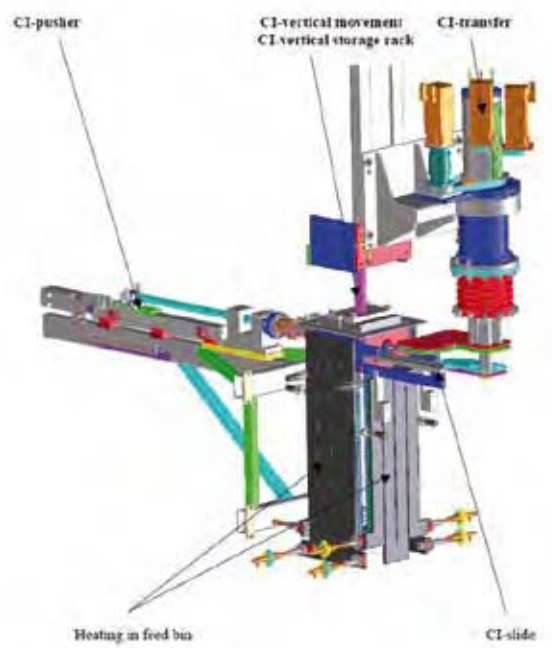


Figure 7. Model of the cassette handling system of the Cassette Infeed (CI) unit.

Cassette Transfer Module

The CI is equipped with a pusher unit that pushes new cassettes from the cassette rack to the CTM pick-up position. A reversed action is required for the CO; hence it is equipped with a puller unit. The CTM does the actual exchange of cassettes. The CTM of the CO takes the cassettes out of the process line, and the CTM of the CI places new cassettes in the process line. Since both units need to be perfectly synchronised, the unit movements are driven by servo motors, which results in a ten-axle motion control system.

Due to the harsh environment with respect to temperature and material choices, as well as due to the rapid but well-controlled movement, the CTM design was very challenging; see Figure 8. The CTM consists of two “jaws” between which the handled cassettes are clamped. The jaws need to be able to individually make a vertical movement in order to clamp and release a cassette. Also the jaws need to be able to move simultaneously in a vertical direction, as well as a horizontal rotation. The vacuum/argon environment and the extreme temperatures demanded that all actuators for the various movements were placed outside the process chamber. A multi-core-axle solution was designed in which each jaw is vertically moved with two axles. The four axles are combined in a single rotating axle. Each axle is individually sealed to prevent contamination of the vacuum/argon environment. A combination of bellows and special elastomer seal is used. The combination of bellow and elastomer seal allows linear and rotational movement, while maintaining a perfect seal on the metal axles.

Figure 8. The Cassette Transfer Module (CTM).

The transition between the metal axles and the high-temperature graphite parts was designed by using a combination of radiation shields and water cooling, in order to meet the given maximum process design temperature for the metal parts. This statement has been confirmed by thorough finite-element method (FEM) analysis. For the hot section of the CTM that is inside the process chamber, graphite or carbon fiber reinforced carbon (CFC) components were used.
The CTM operates at a positional accuracy better than 0.1 mm at gripper point, taking all servo actuators, thermal expansion and deformation of the bins into account.

Cassette pick-up
Due to the process environment and the rapid movement, the cassettes can not be reliably held in place using friction between the parts only. Therefore, a high-accuracy positioning pin system between the cassette and the handler was designed; see Figure 9. In order to overcome an overdefined positional situation when the cassettes are taken over from the track by the CTM, flexible graphite components were constructed to allow a transition phase using a flexible spring element. This spring allows a gentle first contact of the gripper positioning pins with the cassette when lifting it from the carrier positioning pins. The chamfer on top of all the positioning pins allows this transition phase without overdefining the construction. A double-leafspring construction was designed, consisting entirely of CFC.

Conclusions
The design principles used in the handling units for the RGS silicon wafer casting machine can also be used in other technological fields where high-accuracy, high-speed mechatronics is required under vacuum conditions combined with extreme temperatures and strict requirements for materials to meet process contamination limits. Examples of these applications can be vacuum brazing ovens, nuclear fusion reactors, and space applications.

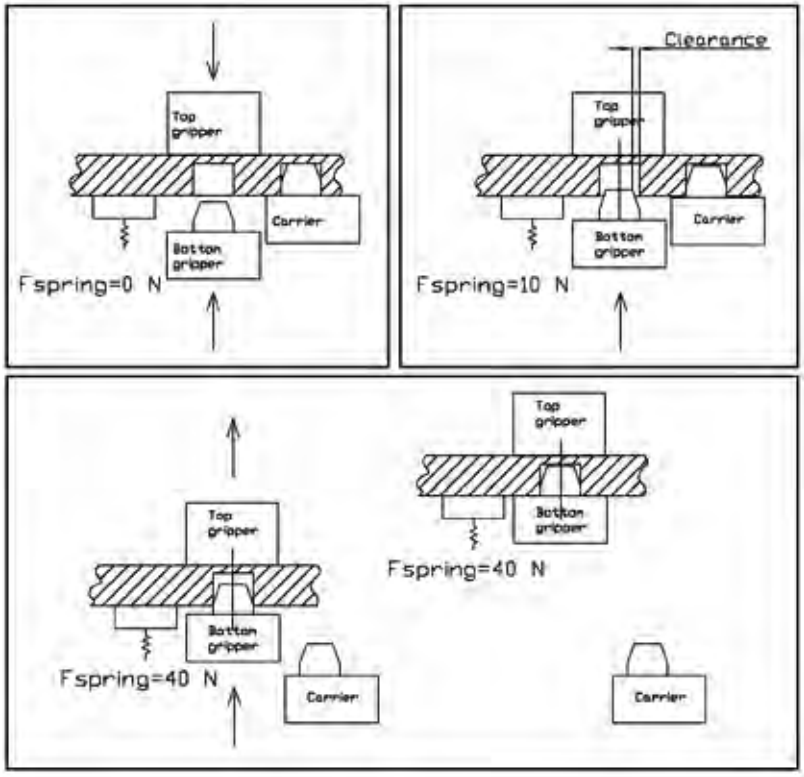


Figure 9. Flexible pick-up without overdefining the cassette position.

For the RGS machine, the design principles required the use of special high-temperature ceramic materials, such as graphite and CFC. Using these ceramics with their special characteristics in high-temperature, high-accuracy handling of fragile products at high speed was a challenging engineering task. By applying finite-element thermal modeling, water or fluid cooling solutions in combination with construction elements such as radiation shields and thermal isolation were found. These solutions guarantee that all materials used are operated below the maximum tolerable process temperatures.

Leakage rates, process environment, accuracy, materials and handling speed requirements formed the challenges to develop a unique mechatronic solution that is an important component in enabling the cost reduction in silicon wafer production for solar cells by the RGS process.

Breaking new ground

Selective Laser Melting (SLM) is a powerful technology that shapes any desired metal part geometry by melting metal powder layer by layer. Using this digital approach, the optimum shape of complex circulation parts can be produced in a single manufacturing step. Such a part not only delivers better performance, it is also more reliable than the complicated assembly it replaces. Furthermore, SLM is the right choice for small metal products, of which thousands can be produced simultaneously. Using this technology, LayerWise offers favourable unit prices and short delivery times. In addition to countless industrial applications, the company manufactures revolutionary orthopedic, maxillofacial and dental implants. The core of LayerWise is producing high-grade parts in any preferred metal alloy using less material and no scrap, reducing unit weight by up to 80%.

• *Rob Snoeijs* •

Metal cutting, milling, EDM (Electrical Discharge Machining) and other high-quality and efficient metalworking processes have a respectable track record on the production floor. Typical for these subtractive methods is that each in their own way is limited in removing part material, despite many tools and accessories.

Design engineers know metalworking processes inside out and take into account their specific limitations up-front. In a way, they design new parts knowing at the back of their minds the production method that will be applied. It would be better if they could concentrate on the functionality of the part to be produced. The geometric limitations of successive metalworking processes force designers to make choices that devaluate the functionality of the part or lead to a complicated assembly instead.

Author

Rob Snoeijs works as a technology writer with LayerWise, an additive manufacturing firm based in Leuven (Belgium).

www.layerwise.com

Building up parts in layers

"At LayerWise we reverse the entire process", says Jonas Van Vaerenbergh, director of the industrial division of LayerWise, a Leuven-based technology firm. "Our core business is Selective Laser Melting (SLM), a technology developed to build up material in layers instead of removing it in different steps. In the meantime, we have optimised the process for a variety of metals and alloys, such as rust-proof steel, hardenable steel, titanium, aluminium and inconel."

in additive manufacturing

In the machine, a high-precision laser is directed to metal powder particles in order to selectively build up a 20 to 40 micron horizontal metal layer. The metal powder particles pinpointed by the laser quickly and fully melt so that the new material properly attaches to the previous layer, without glue or binder liquid.
The powerful fiber laser with high energy intensity operating in the inert area inside the machine guarantees that metal parts being built up exhibit a dense and homogeneous material structure. CAD directly drives the machine without requiring any programming, clamping or tooling. The SLM approach is capable of simultaneously producing metal parts of different shapes in series of up to 2,500 pieces. As this impacts economics favourably, LayerWise is able to offer favourable unit prices and short delivery times.

Unlimited freedom of shape

In addition to producing small components efficiently and cost-effectively, SLM hardly imposes any limitations in terms of geometry. Van Vaerenbergh explains that the layered approach ensures that the laser gains systematic access to any location while building up parts. In this way, the most complex part shapes can be produced, including recesses, ribs, cavities and internal features; see Figure 1. “Usually, the products leaving our facility can not be produced any other way. This is a different ball game for manufacturers because design rules are packed in, removing all obstacles in favour of extreme part optimisation”; see Figure 2.

Take the burner component LayerWise produced for Diametal. Similar to machine manufacturers for food and pharmaceutical companies, this company is regularly challenged with producing complex circulation pieces such as mixers, inlet and outlet components, dispensers, coupling parts and heat exchangers.
The Diametal burner component contains nine undercuttings and six internal cavities. LayerWise applied SLM to manufacture this component as one unit in a single production step; see Figure 3. This is called function integration, because this SLM-produced component replaces multiple parts manufactured using conventional metalworking processes. Assembling these parts takes time, particularly because they need to be connected hermetically, reducing reliability altogether.

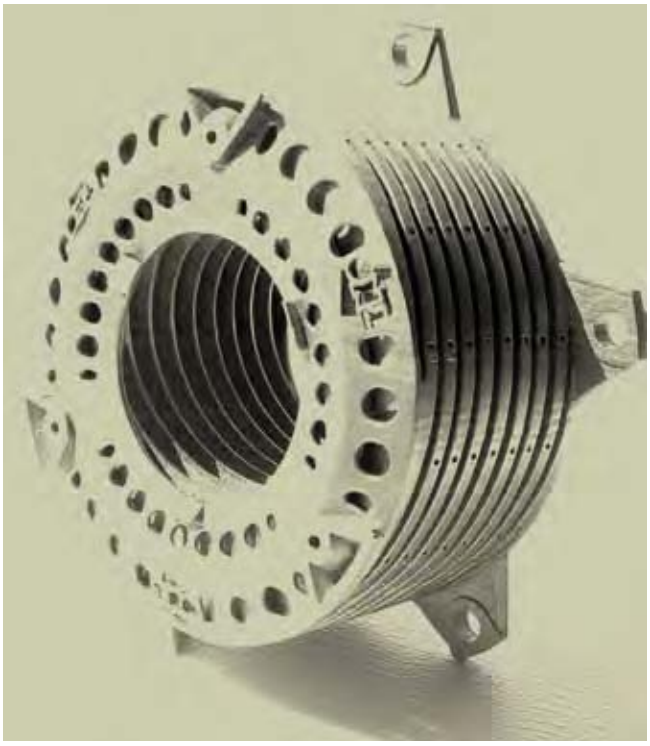


Figure 1. By building up metal parts in layers, the most complex part shapes can be produced, including recesses, ribs, cavities and internal features.

Figure 2. As design rules are packed in, SLM removes all obstacles in favour of extreme part optimisation.

Figure 3. In replacement of a complex assembly, LayerWise produced a single burner component containing nine undercuttings and six internal cavities.

Figure 5. Usually, the products leaving the LayerWise facility can not be produced any other way. Shape complexity is not charged because the production cost is primarily dependent on the weight of the part.

Van Vaerenbergh explains that function integration makes SLM fit for resolving miniaturisation, leakage and assembly issues. “Diametal was not charged for the shape complexity of the part because the production cost is dependent on the weight of the part, showing that SLM offers superior products at a reasonable cost.”

Optimising circulation channels

A perfect example of efficient and flexible design was the production of a component that connects cooling ducts. Firstly, the additive manufacturing process realised 75% weight reduction. Secondly, designers were able to drastically reduce flow resistance by defining channel geometry using freeform surfaces. LayerWise produced the part exactly according to the functional CAD design, resulting in an improvement of the circulation properties by 80%.

According to Van Vaerenbergh, also the manufacture of injection mould inserts yields impressive results; see Figure 4. “Thanks to SLM’s freedom of shape, the cooling channels can be positioned in conformity with the mould shape. This is a major improvement compared to conventionally drilled holes. Optimised channel geometry and location ensure a better controlled cooling process that delivers higher-quality parts that do not warp and contain fewer hot spots. Imagine the economic advantage of reducing the serial production cycle time of moulded plastic parts by 15%.”

Figure 4. Injection moulding quality and speed can be increased by producing injection mould inserts with optimal cooling channels.

Boundaries of technology

LayerWise is the first production centre in Belgium that exclusively focuses on this additive production process for metal parts. The company was founded by Jonas Van Vaerenbergh and Peter Mercelis; both were closely involved in the development of Selective Laser Melting at K.U.Leuven University. LayerWise intensively collaborates with the university, and systematically invests 30% of its resources in Research and Development to push the boundaries of the technology.

“By bringing together technological expertise, production capacity and customer support, LayerWise occupies a unique position on a European level”, Van Vaerenbergh claims. “Our engineers control SLM to such an extent that they are capable of perfecting the technology and realise the most challenging specifications. Today we are able to produce with 15 micron geometric accuracy and build up walls as thin as 0.2 millimeters, which is extremely difficult – if not impossible – using conventional technologies. Also the implementation of process control tools in and around the melting zone is important to guarantee highest part quality”; see Figure 5.

By acquiring full control over the production process, LayerWise achieves a homogeneous microstructure with a relative density of up to 99.98%, for an increasing number of metals and alloys. Research shows that the mechanical properties are virtually the same as those of conventional metals. To prove this, LayerWise systematically carries out mechanical tests regarding density, hardness, elongation and fatigue. In advance, the chemical composition of the bulk metal powders is examined in a chemical laboratory.

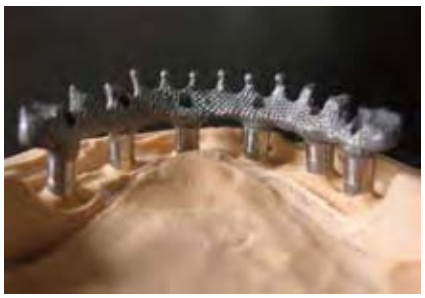


Figure 6. Through patented DentWise technology, geometry and surface retention related limitations set by traditionally moulded or milled suprastructures no longer apply.

Figure 7. The complex shape of a zygoma implant was digitally derived through medical imaging and produced using SLM technology.

Figure 8. Personalised orthopedic protheses are generally produced in titanium, equipped with a fine surface geometry that actively encourages surface retention (Photos courtesy of Mobelife).

Unattended production

The machinery of LayerWise consists of top-quality systems that run around the clock. Quickly producing prototypes is possible, but this activity is usually a leg up to serial production. As CAD files are directly converted into three-dimensional geometry, SLM is a cost-effective metalworking process that allows for unattended production.
After parts are taken out of the production machines, finishing actions start. If desired, conventional metalworking actions can be applied, such as drilling, cutting and EDM. It is also possible to have certain components surface-hardened. As a concluding step, customers can opt for a high-gloss polishing finish.

Dental suprastructures

LayerWise is also heavily involved in medical industries, for which the company manufactures implant-supported suprastructures, for example. On the basis of patient-specific geometry data, acquired through medical imaging or three-dimensional scanning, the personalised structure is designed in software and printed in titanium straight away. As a concluding step, the dental technician finishes off the structure and completes the final prothesis.
“Through digital SLM technology, geometry and surface retention related limitations set by traditionally moulded or milled suprastructures no longer apply”, says Peter Mercelis, director of the LayerWise medical division. “In addition, the implant connections are completed with highest precision”; see Figure 6. DentWise suprastructures are manufactured using ultra-strong titanium alloy (Ti6Al4V, grade V), which outperforms the commonly used titanium grade II in terms of mechanical properties.

Implants

There are more medical applications LayerWise specialises in. During a major maxillofacial (i.e., related to the upper jaw and face) reconstruction, surgeons inserted an implant (the so-called zygoma) manufactured by LayerWise; see Figure 7. The complex shape of the implant was digitally derived through medical imaging and produced using SLM technology. This approach offers the ability to restore the facial symmetry of patients nearly perfectly.

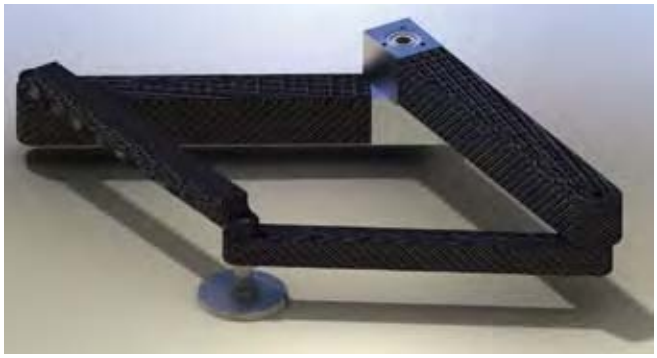
Concerning orthopedic implants, the process of building up metal in layers offers the possibility to design porous bone-replacing structures and integrate them into protheses. This allows for an excellent long-term fixation; see Figure 8. In addition to personalised implants, designed on the basis of medical imaging, SLM technology is used for manufacturing medical instrumentation. For this purpose, LayerWise offers a number of biocompatible metal alloys.

