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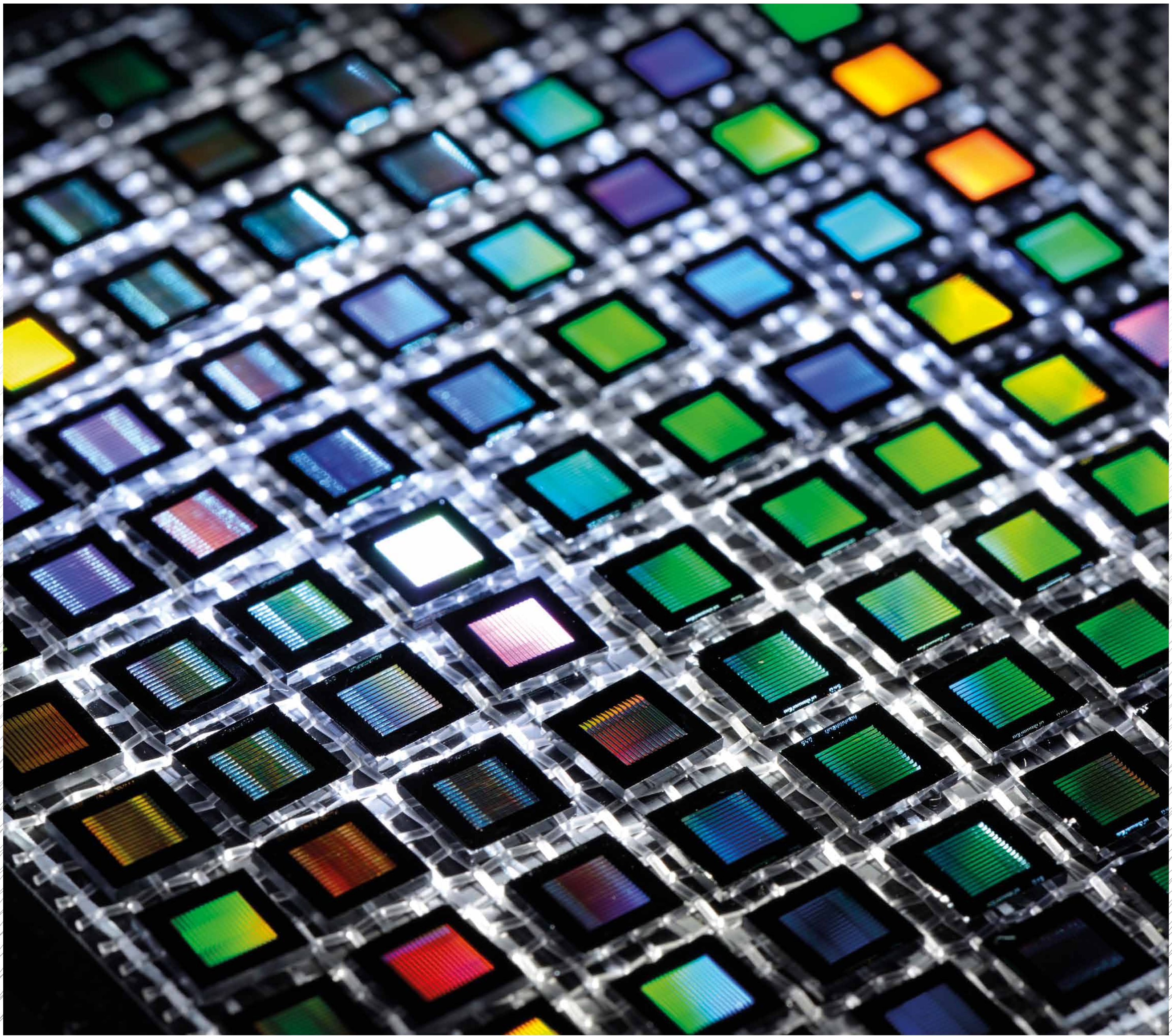
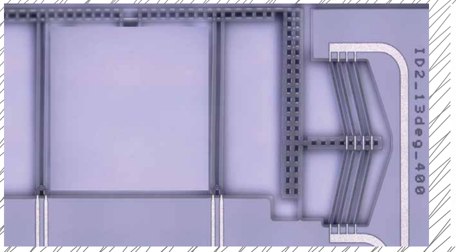