Growing along with the technology

Two years after its inception, LayerWise has grown considerably. Recently, the company appointed a number of European distributors. This is part of the strategy to gradually operate on an international scale. “After propagating the SLM technology and its advantages to different industries, companies now realise that they can truly benefit from the technology”, concludes industrial division director of LayerWise, Jonas Van Vaerenbergh. “Additive metalworking processes change design and production rules completely. By realising projects together with customers, we offer companies plenty of opportunity to create more added value and produce more cost-effectively.”

Rapid manufacturing composites for

Product development in the high-tech precision industry increasingly relies on the application of 'new' lightweight materials, such as carbon fibre composites. However, engineers lack composite know-how and experience. Last year, the Mechatronics department at Fontys University of Applied Sciences started the project 'Composites in Mechatronics', aimed at developing knowledge about carbon fibre composite machine parts, investigating production cost reduction and improving knowledge transfer to SMEs.



• *Henk Kiela, Bart Bastings and Tim de Hond* •

The most commonly used materials in mechanical precision engineering are steel and aluminium. Engineers are familiar with the properties of these materials and can develop complex structures. But because of the end-users' demands, the physical limits of steel and aluminium in today's precision products will be reached soon. It is essential for the high-tech precision industry to develop new products, using 'new', lightweight materials, such as carbon fibre composites. However, using composites will demand a different way of working for the precision engineers, since composites are inhomogeneous and anisotropic materials, whereas steel and aluminium are homogeneous and isotropic materials. Currently, engineers lack know-how of and experience with composites.

Carbon fibre is not a new product and is widely used in the automotive, aerospace and defence industries. Composite manufacturers are confident in producing products for these industries. Products for high-end machinery require a different approach with which composite manufacturers are not familiar. Their mindset is focused on material strength and low weight, whereas the focus in high-end machines is on stiffness and low weight.
For mechanical engineers, carbon fibre machine parts can be of great value, as they allow the realisation of higher accuracy in high-dynamic machinery. This can be attributed to the damping properties (to a large extent an unknown factor) and the low specific weight of carbon fibre composite materials, resulting in high natural frequencies. Another advantage of carbon fibres is the opportunity of creating a variety of differently shaped products.

RAAK project

Since September 2009, the Mechatronics department at Fontys has been working actively on 'Composites in Mechatronics' in a so-called 'RAAK' project (Regional Attention and Action for Knowledge circulation). RAAK is

and lightweight more precision

aimed at knowledge exchange in regional innovation programmes between universities and small and medium-sized enterprises (SMEs). The consortium set up for this project consists of Fontys' Mechatronics department, the INHolland Composites Lab in Delft, the association for the synthetic composites industry in the Netherlands (VKCN/NRK), Q-Sys, and DSPE. The consortium partners and regional SMEs (engineering, manufacturing and end-users) are collaborating to investigate the potential of carbon fibre composites for use in high-tech systems.

The main focus of the project is developing knowledge about carbon fibre composite machine parts. All available knowledge is shared with the partners. The Fontys Mechatronics department is researching what know-how is missing. This has resulted in the development of a test bench on which the material properties of different carbon fibre products can be measured. The products are dynamically actuated on torsion, bending, and push/pull forces, after which the effects of product behaviour are measured. Another project result is the realisation of a manual for composite design in the Finite-Element Method (FEM) software ANSYS©.

Air-hockey Robot

To test the theory, a pilot project was defined in close cooperation with TMC Mechatronics, one of the project partners, and with support from the industrial participants. TMC Mechatronics was working on an air-hockey playing robot. This Air-hockey Robot is intended to serve as an eye-catcher for TMC at conventions and events; see Figure 1.

The engineers at TMC Mechatronics developed this robot with four aluminium arms. The two arms closest to the puck had a square profile with the dimensions 400 mm x 40 mm x 1.5 mm. The other two arms, closest to the electric motor, had a square profile of 400 mm x 60 mm x 1.5 mm. All four arms together had a total weight of 4.92 kg, including the motor interface. The first bending mode of the arms in push direction determines the speed and accuracy of the total system. For the aluminium arms, this frequency is 84 Hz.

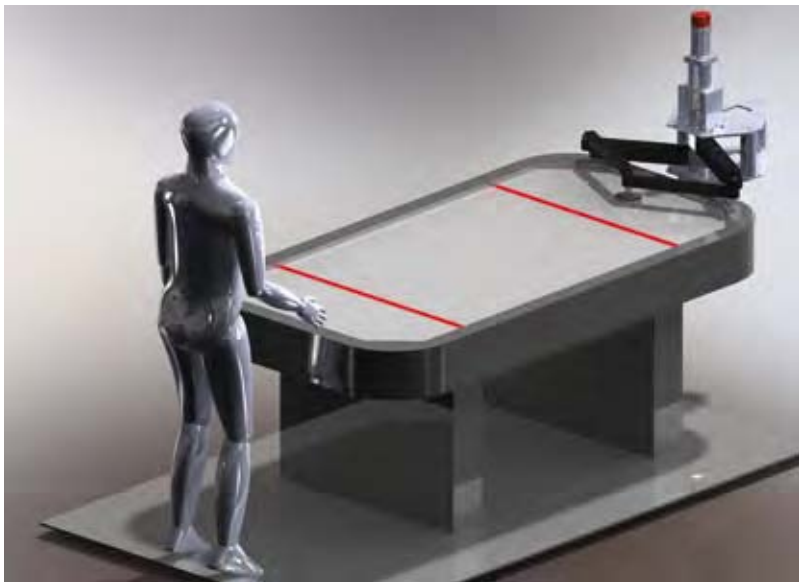


Figure 1. Air-hockey Robot impression.

Mechatronics at Fontys

The authors work for the Mechatronics department in the College of Engineering at Fontys University of Applied Sciences in Eindhoven, the Netherlands. Lector Henk Kiela is head of the department; Bart Bastings and Tim de Hond are researchers. The Mechatronics department conducts applied research in various fields of robotics and high-tech mechatronics, in close cooperation with industry, universities and education.
Know-how about mechatronics, robotics, vision, applied physics, computer technology, mechanical and electrical engineering is put into practice in various projects, such as Low Cost Motion Control, Remote Robotics, and Composites in Mechatronics. Students get involved through internships or graduate projects. In most cases, knowledge and experience is translated into educational material used in the Fontys mechatronics and (in general) engineering curricula.

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TMC offered to use their Air-hockey Robot as a demonstrator in the project. The objective was to increase the robot's performance by replacing the aluminium arms with carbon fibre arms. The goal was to reduce the mass inertia and increase the first bending mode from 84 Hz to at least 200 Hz.

Four students made a complete redesign of the arms and calculated the enhanced performance. During the engineering phase of the arms, the students tried to find an optimum between low weight, high bending stiffness, high torsion stiffness and low production costs.

To achieve this inertia reduction and increase the natural bending mode frequency, first the required stiffness of the arms was calculated. To do this, a model of the robot was made in which the assumptions were that the large arm near the robot has to be stiff in bending direction. The small arms near the pusher were assumed to be rigid in push/pull direction. This resulted in a simple model of one arm and a mass, see Figure 2, with bending stiffness *k* (unknown) and mass *m* (1 kg). The mass was calculated from the mass of one aluminium arm, pusher and all connecting parts, such as bearings.

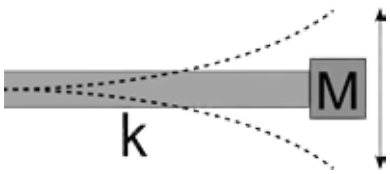

Figure 2. Simple cantilever beam model.

Now the required stiffness of the arm could be calculated with the standard equation for a mass-spring system:

$$f_e = \frac{1}{2\pi}\sqrt{k/m}$$

and thus:

$$k = \frac{f_e^2 \cdot m}{(1/2\pi)^2}$$

which results in a required stiffness of $1.6 \cdot 10^6$ N/m for a frequency of 200 Hz.

For a beam clamped on one side and loaded at the tip, a well-known equation is often used to calculate the deflection for a given load, and thus the stiffness:

$$k = \frac{3EI}{l^3}$$

or when shear deformation is also accounted for:

$$dx = \frac{Fl^3}{3EI} + \alpha\frac{FL}{GA}$$

where α is a geometric constant and *G* is the shear modulus.

This works very well for most (slender) beams made of steel or aluminium. But for carbon fibre the formula does not give usable results, because of the orthotropic behaviour of this material. When a carbon fibre laminate is used to make a square tube, the *E* and *G* moduli *in plane* are different from the *E* and *G* moduli *out of the plane*; see Figure 3.

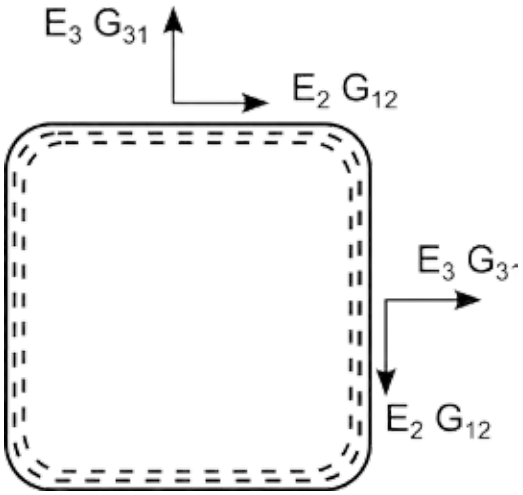

Figure 3. Orthotropic properties of a composite beam.

For this reason, these calculations were only used as a global indication; the final design was based on a FEM model of the composite beam. In this model the total laminate of the beam was modelled as a stack of individual layers with orthotropic properties; see Figure 4. With this set-up it is very easy to change the lay-up of the carbon

fibre lamellas and investigate the effect on stiffness for different lay-ups.

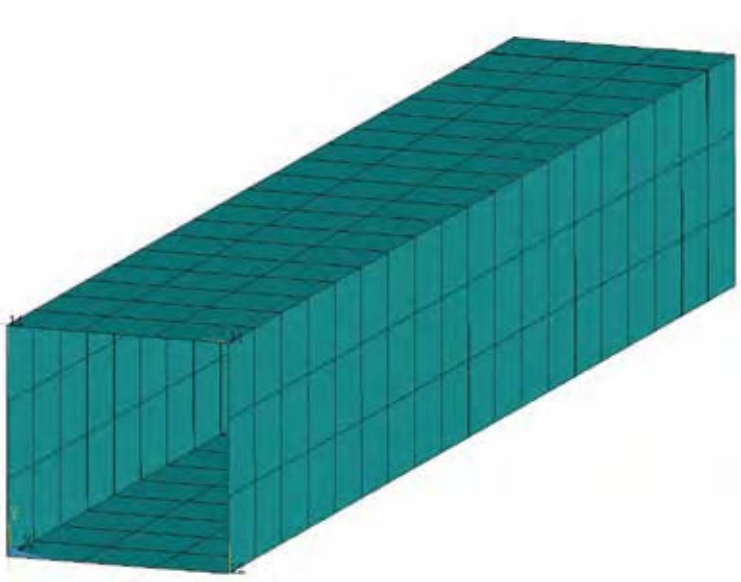

Figure 4. Model set-up, with the sides of the beam modelled as thin shells.

After a few iterations, a lay-up was chosen that resulted in a bending stiffness of $1.6 \cdot 10^6$ N/m (which was the required value) as well as good torsional stiffness. This lay-up consists of one layer with ± 45° fibres on the outside, seven layers of UD fibres in the middle and three layers of ± 45° fibres on the inside; see Figure 5, and see the box on the right for an explanation of composite terminology.

Figure 5. Different layers (the ± 45° fibres in purple, UD fibres in blue) in shell elements.

Composite production

Carbon fibre products are also called carbon fibre reinforced plastics, because that is exactly what they are. A resin, usually epoxy, is used as a matrix material in which the fibres are embedded. The fibres provide the stiffness and strength (the reinforcement), and the resin is used to keep the fibres together.

A frequently used method to put the resin and fibres together is 'Resin Transfer Moulding', were dry fibres are placed in a mould and the resin is sucked in between the fibres through a vacuum in the mould. Another method is when a manufacturer uses pre-pregs, which is an intermediate product of fibres that are pre-impregnated with resin. These pre-pregs are stacked and placed in a mould. A vacuum bag is put over the mould and the entire set-up is placed into an oven or autoclave, where the resin can cure under pressure and heat.

The most important considerations when designing with carbon fibres are the fibre type and lay-up of the fibres. Because the fibres are only stiff in their longitudinal direction, they must be stacked on top of each other at different angles to get stiffness and strength in all directions needed. Such a stack is called a laminate. This means that a designer can tailor the mechanical properties of the laminate to meet his needs.

When the fibres are all in the same direction, this is called UD (unidirectional). A UD lay-up gives a very stiff laminate in one direction (high E-modulus), but is very compliant in all other directions. This is useful when only pure push-pull forces are to be expected. When shearing is important, a ± 45° lay-up is used, because this will result in a very high G-modulus in the shearing direction. Most of the time a combination between these two is used to get the right mechanical properties.

The advantages of carbon fibre over traditional materials such as aluminium and steel are that it has a low weight and that the mechanical properties can be tailored to the designer's needs, but this comes at the cost of more engineering effort to calculate the expected stiffness and strength of a carbon fibre laminate.

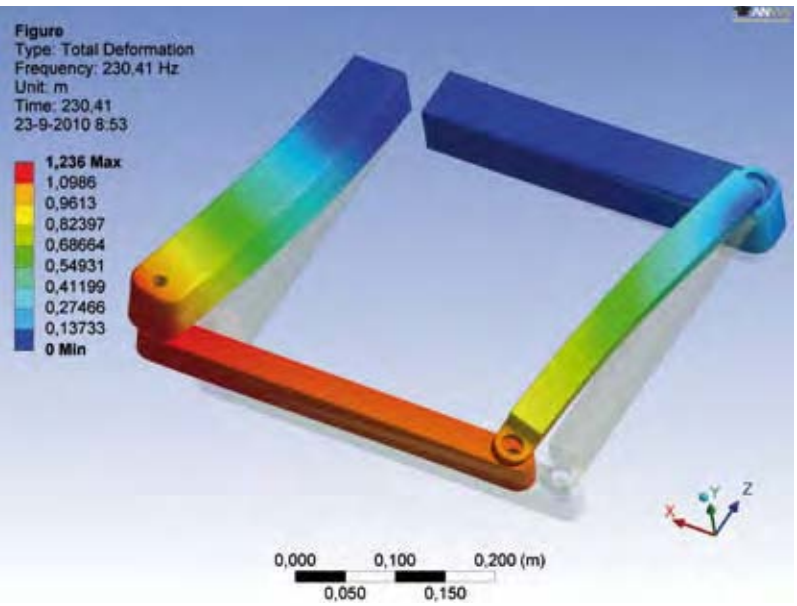

Figure 6. Modal analysis of composite air-hockey robot arms.

These calculations were done for all arms, and finally a model of the entire set-up was made. In this set-up, all degrees of freedom of the model and also the different layer properties were taken into account. A modal analysis was conducted and the first bending mode was calculated to be 230 Hz; see Figure 6.

In the final design, see Figure 7, the weight of the arms changed from 4.92 to 4.66 kg. It has to be noted that most of this mass is closest to the electric motor that drives the arms. This motor does not feel mass but mass moment of inertia. The mass moment of inertia for the aluminium arms was 0.60 kgm^2. The moment of inertia for the carbon arms is 0.23 kgm^2, a reduction of 62%. As mentioned earlier, the first bending mode is very important because it determines the speed and accuracy of the system. This mode increased from 84 Hz to 230 Hz. In theory, the system with carbon fibre arms should perform more rapidly and more accurately, which makes the Air-hockey Robot even more difficult to beat.

Rapid manufacturing

Another goal of the 'Composites in Mechatronics' project is to investigate the possibilities to reduce production costs of carbon fibre products. Carbon fibre parts are classically produced using popular methods such as lay-up on a model or pressing and curing of pre-pregs material in a mould. The model or the mould is generally designed and produced separately, before actual production of one or more carbon fibre parts can be started. For the new application field investigated in this project – the use of carbon fibre machine parts – the production quantities for such parts are generally between 1 and 100. Both the initial

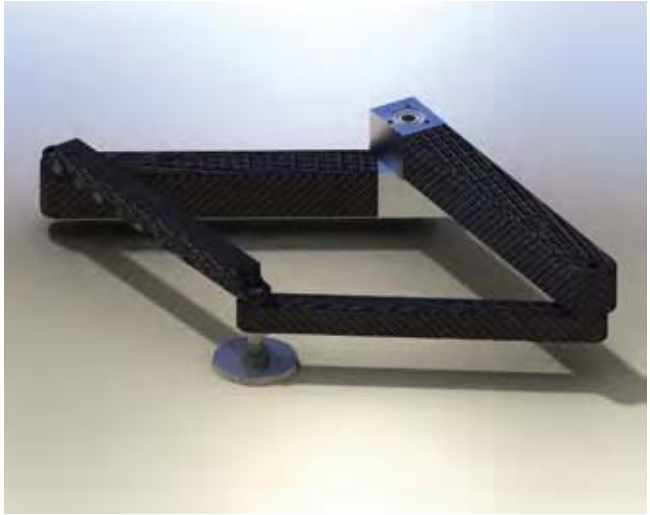

Figure 7. The final design of the air-hockey robot arms.

cost and the lead time before getting the first part can be a problem when using the classic manufacturing methods.