- THEME: **PRECISION TALENT**
- **RECONFIGURABLE** MECHANISMS & ROBOTS
- **ON-CHIP MEMS** FOR PHOTONIC FINE-ALIGNMENT
- PRECISION IN **AM**



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DSPE
Annemarie Schrauwen
High Tech Campus 1, 5656 AE Eindhoven
PO Box 80036, 5600 JW Eindhoven
info@dspe.nl, www.dspe.nl

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Editor
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Advertising canvasser
Gerrit Kulsdom, Sales & Services
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
Drukkerij Snep, Eindhoven
+31 (0)40 – 251 99 29, info@snep.nl

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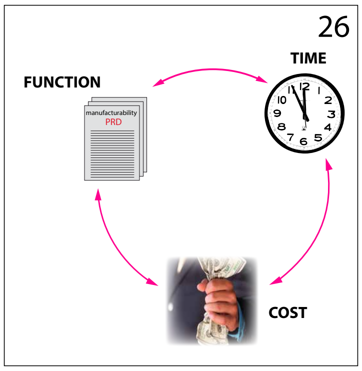

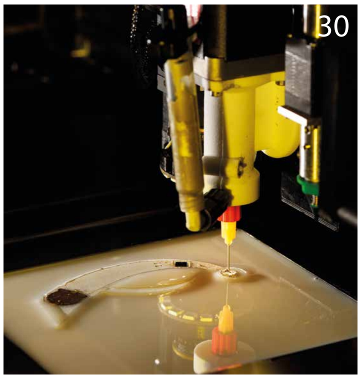

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PRECISION TALENT IN DEMAND


(Photo: Jan Pasman)

The phrase ‘precision talent’ immediately triggers thoughts of micrometers and nanometers, the accuracies that are common in sectors such as semicon and space. This is what the Dutch high-tech community excels in and I am proud to be a part of it. But you can also interpret precision talent differently, namely as designing something that is precisely correct, that exactly meets the specifications and is able to be manufactured at a reasonable cost price. The latter is underexposed in semicon and space, where the highest precision performance comes first. It is important to keep this in mind when reading Mikroniek, as this publication deals mainly with extreme precision.

In 1985, I graduated as a mechanical engineer in *Vervoerstechniek* (automotive engineering). At Océ I learned how to develop copiers and printers. Paper handling was designed with pragmatic knowledge; one could see what was happening. In printheads, micrometers were relevant. Copies and prints were judged using a simple loupe. Once I began working for TMC and now for Demcon, I got in touch with ‘precision engineering’, the domain of micrometers and nanometers.

Are the ‘precision’ engineers in semicon and space different from the engineers I worked with at Océ? I think the answer is ‘no’. Many engineers who had their first working experience at Océ prove it by being successful in semicon projects in the Eindhoven region. Although they had to learn that precision engineering is quite unforgiving: all system aspects such as degrees of freedom, temperature, dynamics, control, etc. have to be taken into account. Even verifying the performance of such nanometer-accurate systems is becoming a challenge in itself. For engineering talents, it is simply an interesting domain with many technical challenges.

In my more than 20 years of experience with recruiting and developing engineering talent, I have learned that the majority is not attracted only to the technical domain he or she is working in. Certainly the ones who are a sort of ‘engineer for life’ are energised by solving any technical design challenge. And more importantly, they want the ‘freedom to operate’: the autonomy to make their own choices. This means even room for making mistakes and the chance to solve them their way, knowing that experienced engineers are nearby and available for consultation and mentoring.