The idea arose to experiment with rapid manufacturing techniques in the process to produce the models or moulds. Rapid manufacturing (RM) has become a mature way of producing plastic parts, not only for commercial applications, but also for part manufacturing purposes. The capabilities of these RM parts are, in general, underestimated. But there are a few interesting features that favour the use of RM for the model or mould, being the design flexibility and the fact that the cost for a complex shape is not different from a simple shape. Other advantages are the short lead time of a few hours between CAD design and the actual part coming out of the RM equipment, and the minimal waste.

Parts can be produced by RM in various plastics and in metal as well if needed to produce stronger parts. With the current technology in RM, metal parts are still quite expensive. Therefore, the choice was made in this project to explore the capabilities of producing a polycarbonate (PC) mould for a complex shape. This experiment was conducted in close cooperation with project partner Airborne Composites. Based on their advice, the mould was split into two halves. Figure 8 shows the resulting mould. The total cost of the PC mould was around € 500, including the man hours to design the mould in CAD.

Then, the carbon part was formed in the mould, using a standard vacuum bag, fabrics and tooling resin that cures at 80°C. Because a vacuum bag, not a pressure bag, was used, a simple mould could be used that did not have to withstand high pressure. The product was cured in a standard oven at a temperature not exceeding 100 °C. The PC has a heat deflection temperature of 138 °C at 66 psi

Figure 8. The polycarbonate mould produced with RM, for manufacturing complex-shaped composite products.

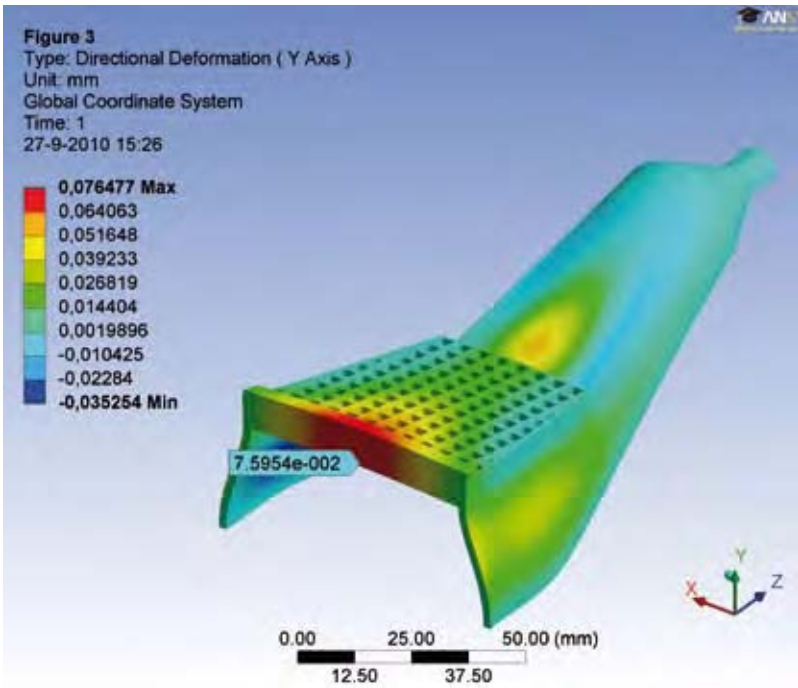

Figure 9. Study of the deformation of the mould due to internal pressure.

(4.6 bar), and 127 °C at 264 psi (18 bar). Due to its amorphous nature, PC does not display a melting point. Airborne produced the carbon part in the mould and simply removed the formed part from the split mould without damaging the mould parts.

Additionally, a FEM study was performed to investigate the possibility of using an RM mould in combination with a pressure bag. This means that the mould has to withstand an internal pressure, otherwise the final product will not meet its dimensional specifications; see Figure 9. An internal overpressure of 1 bar turned out to cause a deformation of the mould of less than 0.1 mm. However, it was decided to use a vacuum bag.

Conclusions

Using RM moulds or models opens up a new way of designing and manufacturing products in small numbers, as it combines low-cost moulds having complex geometries with short lead times. Further work will be done to investigate and compare the cost and lead times of classically produced moulds and RM moulds.

It is obvious that a plastic mould has some limitations. The stiffness of plastic is significantly less than that of metal. This can be partially compensated by using (more) ribs in the mould to support the thin-walled scale forming the parts. Mould behaviour can be optimised for the part manufacturing process by means of the proper use of FEM tools. Thermal limitations are another potential hindrance to the use of RM moulds. It is known that at room temperature, carbon fibre parts only gain 80% of the strength and density they would get in an autoclave. But many machine parts are not designed and optimised for strength. The major design criteria are weight, stiffness and damping (dynamic behaviour). Of these three properties, damping will be favourable for a part cured at room temperature. The fibre volume ratio (the percentage of the total volume that is constituted by fibres) and stiffness will be better when a part is cured in an autoclave. But how much variation in properties can be found, will be part of further research in this project.

By taking into account these design aspects in the manufacturing of high-graded carbon fibre machine parts with the use of RM moulds or models, an important step was made toward low-cost manufacturing with short lead times. Other expected advantages will be explored later in this project, such as fixing metal or plastic attachments for bearings and support functions in the same process step as forming the carbon part in the RM mould. The mould can be modified such that the attached part is fixed to the mould to achieve better accuracies for the completed assembly. This could make post-processing, for example milling of bearing holes, redundant or at least save costs.

Acknowledgement

The authors would like to thank ‘Peters freeswerk en modellenbouw’ for manufacturing the moulds for the air-hockey robot arms, and Refitech for making the carbon fiber air-hockey robot arms using these moulds.

Additive manufacturing of miniature parts

Technologies for additive manufacturing, such as microstereolithography, are becoming ever more suitable for the production of high-resolution miniature parts. The designs can be complex and production can take place directly. These techniques are easily applicable for product development and can help speed up introduction to the market. TNO Science and Industry and Materials innovation institute M2i in the Netherlands carried out a knowledge transfer project on microstereolithography with pilot companies, the results of which will be presented during a Precision-in-Business day in Eindhoven, the Netherlands, on 18 November.

• *Bart van de Vorst and Henk Buining* •

Microstereolithography is a 3D printing method. The principle is shown in Figure 1, while Figure 2 shows an example of microstereolithography in practice. The technique uses a liquid-based photopolymer as building material. This special resin hardens under the influence of light with a certain wavelength. The resin is located on top of a glass plate, beneath which a projector is positioned that can illuminate the resin. Above the glass plate, a building platform is mounted to a linear Z-stage.

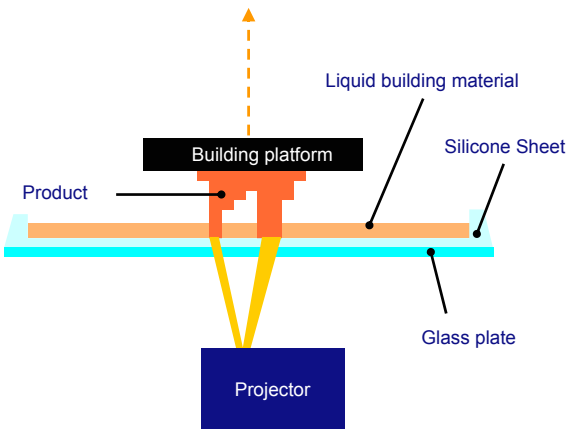

Figure 1. Principle of microstereolithography: the exposure of layers of curable resin with a projector.

In the starting position, the building platform is placed at one layer's distance above the glass plate. The projector illuminates the cross section of the first layer of the product. Curing takes place in the area where the resin is exposed and the first layer of the miniature part is formed on the building platform. Next, the building platform moves up. The first layer is peeled from the glass plate and remains on the building platform. While moving up, new resin flows in between the first layer and the glass plate. Then the following layer can be exposed, producing a new layer on top of the previous layer that was formed on the building platform. This cycle is repeated until the complete product is finished.
Figure 3 shows some examples of miniature parts produced with microstereolithography.

Authors

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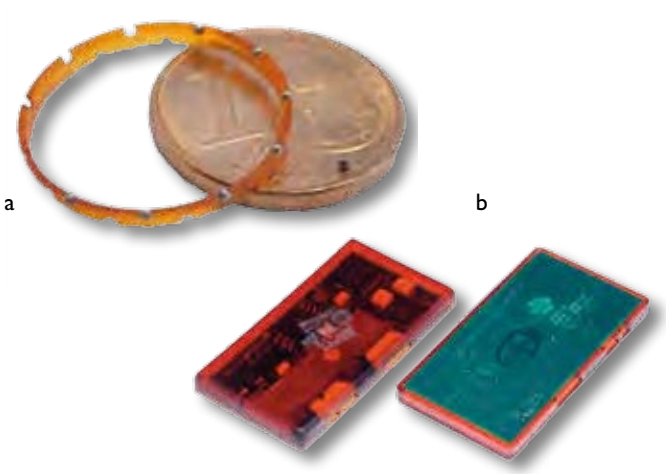
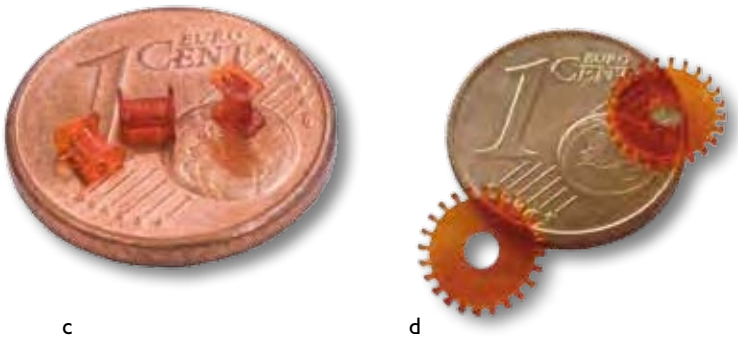
Figure 2. Building process of a microfluidic chip with internal canals.





a b c d

Figure 3. Miniature parts produced with microstereolithography.
(a) Cage for miniature bearing.
(b) Housing of integrated remote sensor.
(c) Functional prototype for micro-injection moulded coil.
(d) Cogwheel for manipulator.

Figure 4. Principle of building a product with volumetric pixels (voxels) in different resolutions.

Using this method, a series of voxel planes are created. They contain individual voxels known as volumetric pixels. The thickness can vary for each single exposure from 10 µm to 100 µm. With high-resolution voxels, smoothly detailed parts can be produced as shown in Figure 4.

Available materials

There is a growing range of photopolymers available for different applications. R5 is a versatile acrylate that produces robust, accurate and functional parts. The chemical resistance is good and the temperature and humidity ranges are broad. There are also resins available that are CE-certified for use in hearing-aid products and that are Class-IIa biocompatible in accordance with ISO 10993. The material mimics traditional engineering plastic ABS, meaning it can be used in many other applications. Some materials have a high wax content, which makes it possible to use the parts for investment casting applications in the jewellery and dental markets.

Support

While the part is being built, the product material is not strong enough to produce a rigid product that can withstand the building forces in advance. The layer being built might bend, particularly when there is an overhang of horizontal features. Therefore, some areas of a product need a lattice

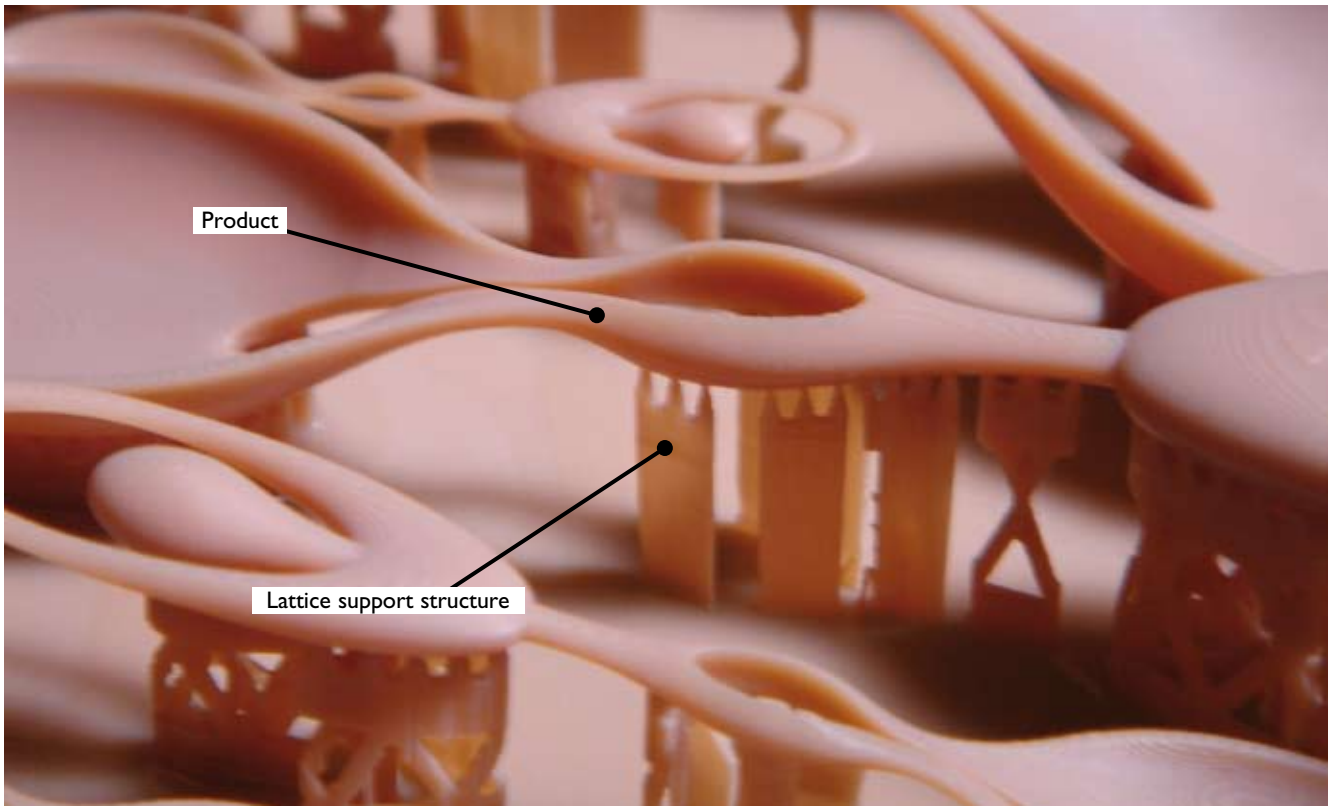


Figure 5. The same principle for stabilising a building structure must be applied to support a workpiece that is built using microstereolithography.

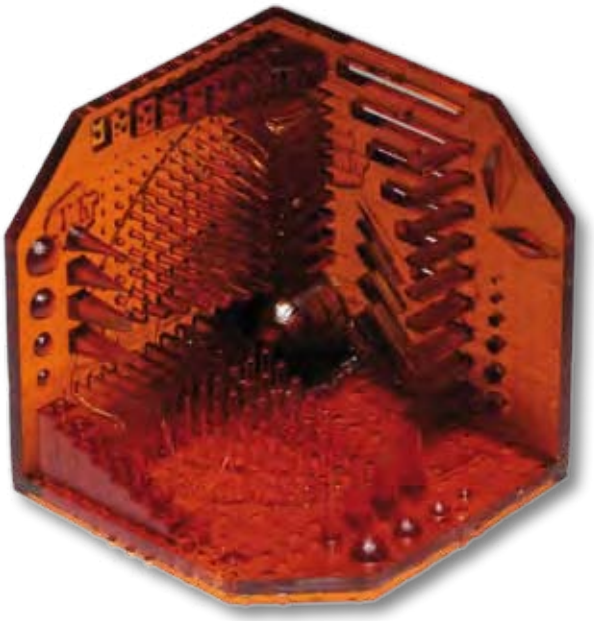


Figure 6. A test workpiece with different product features in different directions, such as small bars and narrow cavities, which highlights process capabilities and can be used to optimise process parameters.

support structure as shown in Figure 5. If possible, however, the use of support structures should be minimised, given that they use material and must be removed manually. Removal is sometimes difficult and could leave marks on the product.

A simple method to minimise support is a clever orientation of the product in the build chamber. The product designer should also bear in mind how support can be avoided. A small slope of 3°, for example, can avoid the need for support under horizontal faces.

Possible features

To explore the possibilities and limitations of microstereolithography, TNO designed a test product as shown in Figure 6. This test product contains different product features such as small holes, small bars and thin plates. The product features are, within a certain range, becoming ever smaller to explore the limits. The features are located in different orientations, exploring the influence of the building direction on the part quality. This test product enables exploration of the effect of the material and process parameters, as well as optimisation of the parameters. For example, while higher illumination intensity gives a stronger product, it causes small holes to be filled with cured resin.

Speeding up the building process

Commercially available equipment for microstereolithography has fixed building cycles and no sensors to control the building process. The movements of the building platform and the start of the illumination follow a pattern with fixed speeds and time frames. The speed is independent of the size of the cross section of the product and must be adjusted to the maximal acceptable

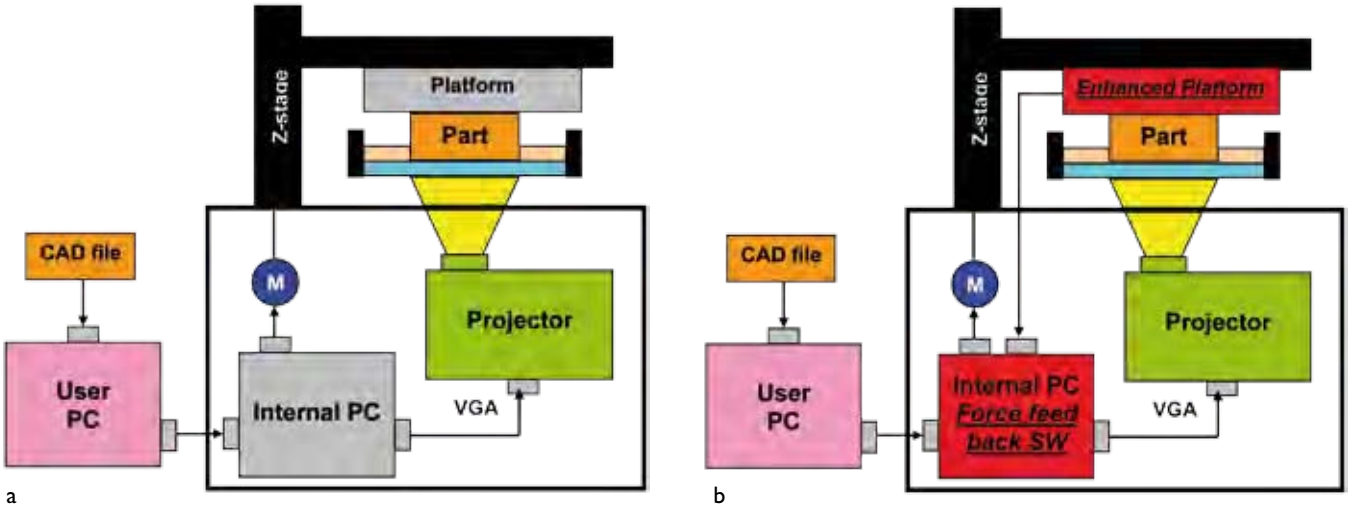


Figure 7. Microstereolithography equipment.
(a) Standard layout with an internal PC directing the building cycle, with standard parameters for all slices of the product.
(b) With tuning kit, having sensors in the advanced building platform and individual process parameters for each layer.

forces in the worst cases. This results in a relatively slow building process of approximately 25 seconds per layer.

TNO Science and Industry has patented an intelligent Force Feedback system in the machine. The controller optimises the movements of the building platform, taking into account process parameters for the specific layer to be built. This results in a safe and fast building process with improved product quality. As shown in the diagram, the controller regulates:

- upward movement of the building platform for a speed-optimised smooth peeling-off of the layer;
- downward movement of the building platform building up a stabilised new layer of resin;
- illumination of the actual layer;
- repetition of the cycle with new parameters optimised for each cross section of the part.

The original equipment as shown in Figure 7a contains a Windows PC with a software suite for the operator to handle the 3D CAD file and to slice the file into bitmaps representing each cross section of the part. The slice file is sent to the internal PC in the machine. For each slice the motor of the z-stage is controlled with standard parameters by the internal PC, while the bitmaps are sent to the projector via the VGA card.

A separate kit for upgrading existing machines has been developed for the implementation of the intelligent control system (see Figure 7b). A modified internal PC calculates the optimised process parameters for each individual layer. The movement of the z-stage is based on real-time force feedback from the sensors in the enhanced building platform.

Higher resolution (factor 10)

Another research project at TNO, which focused on the improvement of product quality by means of a higher resolution of the building process, involved the development of new materials, processes and equipment. Basically, the projector image can be scaled down, while retaining the original high resolution of the DMD (Digital Micromirror Device) chip of, for example, 1280 x 1024 pixels. New optics with higher quality were needed, resulting in an equipment redesign. The projection area was reduced to 3 mm x 4 mm. This results in a projected pixel size of 3 µm; Figure 8 shows an example of a miniature product. To build larger objects, a stepping mode in XY is incorporated.

This equipment processes resin voxels that have a volume one hundred times smaller (see Figure 9). This requires very specific material properties and an accurate illumination cycle.

Lower production costs (factor 10)

A further step towards mass production is to lower production costs. Equipment for microstereolithography is built from components with relatively low prices. In contrast to some other machines for 3D printing, there is no need for a laser with complex mechanics, optics and controllers. Instead, standard technology for computer projectors with no mechanical critical components can be applied. The development of DMD chips used in PC projectors for consumer markets made these projectors cheap and reliable.

Figure 8. Miniature chess castle (height 2.8 mm) containing an internal staircase.

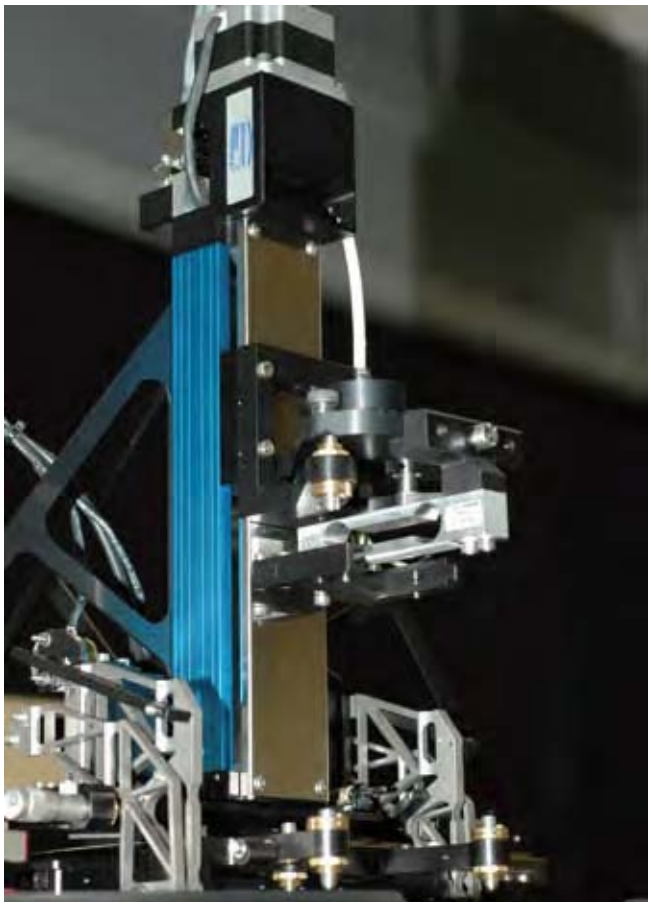


Figure 9. Equipment for highly detailed microstereolithography with voxels of 3 x 3 x 10 μm³.

Knowledge transfer

With special knowledge transfer projects, TNO and M2i make research results applicable in practice. Pilot cases are worked out to demonstrate the capabilities of the techniques. A recent project focused on the use of microstereolithography. Other projects in progress focus on the use of additive manufacturing for medical applications and on coatings on additive manufacturing parts. Another focal point at TNO and M2i is the development of high-end equipment for micro-milling techniques. In this way, TNO and M2i help to bring innovative techniques to the market.

Acknowledgment

This research was carried out under project number MT.09098 in the framework of the Research Program of the Materials innovation institute M2i (www.m2i.nl).

Precision-in-Business day: microstereolithography

The most important results of the microstereolithography project will be presented on what is known as a PiB-day organised by DSPE in Eindhoven, the Netherlands, on 18 November. See the programme on page 64. Registration by e-mail.

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When precision cannot stand the heat

In precision systems, thermal effects have a large influence on system performance, regarding accuracy and throughput, especially under extreme conditions (for example, vacuum or cryogenic). Therefore, it is crucial to give this aspect sufficient attention in the design phase. This article focuses on the control of thermal behaviour of precision systems. Topics include the proper choice of materials, design principles, passive or active temperature conditioning and the compensation of thermal deformations.

• ***Ronald Lamers*** •

From its invention in 1656 by Dutchman Christiaan Huygens until the 1930s, the pendulum clock, as shown in Figure 1, was the world's most precise timekeeper. It uses a pendulum, a swinging weight, as its timekeeping element. Huygens was inspired by investigations of pendulums by Galileo Galilei beginning around 1602. Galileo discovered the key property that makes pendulums useful timekeepers: isochronism. It means that for small swings the period of swing of a pendulum is approximately constant. Successive swings of the pendulum, even if changing in amplitude, take the same amount of time. The introduction of the pendulum, the first harmonic oscillator used in timekeeping, increased the accuracy of clocks enormously, from about 15 minutes per day to 15 seconds per day.

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The period of swing of a simple gravity pendulum depends on its length, the acceleration of gravity, and to a small extent on the amplitude of the swing. It is independent of the mass of the bob. If the amplitude is limited to small swings, the period T of a simple pendulum, the time taken for a complete cycle, equals $2\pi\sqrt{(L/g)}$, where L is the length of the pendulum and g is the local acceleration of gravity.

The largest source of error in early pendulums was associated with slight changes in length due to thermal expansion and contraction of the pendulum rod with changing ambient temperature. This was discovered when people noticed that pendulum clocks ran slower in summer, by as

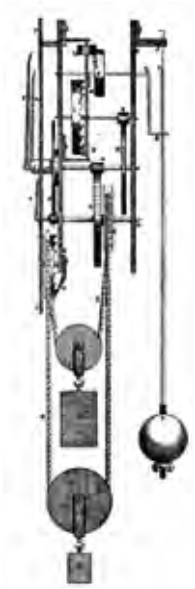


Figure 1. Huygens' pendulum clock. (Source: Wikipedia)

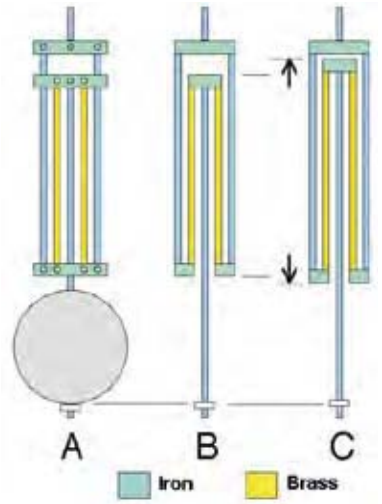


Figure 2. Harrison's gridiron pendulum clock. (Source: Wikipedia)

much as a minute per week. A pendulum with a steel rod will expand by about 11.3 parts per million with each degree Celsius increase (ppm/°C), causing it to lose about 0.5 seconds per day per degree of temperature change.

The most widely used compensated pendulum was the gridiron pendulum, shown in Figure 2, invented in 1726 by British clockmaker John Harrison. The gridiron pendulum did not change in length with temperature, so that its period of swing stayed constant when ambient temperature changed. It consists of alternating brass and iron rods, assembled in such a way that the effects of their different thermal sensitivities cancel each other.

Around 1900, low-thermal-expansion materials were developed and used as pendulum rods, which made elaborate temperature compensation unnecessary. In 1896, Charles Édouard Guillaume invented the nickel steel alloy Invar. Invar has a coefficient of thermal expansion (*CTE*) of around 1.2 ppm/°C, resulting in pendulum temperature errors of about 0.05 seconds per day. This residual error could be compensated to zero with a few centimetres of aluminium under the pendulum bob, compensating the expansion of the Invar rod. Later, fused silica was used, which had an even lower *CTE* (0.55 ppm/°C).

Thermo-mechanical design

The use of low-*CTE* construction materials and design principles such as the gridiron pendulum are still common practice in precision engineering. Invar is still used as construction material in some of the most advanced machines. Modern construction materials include Zerodur (*CTE* ~ 0.02 ppm/°C) and silicon carbide; see Figure 3.

In general, thermal problems in precision engineering are related to the expansion and contraction of materials as a result of internal (actuators, electronics, cooling water, etc.) or external heat sources/sinks (environment, people, processes, etc.). To avoid these problems, it is best to locate the heat sources away from the critical components. In most cases, this is not possible, so one has to deal with the effects of thermal disturbances.

When tackling thermal effects, three main steps can be defined:

- Material selection and geometry.
- Thermal conditioning.
- (Software) compensation.

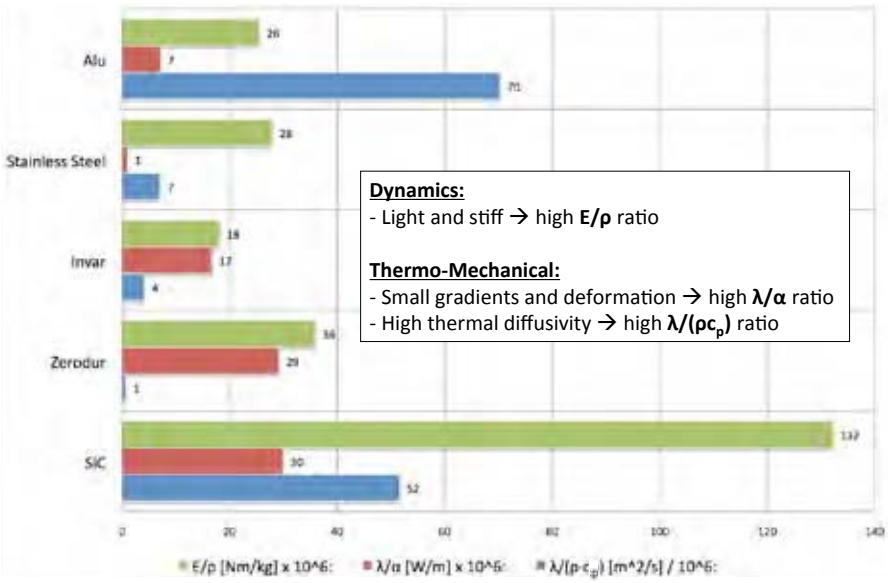


Figure 3. Material properties of some typical construction materials.

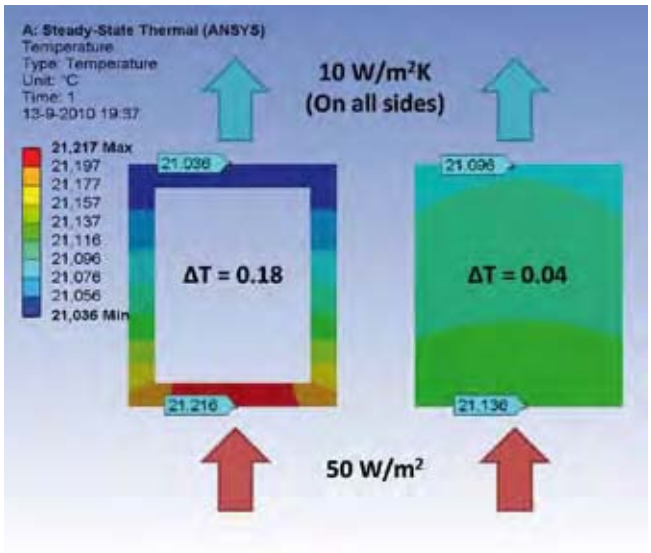


Figure 4. Cross sections: gradient reduction ~ factor 4.

Besides the above mentioned aspects, also predictive modelling and thermal measurements are important topics to discuss. However, these are not covered in this article.

Material selection

The choice for materials with a low coefficient of thermal expansion (*CTE*) α is often proposed when dealing with thermal effects. Bending deformations caused by temperature gradients are often more significant than homogeneous expansion (or contraction). This means that not only the *CTE* is important, but also the thermal conductivity λ. The higher the thermal conductivity, the smaller the temperature gradients and thus the bending deformation. In order for a structure to be insensitive to spatial temperature gradients, a material with a high λ/α ratio must be selected.

When dealing with dynamic thermal disturbances, the thermal capacity also becomes important. The material properties that determine the thermal capacity are the density ρ and the specific heat c_p. Different components in a structure, e.g. a metrology loop, will have different thermal capacities. Changes in temperature will cause dimensional changes of all components in the loop (errors). The components will react differently, unless they all cancel out around the metrology loop, which is unlikely in any situation involving dynamic temperature variations.

Besides the thermal capacity, the thermal diffusivity is an important material property as well. The thermal diffusivity is defined as $\lambda/(\rho c_p)$. A high thermal diffusivity means that a transient heat distortion is quickly spread out to a uniform temperature distribution. The sensitivity to thermal gradients and the thermal diffusivity can be combined to the characteristic $\lambda/(\alpha\rho c_p)$, which expresses the capability of a material to maintain its shape due to temporal and

Figure 5. GAIA test set-up built by TNO Science and Industry.

spatial temperature variations. Material properties for some (typical) construction materials are shown in Figure 3.

From this outline, it is clear that when dealing with thermal effects, not only the *CTE* is important, but also λ, ρ and c_p. When dealing with thermal stresses, also the Young's modulus E becomes important. This complicates material selection for thermal stability, compared to e.g. dynamics (vibration), where in most cases one only strives for a material with a high E/ρ ratio (specific stiffness).

Geometry

An important design philosophy within precision engineering is concerned with design principles for precision. One of the pillars of this design philosophy is design for stiffness. The intention is to design a structure, for instance a frame, in such a way that the (mechanical) natural frequency is maximised in order to achieve maximum positional accuracy. The definition of the natural frequency is the square root of the stiffness c divided by the mass m, $\sqrt{(c/m)}$. When striving for a construction with a high natural frequency, one aims to maximise stiffness and minimise mass. This often leads to box-like constructions made out of sheet metal.

From a thermal point of view, one often wants to maximise conduction through a structure so that a transient thermal disturbance is quickly spread out to a uniform temperature distribution, limiting thermal gradients and thus bending deformations. In that case, structures with solid cross sections are preferred over box-like constructions. After all, metal still conducts heat a lot better than air. However, by using sheet metal constructions, the opposite is achieved, as illustrated in Figure 4.

In Figure 5, a test set-up is shown for the optical system of the GAIA satellite [1]. The set-up was built on a large aluminium base plate. The optical path can be designed such that it is insensitive for homogeneous expansion. Only bending deformations disturb the optical path. The high thermal conductivity of aluminium minimises temperature gradients and thus bending deformations. The total mass of

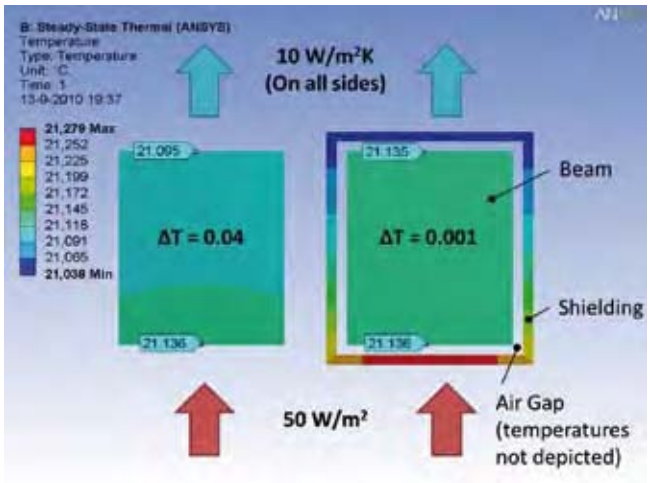


Figure 6. On the right, the beam is enclosed by thermal shielding: gradient reduction ~ factor 40.

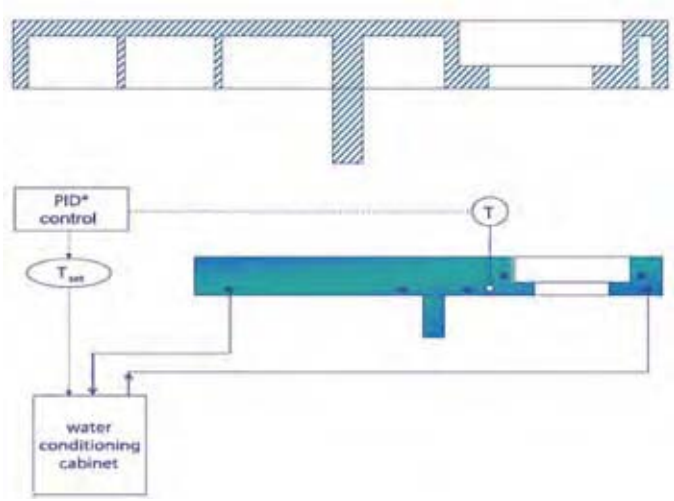


Figure 7. Traditional Invar sheet-metal metrology frame versus solid aluminium metrology frame.

the test set-up is 335 kg. Because of this high thermal capacity temperature changes can only develop slowly.

Thermal contact resistances between different components can also have a strong effect on the thermal behaviour of a structure, but are not further discussed here. If the selection of the right material and the application of the proper geometry do not result in the desired system performance, the next option is thermal conditioning of the construction. This can be done passively or actively.

Passive thermal conditioning

The most popular passive technique is applying thermal insulation to reduce the rate of conductive heat transfer. In order to shield a structure from thermal radiation, it is possible to apply a coating with a low emissivity ε, reducing both absorption and emission. In reverse, absorption and emission can be increased by applying a high emissivity.

In [2] a metrology frame is described that is enclosed in an aluminium box, which due to its thermal capacity acts as a low-pass filter for dynamic thermal disturbances such as operators and environmental fluctuations. The high conductivity of aluminium creates a uniform temperature distribution over the shield, thereby also creating a uniform heat load on the metrology frame inside and thus reducing thermal gradients in the frame; see Figure 6. Other techniques include creating a mini-environment, using IR-shields and applying large thermal masses, as illustrated in the GAIA satellite test set-up.

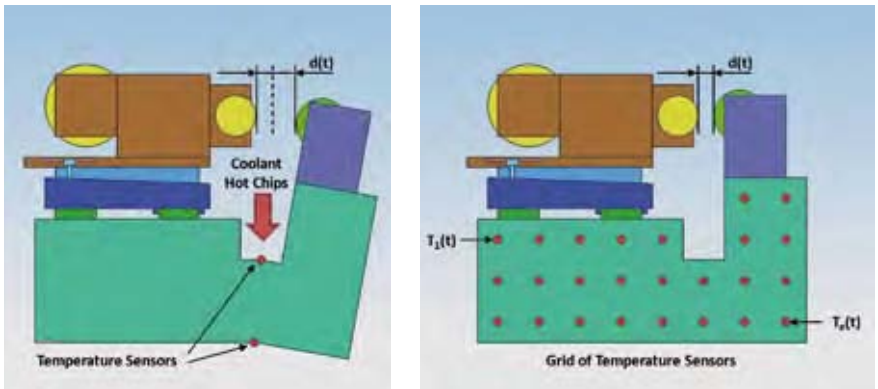
Active thermal conditioning

The most popular active technique is cooling, which can be for instance water, oil or air cooling. This can be done ‘open loop’ or ‘closed loop’. Besides using channels, it is also possible to apply showers for thermal conditioning of a structure. As described in [3], a metrology frame made out of Invar plates, which was used for an ASML wafer stepper, was replaced by an solid aluminium frame with closed-loop water cooling; see Figure 7). Because of the thermal properties of aluminium, active water conditioning is highly effective. The internal conduction is high enough to enable excellent conditioning of the entire frame. The relatively large heat capacity of aluminium ensures that temperature fluctuations, of the environment as well as the cooling water, are dampened very well. Next to the above mentioned advantages, this solution yields significant reductions of cost price and lead production time.

Besides conditioning techniques involving gases or liquids, it is also possible to apply thermal actuators. A simple example is placing a heating element next to a drive system. When the drive system is powered, heat will be dissipated. By applying a control loop, the heating element guarantees that always the same amount of heat will be dissipated, even when the driving system dissipates less or no power. In this case, heat dissipation remains constant and the structure will reach a thermal steady state, so that thermal stability is achieved.

Compensation

If the right choice of material and geometry and the proper application of conditioning techniques do not lead to the desired system performance, the last option is to apply compensation techniques. If the dominant thermal deformation can be identified, it may be possible to compensate for this deformation using the machine controls (software). This is illustrated in Figure 8a [4], which shows a machine tool. When machining a workpiece, hot chips and cooling fluids are washing down on the machine base; causing it to deform (bending). This deformation leads to an error (displacement) between



a b

Figure 8. Thermal compensation using temperature sensors.
(a) A simple sensor configuration.
(b) A sensor grid.

cutting tool and workpiece. Temperature sensors are placed at the bottom and top of the machine base. The thermal deformation of the machine base can be predicted by determining the relation (sensitivity S) between the measured temperatures (T_{top} and T_{bottom}) and the thermal deformation d.

$$d = S(T_{top} - T_{bottom})$$

The sensitivity can be determined analytically (modelling) or empirically (measuring). By applying a software correction, based on this relation and the measured temperatures, the control system of the machine tool can compensate for the thermally induced deformation.

It is not always easy to determine the dominant thermal disturbance or deformation in a machine tool. In many cases, several dominant heat sources are present that influence the thermal stability, such as the drive systems and the environment. In that case, a grid of temperature sensors can be placed on the machine base, as illustrated in Figure 8b. The relation between the measured temperatures and the thermal deformation of a certain point of interest, for instance between the cutting tool and the workpiece, can be expressed in matrix form as:

$$d = [s_1 \quad \dots \quad s_n] \begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix}$$

Determination of the sensitivity vector can be accomplished by placing a local heat source on each temperature sensor location in turn. In that case, n different temperature distributions and n different deformations (at the point of interest) are measured. The sensitivity vector can be determined by the relation:

$$[s_1 \quad \dots \quad s_n] = [d_1 \quad \dots \quad d_n] \begin{bmatrix} T_{1,1} & \dots & T_{1,n} \\ \vdots & & \vdots \\ T_{n,1} & \dots & T_{n,n} \end{bmatrix}^{-1}$$

Also in this case, the sensitivity vector can be determined either analytically or empirically, or in combination. The number of temperature sensors can be reduced by removing those sensors with the smallest sensitivity [2]. Compensation techniques are more and more applied in precision machines, especially in machine tools and measuring machines. The aforementioned techniques are simple examples. More advanced techniques are being developed, such as thermal system identification (e.g. thermal mode shapes). These techniques are explained in more detail in [5].

Conclusion

Three basic steps have been defined to tackle thermal effects in precision systems. These steps are the selection of the proper construction material in combination with the right choice of geometry, the application of passive and active thermal conditioning techniques and software compensation. A brief outline of these three steps has been given, but important subjects such as modelling and measuring have not been discussed.

Thermal effects in precision systems are becoming more and more important. The subject is still under development and not much knowledge is available in textbooks. Therefore, it would be appreciated by many if engineers would share their knowledge on the subject, e.g. in a professional journal like Mikroniek.

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A new roadmap

Earlier this year, a new long-term Technology Investment Roadmap was drawn for the Dutch high-tech industry. The roadmap provides an overview of trends in the fields of systems technology, component technology and manufacturing technology. Succeeding the 2004 Precision Technology Roadmap, which primarily focused on technology ('precise to within a nanometer, quick to within a micrometer'), the 2010 roadmap has a more strategic approach and is of particular interest to various suppliers in the high-tech industry. Mikroniek included a preview of this roadmap in the February issue, which will now be presented in more detail. Later this year, Berenschot, DSPE and TNO Science and Industry will organise a Technology Investment Roadmap day for interested companies.

The call for a long-term Technology Investment Roadmap came from Dutch original equipment manufacturers (OEMs). The objective was to analyse their technological needs and vision in the areas of nano-electronics, embedded systems and mechatronics, to explore directions for technological solutions, to identify the various roles in the supply chains and to describe the interactions between the relevant parties, including OEMs, their supply chains, research institutes and visionaries.

World-class

In recent years, Dutch OEMs have demonstrated that the Netherlands plays a world-class role in high-tech systems, thanks to the support of a competent supply chain. This supply chain's added value, however, could increase if more "ownership" were taken in designing and sustaining functional modules for these OEMs. As the number of OEMs is small, the supply chain's dependency and vulnerability has to be reduced by growth, either by attracting foreign OEMs or by forming new Dutch OEMs in new markets. Besides, ongoing innovation is required in systems, component and manufacturing technologies. The roadmap aims to offer new insights and tools to suppliers for exploiting foreign markets, developing new application areas and applying new-generation manufacturing technologies. The markets that are addressed include health care, energy & power, ICT, lifestyle & leisure, and transport, logistics & security.

Systems engineering

The roadmap is primarily intended for Dutch high-tech suppliers regarded as 'masters of manufacturing'. They must continue to anticipate the ever dominant trend of functional outsourcing at a high bill of materials level by today's OEMs. The building blocks that are given to suppliers in this way are characterised by their low volume, high mix and high complexity – in other words, small numbers, multiple product versions and advanced technology. To create clarity in such a complex situation,

Technology Investment Roadmap Day

On 23 November, Berenschot, DSPE and TNO Science and Industry will host a Technology Investment Roadmap day in Eindhoven, the Netherlands, for suppliers who want to explore the future of the high-tech industry in relation to technologies and markets. For a detailed programme, see page 63.

– II. Overview

The new roadmap covers a wide variety of application areas.

Roadmap partners

The new roadmap for the high-tech industry in the Netherlands was drawn by Berenschot at the behest of Point-One, Brainport Industries and DSPE.

Point-One is an open association of and for high-tech companies and knowledge institutes in the Netherlands working on research and development in nano-electronics, embedded systems and mechatronics. For Point-One, the roadmap is a means of enabling High-tech Systems & Materials, a key field that includes the above-mentioned domains, to grow from a current turnover of €20 billion to €30 billion in four years.

Brainport Industries is an initiative of Brainport, the innovation network of the Southeast Netherlands top technology region. The aim of this initiative is to enhance the industrial infrastructure in the region on the basis of the philosophy of open supply chain collaboration.

The Dutch Society for Precision Engineering (DSPE) is a professional community and interest group for precision engineers in the Netherlands. One of its ambitions is the promotion of 'Dutch precision'.

With its head office in Utrecht, Berenschot is an independent management consultancy firm with more than 500 employees in the Benelux region. Berenschot's competences include organisational development & management, research & benchmarking, and strategy & marketing.

www.point-one.nl
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the roadmap designates generic building blocks that can be identified in dozens of different systems for various application domains. Figure 1 provides an overview of this systems view. By thinking about building blocks in this way, suppliers can utilise their specific expertise in different areas of application.
Relevant trends concerning these building blocks include the complexity of motion control, increasing speed and accuracy of positioning, sustainability and low power, wireless powering, non-contact measurement, and applications in extreme vacuum.

Components

This systems approach was also a key element in the previous roadmap and now prevails in Dutch industry. In addition to systems, there is currently also a strong focus on components. A dominant trend is miniaturisation (for micro-electronics this is reflected by Moore's law): more functionality in the same volume, and an increased functionality in one component or module. For example, more and more sensors and actuators are built as MEMS (Micro Electro Mechanical Systems). To add to the complexity, 2D structures are being replaced by 3D structures. Nanotechnology introduces new functionality, such as nanomotors, nano-antennas and nano memory tubes, and additional functionality can also be obtained by merging technologies, for example electronics with mechanics, fluidics or photonics.

New manufacturing technologies

Naturally, everything that is new in terms of systems and components must be manufacturable and affordable. In the Netherlands, however, knowledge of manufacturing technology is at risk of disappearing at a time when exciting developments in manufacturing are taking place, e.g. the emergence of deposition technologies such as Atomic Layer Deposition, electroforming and metal printing. With some sixty different manufacturing technologies available, the careful selection of a processing strategy is of crucial importance. Manufacturing components increasingly requires a combination of removal, deposition, cleaning and inspection technologies. New materials, such as ceramics, engineering plastics, composites and biomaterials, demand that existing processes are adapted or new manufacturing processes developed.

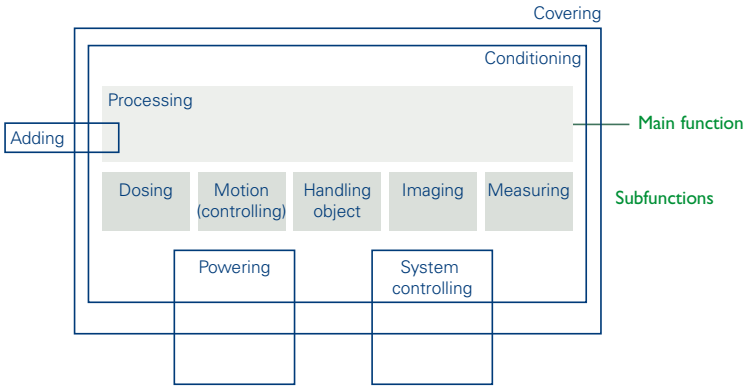


Figure 1. A systems view of high-tech product development.

Besides general trends (high speed, low cost, low power, less waste), specific trends can also be discerned; see Table 1.

Table 1. Specific trends in manufacturing.

• Breakthroughs in deposition technologies, offering more design freedom and making smaller series affordable, for example, dosing, printing and jetting of metals.
• Deposition technologies for single products and spare parts.
• Serial processing (milling-measuring-polishing) with minimal object handling.
• Hybrid processing (for example, electro-chemical machining and milling).
• Handling of small and soft (non-stiff) objects.
• Cleanliness for vacuum applications of components.
• Increasing precision (also in 3D) following the so-called Taniguchi curves that relate technology with precision.
• Combined processing and in-line monitoring for enhanced precision and throughput.
• Contact-free measurement because of decreasing sizes of workpieces and components.
• New processes in the field of connection technology for the placement and connection of precision components.
• Increasing computer control of processes.

Supply chain development

Organisational changes have been introduced in response to the aforementioned technological trends. OEMs are outsourcing at a high bill of materials level and increasingly involve their suppliers in the early stages of product design, demanding the utmost of their creativity and resources. Along these two lines (involvement with the bill of materials and involvement in the product creation process) suppliers can specialise as either system innovators, system integrators, product specialists or process specialists, each with their corresponding competences; see Figure 2.

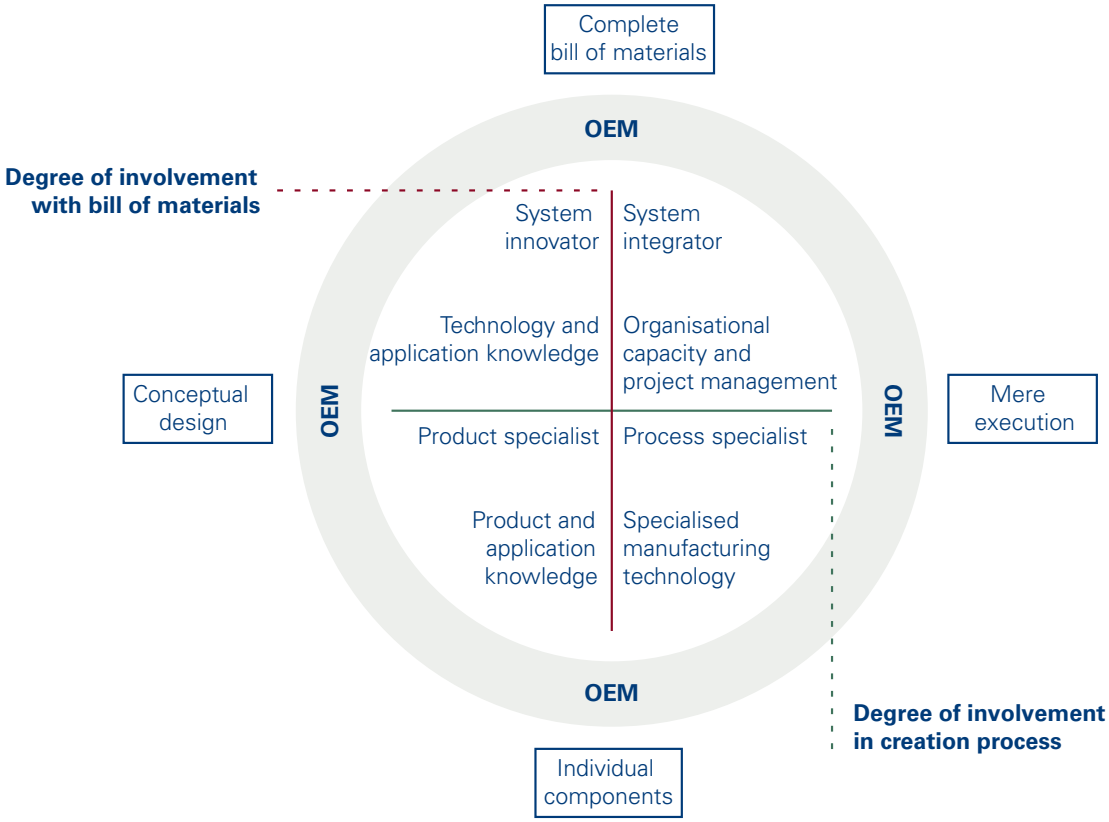


Figure 2. Specialisation of high-tech suppliers according to their degree of involvement with the bill of materials (from individual components to (sub)systems) and the product creation process (from mere execution to conceptual design).

Opportunities in new end-markets

Based on the above outline, numerous opportunities for high-tech system developments and promising markets can be identified, including:

- health care applications based on optical devices and fluidics beyond the traditional field of the so-called big irons (scanners);
- development of manufacturing technologies for living materials;
- robotics (for reasons of human safety or cost reduction);
- micro-reactor technology for producing minute quantities of specialty chemicals;
- 3D deposition technologies.

In conclusion

The long-term Technology Investment Roadmap with its overview of systems, component and manufacturing technologies is meant as an “opening offer” for the high-tech eco-system. This eco-system includes high-tech supply chains, universities and other knowledge institutes, and parties that may act as supply chain and eco-system directors. The roadmap outlines the opportunities, and the insights presented may help to promote collaborations and achieve technological breakthroughs. A proposal for a collaborative development programme for manufacturing technologies is presented as an initial example; subjects include metal dosing, 3D electroforming, contactless and dry processing methods, new hybrid technologies, computer-aided technologies, low-volume connection and assembly systems, in-line and 3D freeform measurement.

There is work to be done for Dutch high-tech suppliers.

"Mechatronic engineers curious and

Mechatronics is hot in the Netherlands. Therefore, Dutch universities of applied sciences (Dutch abbreviation, HBO) intensify their efforts to deliver more and better mechatronic engineers. Avans Hogeschool in Breda was in 2009 the second HBO-institution in the Netherlands – after Fontys in Eindhoven – to appoint a lector in mechatronics. A special lectorate, because it even extends to the level of higher secondary professional education (MBO, in Dutch; HBO being the tertiary level). Mikroniek interviewed lector Jos Gunsing about mechatronics in the Netherlands, his vision and his plans.

• *Jan Kees van der Veen* •

Enthusiasm, openness and curiosity are words that characterise Jos Gunsing. Although the interview takes place in a noisy room and is now and then interrupted by passers-by, Gunsing manages to convey his message convincingly. He leaves the impression of a man fascinated by technology, with a clear mission that he is ready to communicate with anyone, anywhere, anytime. There is no hesitation in his answer to the first question.

"Are Dutch people good at mechatronics?"
"Yes! We are traditionally good in high-tech, look at successful Dutch high-tech companies like ASML, Océ and Philips. But, even more important, we are good at working together. We love 'poldering': debating, bargaining, helping each other, building something together. We flourish in teams, *interdisciplinary* teams with specialists from different technologies, or *interfunctional* teams with people from R&D, production, marketing, purchasing, etc. We like working in an 'orderly chaos' that challenges our creativity and perseverance. Therefore, mechatronics, a discipline that forces traditional bastions as mechanical engineering, electronics and informatics to open up and co-operate, is a perfect playing field for the Dutch. The other side of the medal is that we are not good at tightly planned, step-by-step, risk-avoiding development, such as in the automotive industry. This usually comes with bureaucracy and we hate that."

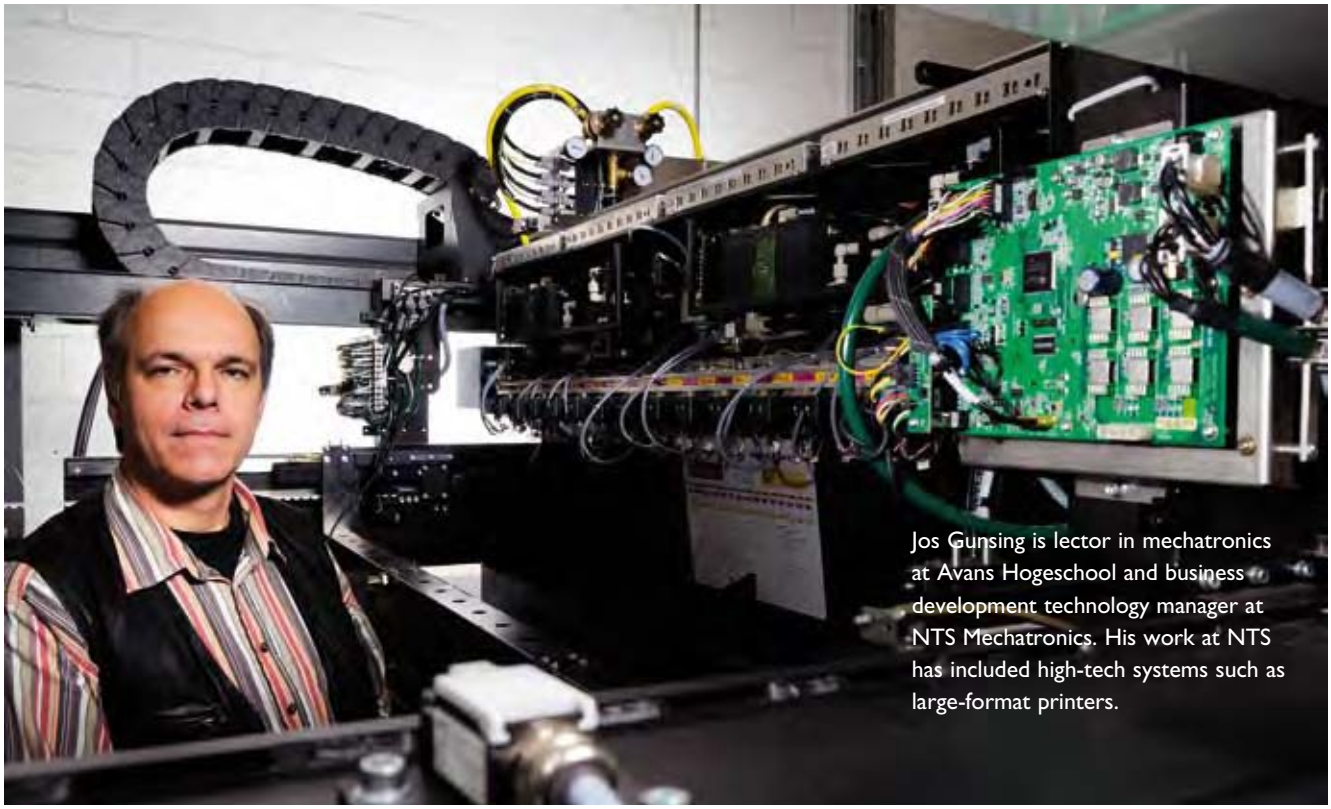
Author

Jan Kees van der Veen is a freelance technical journalist living in Son, the Netherlands.

Roadmap: robotics

Jos Gunsing started in March 2009 on a part-time basis as lector at Avans Hogeschool in Breda. For two days a week he is still business development technology manager at NTS Mechatronics in Eindhoven, the Netherlands. At Avans he got the task to set up and lead a mechatronics research group. This lectorate now consists of five people, Gunsing and four teachers, who do this work besides their regular teaching job. Gunsing himself does not have a lecturing task.
Gunsing realised, when he started, that his group – the lectorate – would have to restrict itself: mechatronics is too broad to cover with just five part-timers. What would be an

are open-minded, communicative”



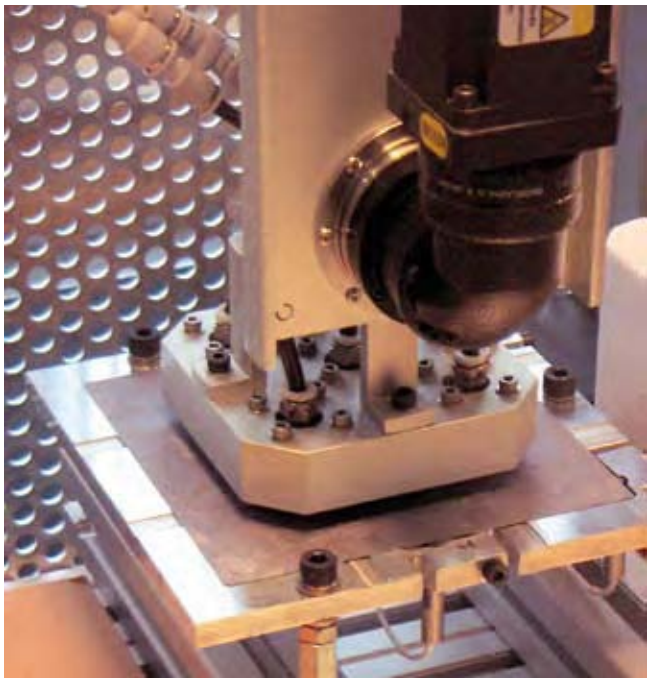
Jos Gunsing is lector in mechatronics at Avans Hogeschool and business development technology manager at NTS Mechatronics. His work at NTS has included high-tech systems such as large-format printers.

interesting area to focus on? He organised brainstorming sessions with companies participating in the lectorate to lay down a mechatronics technology roadmap for the coming 5-6 years, with the emphasis on robotics. After many discussions, he chose gripper technology as focus area for his group.

“Why gripper technology?”
“Grippers are essential in any robotic system, but there is huge diversity in the environments they are used in (production, logistics, healthcare, …) and in the objects they pick up (boxes, plastic bags, wafers, electronic components, eggs, …), hence the variation in gripper requirements is huge. Think of speed, accuracy, cost and development time. The requirements are getting tougher all the time, but still suppliers of grippers, all having their own niche of the market, hardly co-operate. Consequently, the wheel is reinvented over and over again. Our target is to develop a family of grippers with maximum reuse of technology and knowledge.
The four people in my group are each responsible for a theme within gripper technology. The themes were selected in co-operation with regional mechatronic companies like Bosch Rexroth, CSi and Van Uitert, which will be involved in the forthcoming research projects. As the group is still in its start-up phase, concrete results of projects cannot be shown yet, but there will be in the near future.”

Themes

1) Vision in Mechatronics
   “With the latest advancements in electronics and software, 3D vision now comes into reach, a promising technology in making grippers faster and more accurate. We are looking at low-cost solutions using FPGA technology. With Henk Kiela, lector in Mechatronics at Fontys Hogeschool, and Erik Puik, lector in Micro



In the Bernoulli gripper a high-velocity air stream is passed over the surface of a delicate, flat object, for example a solar wafer, so that the local pressure drops and the object is drawn towards the gripper. Avans students built a prototype. (Photo courtesy Bosch Rexroth Tech Centre Europe)

Systems Technology / Embedded Systems at Hogeschool Utrecht, we have submitted a joint request for subsidy of this activity."

2) Force-steered gripping
"Grippers used for handling fragile or vulnerable objects cannot use fixed force, as the danger of damaging the objects is too high. They need force feedback, which means that force sensors are built in the 'fingers' of the gripper and that subtle control algorithms adapt the gripping force to the resistance of the object. This is still a tough challenge for mechatronic engineers. By the way, did you know that the holy grail in gripping is placing bags with potato chips in a cardboard box? The chips are not allowed to break as it causes 'potato dust' to accumulate at the bottom of the bag, which is commercially unacceptable."

3) Mechatronic design methods
"Mechatronic engineers must be able to think at system level and to make a technology trade-off at the beginning of each project. For example, high-accuracy positioning can be done with high-precision mechanical components, but if production numbers are sufficiently high, it may be worthwhile building in position sensors and investing in the development of dedicated control software. We asked the Embedded Systems Institute in Eindhoven to help us building up knowledge for making such technology trade-off decisions."

4) "Still to be defined, but a teacher has already been appointed."

"Are you also involved in the mechatronics curriculum at Avans?"
"Yes, although the mechatronics group and the curriculum are separate activities. Avans Hogeschool offers, for a number of technical studies, a four-year curriculum concluded with a Bachelor degree. In the past, students spent their third year within a company. This internship has now been shortened to a half year, to give the students extra time to follow broadening courses ('minors'). Also new is that, during their internships, they come back to school once every two weeks to report for an audience of teachers and fellow students about their findings. This works very well.
Mechatronics is not an official study (yet), so Avans Hogeschool cannot offer it, but since a couple of years, students in mechanical and electrical engineering can opt for a mechatronics specialisation. They get a special package of courses, focused on mechatronics. In 2009, the school delivered 17 bachelors with a mechatronics specialisation and this year we expect 35 to 40. The mechatronic industry is happy with them; our graduates have no problem finding a job.
Together with three other universities of applied sciences – De Haagse Hogeschool, Fontys and Saxion Hogeschool – we have submitted a request to the minister of education to have Mechatronics officially recognised as a new study.

Avans student operating a mechatronic test set-up.

About lectureships or lectorates

Lectureships are a relatively new phenomenon in the Netherlands. Since 2002, the Dutch universities of professional education (HBO) have a research task in addition to their educational task. The research has to be application-oriented and directly driven by the needs of industry. The function of lector was created to strengthen the link between school and industry. Usually lectors are recruited from the industry and work part-time at school, part-time in the industrial company they come from. In this way, optimal use can be made of their professional network.

Lectureships bring advantages for the schools as well as for the industry. Previously, HBO teachers were more or less cut off from technological developments taking place in industry, and their knowledge tended to become outdated. Consequently, when students did internships and graduation projects at companies, teachers could do little more than monitor and guide the process as they were no content experts. This situation is now improving. The advantage for industry, in particular for SMEs, is that participating in research projects opens up new horizons, as it helps to look at the technologies of "the day after tomorrow".

A strange thing about lectors (or lectureships) is that lectors do not lecture...

Recently, permission was granted, so that – after subsequent accreditation – we can start with the official Mechatronics Bachelor study in September 2011."

"And you are involved in the MBO mechatronics curriculum as well?"
"Avans has many students coming in from higher secondary professional education (MBO), with a mechatronics diploma. They want to continue in mechatronics at the tertiary level (HBO), but up to now the connection was poor. Together with MBO colleagues from nearby Tilburg we try to create a smooth mechatronics learning trajectory for these students with as little gaps and overlaps as possible. MBO and HBO teachers are talking with each other on a regular basis now and both parties, as well as the students, benefit.
Noteworthy is that the MBO school in Tilburg, like us, has selected focus themes in mechatronics: vision, choice of materials, sustainability & energy consumption and 'the practical understanding of physical concepts'. The last theme is quite challenging: it came from a rather alarming finding that students who learned about mass, friction, damping and other physical concepts have great difficulty envisioning these phenomena in real. They need much more practical instruction to get these insights. We are working on that."

"What makes mechatronic engineers different from other engineers?"
"Mechatronics is an area where several disciplines meet. Mechanical engineering, electrical engineering and informatics of course, but also mathematics, man-machine interfacing, materials science, etc. Mechatronic engineers always keep the system view, but at the same time they must have sufficient knowledge of the underlying technologies to be able to make practical design decisions. They have to hop between two levels all the time. They have to be open-minded, curious and communicative. Indeed, this makes them different from their M-, E- and I-colleagues.
This was radically different in the past. In industrial automation projects the mechanical engineers were always in the lead. The electrical engineers were called in to develop the electromechanical devices and the electronics to drive them. And when that was done, the software developers came in to 'clean up the mess' that could not be solved by their predecessors. This situation has now completely changed. All disciplines are part of the team from day one.
Recently, at Avans Hogeschool, Technical Informatics was brought together with Electrical and Mechanical Engineering in one department. The school is now in an excellent position to bring education in mechatronics to a new level.'

"What will the future bring for mechatronics in the Netherlands?"
"If we make the right choices, mechatronics has a bright future. To our policy makers I would say: do not fritter away your money and resources on projects with little future, but support the strong sectors, leave the weak sectors alone. Mechatronics is such a strong sector. Help Dutch companies excel in what they are good at. It is impossible to be good at everything in our small country. To the entrepreneurs I want to say: dare dreaming of the future now and then, look further ahead than tomorrow. And always be prepared for change. The entrepreneurs I can best talk with are the ones who can switch smoothly between the short term and the long term. I admit, though, that there is still some mission work to be done!"

Information

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Towards the practical dynamic

Dynamic error budgeting is a tool for designing high-precision systems. Its application, based on practical rules, to the specification and design of an accurate XY-θ stage is presented. It was concluded that all specifications of the stage could be met using this method.

• *Thijs ten Dam and Robbert van der Kruk* •

Author

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This article is based on a poster presented at the 2010 euspen Conference in Delft, the Netherlands.

www.boschrexroth.nl
www.rocoma.nl

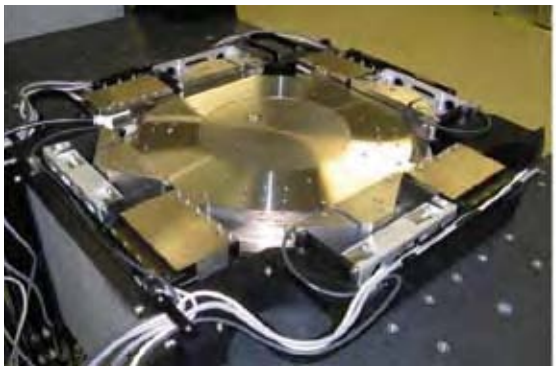
Dynamic error budgeting (DEB) [1] is a tool for designing high-precision systems. It is a first-time-right method, based on predicting disturbances and dynamics in the specification and design phase of a mechatronic system. During normal operation, systems will be subjected to many different disturbances. The power of the controller to eliminate the effects from such disturbances is generally limited and thus accuracy, as measured at the system sensors, is limited.
During the design of new systems, it is required to be able to predict the performance. To give such predictions, models of the system behaviour are made. Such models, when properly used, allow for the design of suitable control schemes. In many cases the design will be optimized to achieve a certain dynamic response or a certain error-correction capability as a function of frequency. For the user however, it is required to predict the position errors as a function of time under the influence of all potential disturbance sources.

Application

Dynamic error budgeting has been applied to the specification and design of an accurate XY-θ stage; see Figure 1. The required stage position error (noise) was 50 nm (3σ) on a VCC floor [3], a common standard for most lithography and inspection equipment to 1 µm detail size.

Modelling

The DEB method as introduced by J. van Eijk et al. in 2004 [2] is an approach that builds upon the use of Parseval's theorem linking frequency-domain and time-domain data; see Figure 2. In this method the different disturbance sources are identified during design. Suitable estimates of the magnitude and frequency content are determined and used to act upon the



application of error budgeting

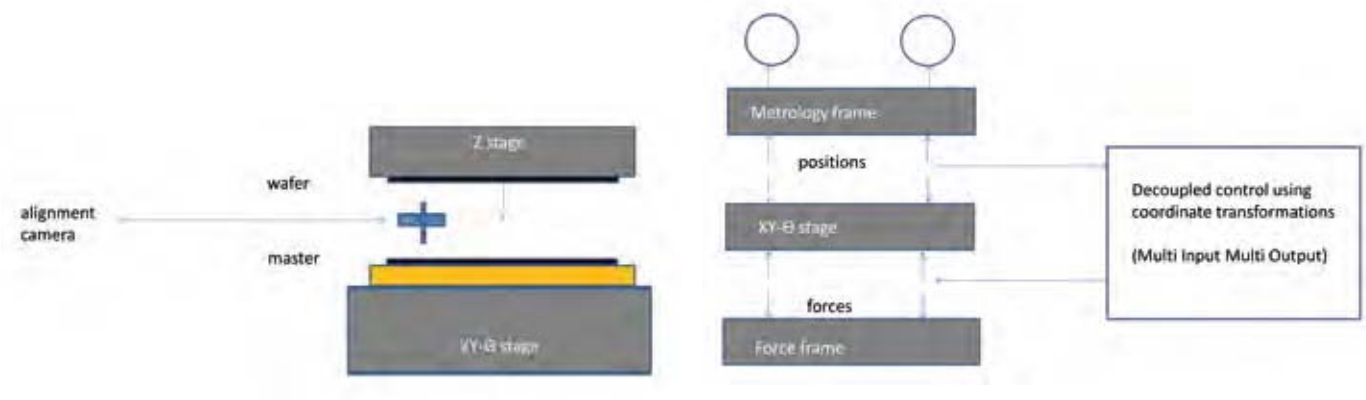


Figure 1. XY-θ stage (see also previous page) using air bearings, linear motors, linear encoders and a force frame.

model of the controlled system. The closed-loop frequency-domain transfer functions of the design are used to propagate each disturbance to the performance variable to obtain the power spectral density (PSD) of the performance. Based upon this information the total performance in the time domain can be calculated statistically. The individual contributions can be identified and the dominant dynamic effects can easily be seen in the cumulated power spectrum (CPS) over the relevant frequency range.

Design

Design choices such as bandwidth, frequency of vibration isolation, and use of force frames have been made on basis of DEB results and applied to the model of the stage and the disturbances; see Figure 3.

Verification

Comparing measured 3σ values to calculated 3σ values, it can be seen that results on a typical clean room floor are significantly better than the specification; see Figure 4. The actual noise level from the floor is less than specified. Applying the actual floor disturbances to the models results in the cumulated amplitude spectrum (CAS) of Figure 5. It shows a model accuracy of 1.2 nm. The small deviation might be due to the air bearings and measurement accuracy. The main disturbance is from floor vibrations

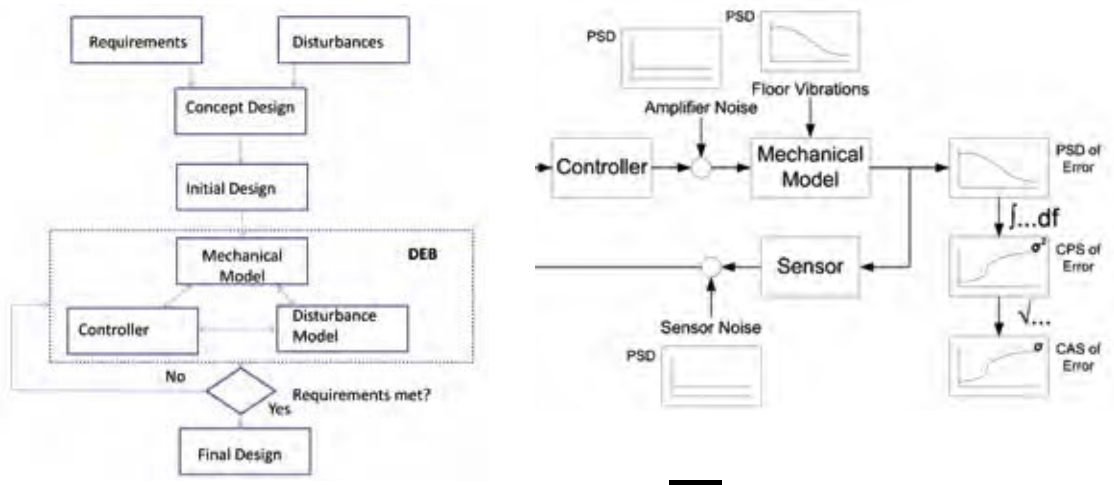


Figure 2. Design method and modeling.

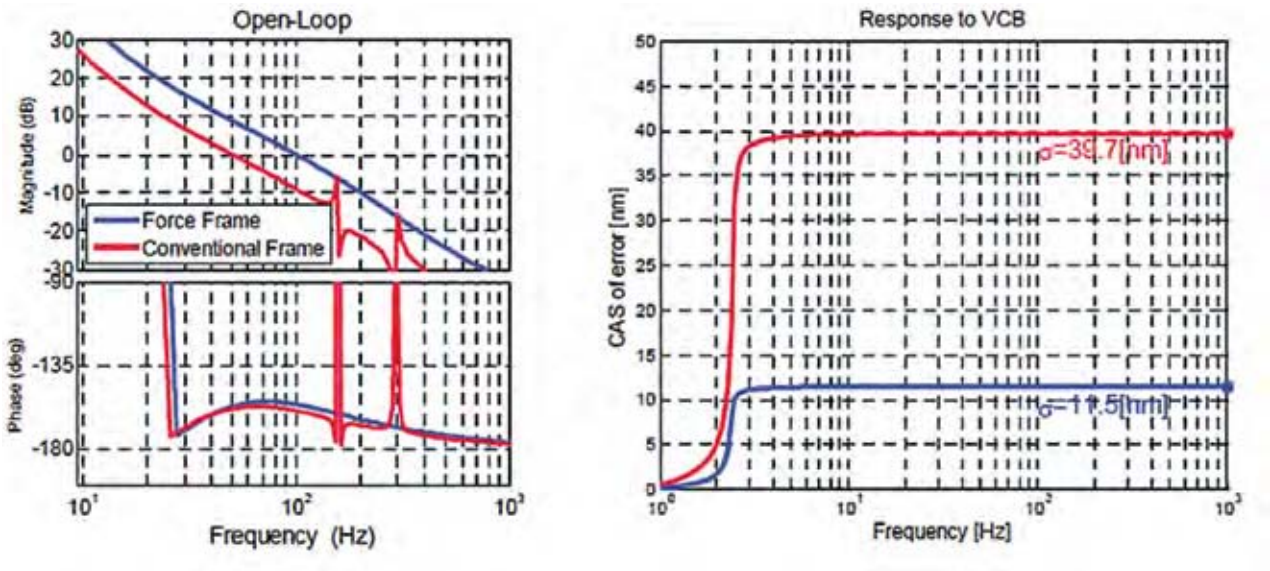


Figure 3. Influence of force frame on accuracy, and summary of design choices (see table below).

Options	Colin Gordon floor		Force frame		High base suspension	
	VCB	VCC	50 Hz servo bandwidth	100 Hz servo bandwidth	2.5 Hz vibration isolation (air mounts)	5 Hz vibration isolation (rubbers)
1	x		x			x
2		x	x			x
3	x		x		x	
4	x			x		x
5	x			x	x	
6		x		x		x

Amplifier noise

To drive the linear motor, the NYCe4000 motion controller from Bosch Rexroth was used. The Pulse Width Modulated amplifiers have a smaller error contribution (2 nm) than expected (5 nm); see Figure 6. The error due to the modulation frequency of 96 kHz can be neglected. The 2 nm contribution to the end result is mainly caused by the analogue-to-digital conversion and noise in the current feedback loop.

Practical application rules

Figure 7 shows the principle of the DEB method. In blue practical rules for successful application have added. The validated model can also be used to check the original theoretical Gordon VCC specification; see Figure 8. Its value is 43.1 nm.

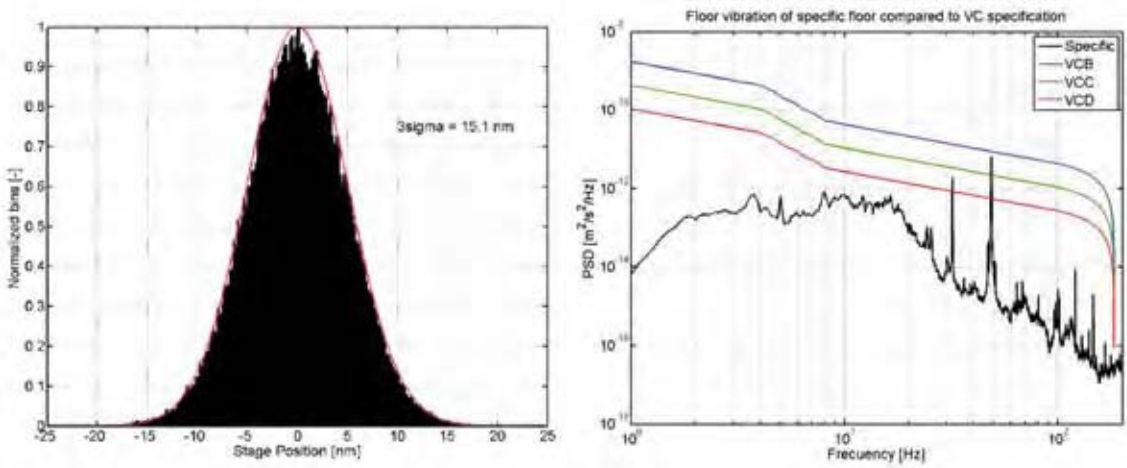


Figure 4. Repeatability error distribution (on the left), and noise from floor and position noise.

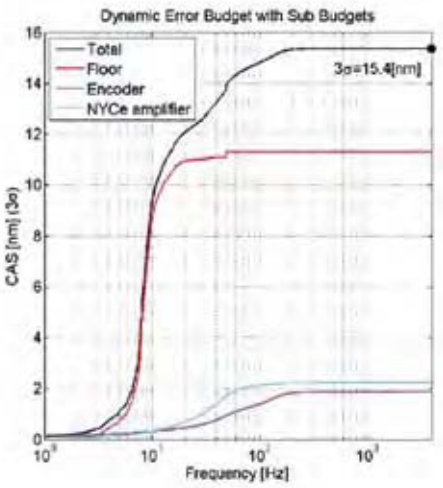


Figure 5. Simulated error budget using actual noise from floor.

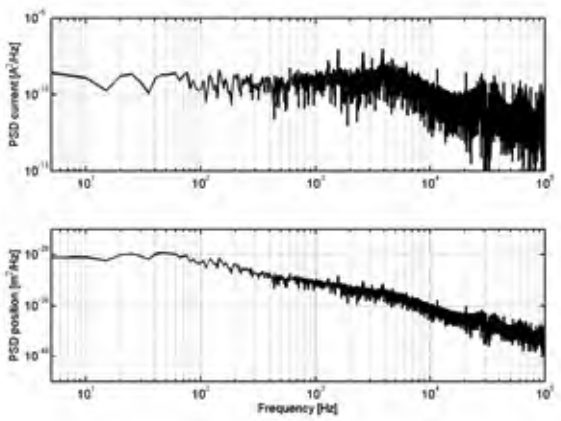


Figure 6. The power spectrum density (PSD) of the PWM amplifier of the NYCe4000 motion controller.

Further improvements using DEB

Based on the verified model further improvements of the accuracy can be shown. The integrator frequency can be increased to 20 Hz without losing too much phase margin. This could improve the performance from 15 nm to 9 nm. Decreasing the suspension eigenfrequency of the vibration isolators from the original 8 Hz to 4 Hz improves the accuracy to 7 nm at a higher cost price of the stage.

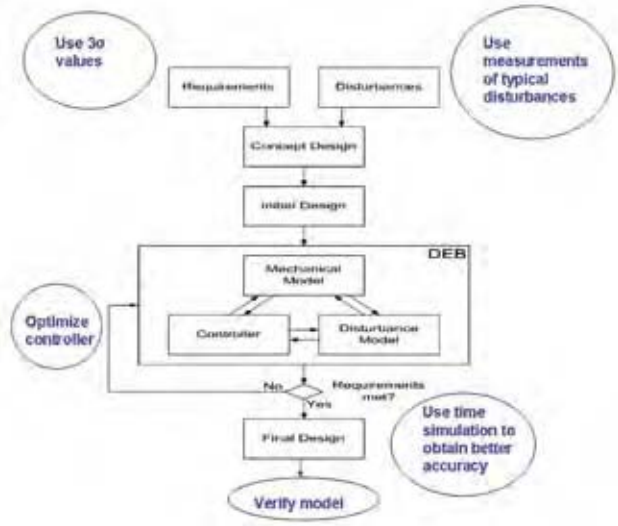


Figure 7. DEB design method and practical application rules (see table below).

Use 3σ values Gaussian	For specific purposes 3σ values, indicating 99.75% of a signal is within specification, are recommended to use and agree upon at the start.
Use measurement of typical disturbances	Colin Gordon floor specification is a theoretical method to indicate the floor disturbances. In practice the disturbances have different patterns. This results in a conservative value for the design and hence risk of over-engineering.
Optimise controller	Both mechanical concept and controller scheme including its parameters should be evaluated. In this case, the integrator value has a significant impact on suppressing the low-frequency disturbances.
Use time-domain simulation to obtain better accuracy	The DEB method is based on independent disturbances. By use of a closed-loop system some disturbances will be correlated. In a time-domain simulation these become visible, resulting in more accurate values. In this case the results are better.
Verify model	Do not only verify the results versus specifications, but also validate the model with the measurement. In this case, the amplifier noise of the NYCe4000 controller and the floor noise were measured separately. The resulting validated model can be used for further optimisation without changing the system and using its operation time.

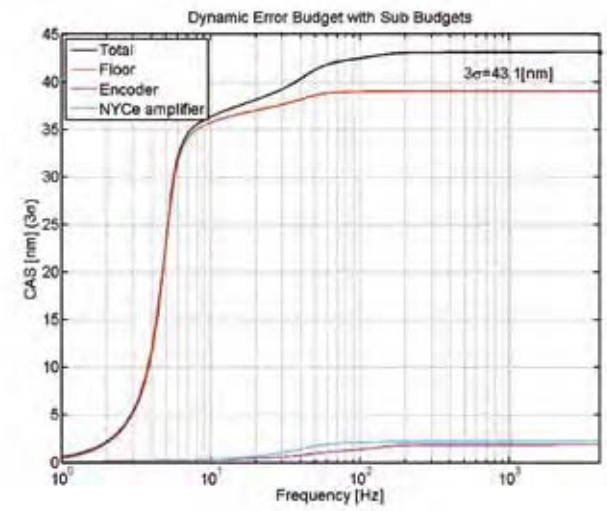
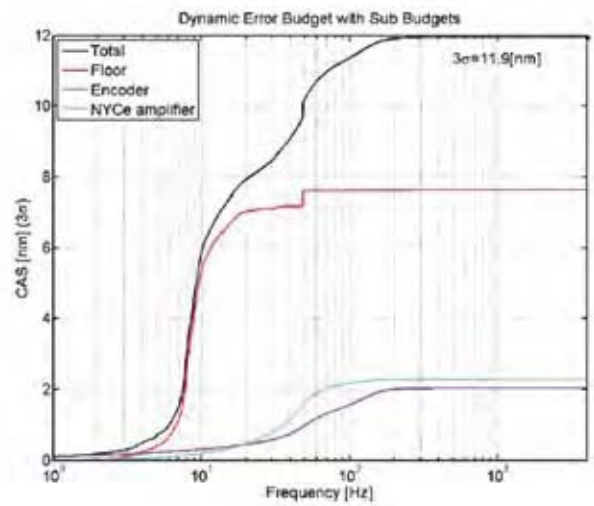


Figure 8. Cumulated amplitude spectrum on VCC floor (suspension frequency 5Hz).



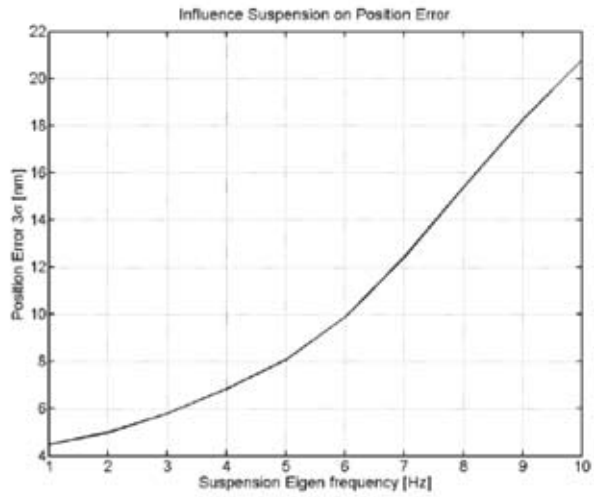


Figure 9. Error budget with optimised integrator value in controller; below, frequency of vibration isolation versus accuracy.

Conclusions

All specifications of the XY-θ stage were met using dynamic error budgeting. The Colin Gordon floor classification [3] is a conservative value for predicting performance; it is more accurate to measure characteristic floors. DEB results should be analysed with care. The DEB tool is based on uncorrelated disturbance sources. It can be proven that most common disturbance sources, i.e. encoder resolution, are not uncorrelated. Therefore, time-domain simulations can provide more accurate results, since correlation of the disturbances is taken into account.

Acknowledgements

The authors would like to thank Jan van Eijk from Mice BV and Dick Laro from MI-Partners for their collaboration in the project [4] on which this article was based.

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The rules and the game

In Europe, a colourful palette of R&D funding programmes exists that have been set up by the European Union, the various member states unilaterally as well as through intergovernmental initiatives. Companies, however, are often very reluctant to join EU-funded R&D projects for a variety of reasons. As a result, many funding facilities remain unused by potential project participants, even when the rules are there for all to be known and to be applied in a 'funding game' that can be played in a smart way.

• *Luuk van der Laan* •

European R&D funding programmes include the European Framework Programmes, CATRENE, ENIAC and EPoSS, to name a few. Under such programmes, each with their own R&D scope, such as energy, nanotechnology, mechatronics, climate, etc., parties interested in joining forces in their R&D activities can draft project proposals to be submitted for funding. These programmes are always laid down in a set of rules that apply to the individual programme and that sometimes refer to one another.

SEVENTH FRAMEWORK PROGRAMME

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Luuk van der Laan, attorney-at-law, is a private lawyer with his own law firm originated in the Netherlands, while currently holding office in Sønderborg, Denmark. With 20 years of experience in legal practice, of which 8 years as in-house lawyer for Philips Electronics, he builds on a large base of business insights and know-how in such fields as intellectual property, multi-party cooperation and alliances, as well as the common range of R&D, supply and distribution relations.

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Cluster for Application and Technology Research in Europe on NanoElectronics, www.catrene.org

Reluctance

In practice, however, there is significant reluctance to join EU-funded R&D projects, often for one or both of the following two reasons: the rules that apply to the funding are unclear, and companies do not wish to give away their ideas to others, possibly operating in the same field, while the policy of how and to what extent intellectual property should be shared is not known. “What if a large party in my market runs off with my ideas?” and “Am I not creating my own competition?” are questions often heard.

Apart from that, the paperwork and reporting obligations involved in joining EU- or nationally funded projects are other hurdles to be negotiated, as is the potential risk of incomplete reporting that might result in funding received being reclaimed. Lastly, the international character of EU-funded projects sometimes scares off potential participants. As a result, many funding facilities remain unused.

The rules

Most R&D funding programmes require a certain policy on intellectual property (‘IP’) involved in a project in order to boost open innovation, as this is considered essential for Europe to stay amongst the top global technology centres. These IP policies, however, do not require parties to give away their own know-how and IP or to allow project partners to use their IP for free. In short, the most common IP policies contain the following principles, which may, of course, differ for individual programmes:

- IP existing at the start of the project should be made available to project partners for the project itself and, sometimes, for the use of new IP developed during the project, for commercial purposes. However, in the latter case royalties can usually be charged.
- New IP developed during the project will usually be owned by the parties who developed such IP and is further licensed to other partners in the project, for the project itself. Sometimes licensing for commercial use is also mandatory, but in that case royalties can be charged.

Agreement

In addition to the rules governing a funding programme (programme rules), there is always a separate agreement between the parties (Project Cooperation Agreement, PCA) in which additional rules can be agreed upon. The programme rules usually even require such a PCA. In relation to the licensing of existing or new IP, the parties can distinguish between different fields of use in a PCA. For example, a license for commercial purposes can be required, while excluding the specific field of use of the owner(s)/inventor(s) of the IP. This way project partners enjoy one another’s creativity in a project without the risk of creating a competitor. Know-how is not always as freely disseminated as IP rights. The use of a project partner’s know-how may, for example, be limited to ‘the sole purpose of the project’, excluding use for further *internal* R&D activities of the project partner.

The game

Applying the rules to the game in a smart way is how most commercial ‘threats’ can be addressed. First of all, when planning to join a project, it is best to join from the start, thus being able to influence the IP requirements in a PCA. When joining later, you may save on the cost of using (external) advisors, but you can only accept or reject (and not influence) the conditions already in place. And you should be aware that in many funding programmes, the cost of advisors for the start-up of a project eligible for funding may run to 75% or 100%.

Next to that, a significant proportion of the technology applied in products or services depends on a range of IP rights, including (software) copyrights. If a company develops or has developed part of its *essential* IP outside a project, this will usually not be available to potentially competing project partners, unless the owner of the IP grants a licence. Furthermore, mandatory IP licensing requirements can also pay off. Next to an inventing company’s own manufacturing and sales activities, licence fees can be earned, so that earnings on IP are doubled.

European Nanoelectronics Initiative Advisory Council,
www.eniac.eu

www.smart-systems-integration.org

Hurdles and risks

The paperwork involved in entering a joint R&D project sometimes seems a burden difficult to oversee. However, (almost) every project has one partner assigned with the task of being the coordinator. This is usually a party that has gone through the process many times before and can clearly indicate each partner's task in the starting phase as well as when reporting on progress and results is required. The risks that funding authorities reclaim funds already received due to improper or incomplete reporting is limited. If reporting is considered insufficient, they will usually ask for additional information only. Actual reclaiming is rare and is usually related to situations in which the funding has been spent on purposes other than that for which it was granted or in a very inefficient way. Both instances are controllable.

Summary

Joining EU-funded R&D projects provides welcome financial support. When done in the correct manner, it enables the players to enjoy one another's ideas and creativity – which is exactly the purpose of open innovation – without having to fear that others will 'run off' with their ideas for free or that they will be helping others to compete in their field of technology or business at no expense. The costs of getting a grip on and influencing the applicable rules do not have to be extreme and can sometimes even be shared with partners. In short, these are opportunities not to be missed.

DCMM Customer Day

On 4 November, the second DCMM Customer Day will be held in Delft, the Netherlands. Visitors will be informed about ongoing research within the Delft Centre for Mechatronics and Microsystems. About fifty projects within the following topics will be presented:

- Adaptive Optics
- Automotive / Vehicle Mechatronics
- Bio Medical Instruments
- Mechanics, Dynamics and Optimisation
- Micro / Nano Electronics and Sensor Systems
- Micro/Nano Engineering & Manufacturing
- Mobile Robots and Humanoids
- Precision Mechatronics

Visits are offered to the DIMES facilities and the new Van Leeuwenhoek Laboratory. Participation is free of charge, registration before 22 October at www.aanmelder.nl/customerday.

DCMM is one of the thirteen Delft Research Centres by which Delft University of Technology concentrates its research activities, and brings together groups from Mechanical Engineering and Electrical Engineering / DIMES (Delft Institute of Microsystems and Nanoelectronics) in a collaborative research programme.

www.dcmm.tudelft.nl

Manufacturing technologies to support “Big Science”

A number of exciting large-scale projects are underway at present in Europe whose successful delivery will involve pushing the boundaries of precision engineering and nanotechnology. Such projects need to identify and partner with outstanding companies and research institutes who can support them in their endeavours. On 25-26 November, euspen (European Society for Precision Engineering and Nanotechnology) organises a meeting, “Manufacturing Technologies to Support Large Science Projects”, to bring together those leading the “Big Science” challenges with potential industrial and research partners. Attending companies and research institutes will have the opportunity to hear from and meet with those leading the technology challenges. Topics include ground- and space-based telescopes and laser and X-ray optics; a commercial session is also included in the programme. The meeting will be held in Paris, France.

www.paris2010.euspen.eu

Changing business models in software development

Sioux Embedded Systems and Verum Software Technologies have closed a commercial partnership agreement around Verum’s ASD:Suite toolset for rapid development of defect-free software for complex systems. Sioux offers its customers a range of unique business models for outsourced software development.

In order to meet increasing demand for high-quality complex software development, Sioux decided to employ Verum’s ASD:Suite. Sioux had evaluated ASD:Suite, to conclude that it can significantly improve the time to market and productivity (+400%) of their development projects, whilst also greatly improving the quality of the finished product.

Sioux Embedded Systems is member of the Sioux Group, headquartered in Eindhoven, the Netherlands. Verum Software Technologies, based in Waalre near Eindhoven, recently decided to focus on product development and to scrap their consultancy group.

www.verum.com
www.sioux.eu

DAQ trends by HBM

HBM, a global player in data acquisition and analysis, recently undertook an international survey of data acquisition (DAQ) trends. Some 600 professional engineers participated in this worldwide survey. Ease of use and performance, precision and quality were considered the most important features in a DAQ system. One strong trend is towards high channel counts, up to more than 64 channels. Also there is a clear need for accurate equipment with over 20% of respondents requiring accuracies of up to 0.05% of the measured value. The higher number of channels being demanded does not, according to HBM, imply any moves towards lower accuracy. Over 10% of respondents utilise sampling rates of more than 50,000 samples/sec.
The survey results will help HBM to better respond to market demands. An example of a HBM product in this field is the QuantumX universal data acquisition system.

A member of HBM's QuantumX family of universal data acquisition systems.

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Engenia - courses at an academic level

Engenia is a new organisation for training and education at an academic and post-tertiary professional education level. Its target group includes companies in the technology and process industries. Engenia is part of Mikrocentrum and is situated in Eindhoven. Courses are offered all over the Benelux and can be given in-company as well. One of the courses next autumn is Bearings in High Tech Systems.

(Photo: Bosch Rexroth)

The four-day Bearings in High Tech Systems course given by tutors from Delft University of Technology Dr Anton van Beek and Dr Ron van Ostayen addresses the following topics.

- Day 1: basic design principles of high-tech systems, design for stiffness, system accuracy, error budgeting, calculation of resolution, accuracy and repeatability, errors in translation and rotation, Abbé error and dynamic modelling in MathCAD.
- Day 2: bearing selection, limiting factors for bearing stiffness, Hertz theory, vibration and resonance, rolling, sliding, backlash, preloading, virtual play and tribology in vacuum and flexures.
- Day 3: design of hydrostatic and air bearings, optimisation of bearing systems, constrained versus overconstrained bearing structures, capillary versus orifice compensation, bearing stability and vacuum-preloaded bearings.
- Day 4: FEM modelling of bearing structures using Comsol Multiphysics, Reynolds equation and the effect of elastic distortion of the bearing surfaces.

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2010 Precision Fair

The 2010 Precision Fair will take place on 1 and 2 December, once again at the NH Conference Centre Koningshof in Veldhoven, near Eindhoven, the Netherlands. The fair is organised by Mikrocentrum with support from DSPE and the Agentschap NL. Under the heading "Business in Precision Technology", this tenth edition of the fair will include over 200 exhibitors, a topical lecture programme and the Technology Hotspot, featuring over twenty knowledge institutes from the Netherlands, Germany and Belgium. A Brokerage Event / Match Making will be organised by innovation network Syntens, Enterprise Europe Network and Mikrocentrum.

www.precisiebeurs.nl

Technology Investment Roadmap day

On 23 November, Berenschot, DSPE and TNO Science and Industry will host a Technology Investment Roadmap day for suppliers who want to explore the future of the high-tech industry in relation to technologies and markets. For an overview of this roadmap, initiated by Point-One, see page 44.
As mechatronics is a broad and extremely diverse area, it is crucial for companies to choose their position in the supply chain carefully and to attune their investments to the relevant technology trends. From technology trends to business opportunities, it is up to the entrepreneurs.

The TIR-day in Eindhoven, the Netherlands, is facilitated by Point-One, Brainport Industries, High Tech Systems Platform, Agentschap NL (agency of the Dutch Ministry of Economic Affairs), and the regional development agencies BOM, Liof and OOST NV.

The programme starts at 9.30 h.

Morning session: Knowledge sharing

- The need for chain collaboration in the mechatronics industry
  Hans Dijkhuis (ASML)
- Towards a high-tech supply chain: chain developments and suppliers' responses
  Daan Kersten (Brainport Industries / Boer & Croon)
- What expectations does an OEM like ASML have of supply chain development?
  Jos Benschop (ASML)
- Which technological developments will influence the future market?
  Jan van Eijk (Delft University of Technology)
- Which new technology markets will emerge?
  Arnold Stokking (TNO)

Lunch

Afternoon session: TIR and workshops

- TIR presentation
  Joost Krebbekx (Berenschot)
- Parallel workshops
  - Mechatronics, *Maarten Steinbuch (Eindhoven University of Technology)*
  - Manufacturing technologies, *Andre Hoogstraten (TNO)*
  - Precision instruments, *Herman Soemers (University of Twente)*
  - Handling, *Rob Munnig Schmidt (Delft University of Technology)*
  - Opto-mechatronics, *Jan Nijenhuis (TNO)*
  - Electronics, *Ton Backx (Eindhoven University of Technology)*
  - New materials technology, *Sander Gielen (TNO)*
- Closing
  Marc Hendrikse (NTS-Group and Brainport Industries)

The Technology Investment Roadmap covers a wide variety of application areas.

Precision-in-Business day: Microstereolithography

The most important results of the TNO and M2i microstereolithography project (see page 28) will be presented on what is known as a PiB-day organised by DSPE on 18 November. It will take place at TNO in Eindhoven, where the equipment and products are shown. Attention will also be paid to additive manufacturing with metals, as well as micromilling. Please register by e-mail (info@dspe.nl) before 8 November. Participation is free and presentations will be in Dutch.

Programme

1.30 p.m.	Welcome and introduction, *Robert Swinckels (DSPE)*
1.45 p.m.	Introduction to Rapid Manufacturing, *Henk Buining (TNO)*
2.15 p.m.	Microstereolithography, *Bart van de Vorst (TNO)*
2.45 p.m.	Laboratory visit
3.45 p.m.	Break
4.00 p.m.	RM with metals, *Jonas Van Vaerenbergh (LayerWise)*
4.30 p.m.	Micromilling, *Han Oosterling (TNO)*
5.00 p.m.	Closing, *Robert Swinckels*

Introducing DSPE board members: Jasper Winters

Being a relative newcomer in the field of precision engineering, I was looking for a way to get an additional view on this intriguing world, besides my scientific education and the 'first job' experiences. What better way than to join DSPE, with its roots in the rich history of Dutch precision engineering and the ambition to cooperate with similar organisations abroad as well?

As a recent graduate from the precision and microsystems engineering group at Delft University of Technology, I am fascinated by the challenges and opportunities of high-tech systems. During my education, I came to enjoy the synergy of the many different expertises that form the field of mechatronics. My first experience with the high-tech application of mechatronics was during an internship at Mapper Lithography, which was also the time I started activities for DSPE. Being intrigued by applied mechatronics, I did my M.Sc. thesis at TNO Science and Industry in the area of pick & place technologies for 3D-IC. After graduation, I stayed with TNO, where I am now working on the design and realisation of innovative mechatronic systems. I enjoy the process of defining system requirements and finding a suitable solution with a mechatronic system design approach.

About a year ago, I started my activities for DSPE with reviewing and submitting articles in the 'Precisiematrix', nowadays known as the article database. Thus the ongoing process of translating the website to English was started and the new DSPE website was launched. If you have not visited the website recently, please do so. I also would like to use this opportunity to ask you to actively contribute to the website, by sharing your knowledge with your fellow engineers in the Knowledge Base, www.dspe.nl/knowledge_base. The DSPE website is meant for you, and therefore it should support your needs. If you have any suggestions, remarks or questions regarding the website, please let me know.

jasper.winters@dspe.nl

DSPE general assembly

In September, the DSPE board gathered for a general assembly, comprising some 20 persons. The meeting was held on "holy ground", namely the first factory of the Philips brothers, who in 1897 started to produce lamps. In lively discussions the main areas of DSPE interest were covered, including Mikroniek, the website, the certification programme, Precision-in-Business days, the Young Precision Network and the relations with foreign precision engineering communities.

www.dspe.nl

Mikroniek guide

Bearing- and linear technology

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