The main challenge today is educating and developing mechanical designers. ‘System engineering’ sounds sexier than mechanical design; and biomedical engineering is attractive to female student engineers. These student ambitions seduce universities into thinking as marketers. I do think it is important to develop the discipline of system engineering, and Dutch engineers even excel in system engineering. However, a unique high-performance system is built upon deep and solid knowledge of disciplines like mechanical, electrical, software and control engineering, physics, etc. To graduates who have been trained in mechatronics, I’d like to say: “Now first learn a proper discipline, then move on and develop your (precision) talent.”

Precision engineering is in need of more high-level mechanical designers. So let us, as well as emphasising system thinking, identify and honour the new role models that show student engineers the beauty of a creative single-discipline solution.

Toon Hermans
Managing director Demcon Eindhoven, DSPE board member
toon.hermans@demcon.nl, www.demcon.nl

REFLECTIONS ON SYSTEM ARCHITECTING

A system architecture, according to Wikipedia, is the conceptual model that defines structure, behaviour and other aspects (or 'views') of a system. Such a model can be used to guide the design of a system and determine its success. In the precision engineering and mechatronics domain, where systems can be very complex, system architecting, i.e., the art of defining and maintaining a system architecture, is a crucial discipline. Ger Schoeber, manager Innovation & Technology at Hotraco and course leader of the famous "System architecting" training course, presents some reflections on this very special (precision) talent.

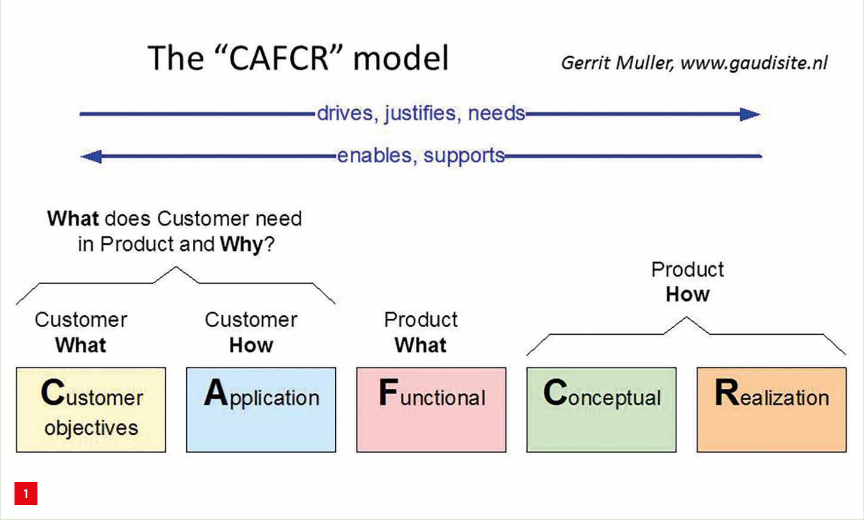
The pioneer in the field of system architecting, at least from the Dutch perspective, is Gerrit Muller, who has worked at Philips Medical Systems, Philips Research and ASML and is now a research fellow at TNO and a professor in systems engineering in Norway. On the basis of his own experience as a system architect, he developed the so-called CAFCR method (Figure 1), which employs five 'views': Customer Objectives, Application, Functional, Conceptual, and Realization [1].

The method provides the structure for an iterative process in which a chain of questions has to be answered: Who is the customer? What is his application? What is the function of the product in the application? With what concept(s) can this be achieved? Is this concept feasible? What are the constraints? Are there new opportunities? [2]

Definition

Muller used the CAFCR method as the foundation for a new training course, called Sysarch ("System architecting"), which was launched around 2000. In 2002, Ger Schoeber (Figure 2) joined as a teacher and he has now been the acting course leader for many years. On the course provider's site [3] a clear definition is given:
"System architecting is the art and science of designing and building multi-disciplinary systems. The responsibility and the challenge for the system architect is to translate the requirements of the many stakeholders into a system architecture blueprint. He/she will do this based on a solid knowledge of the problem domain, the business context, the human context, the solution domain, technology roadmaps and preceding architectures. The system architect provides the vision, develops the outline for an integral design, keeps the overview and takes care of the design consistency. He/she provides the context for the development activities that will be carried out by large multi-disciplinary teams of specialists."

1 *The CAFCR method.*



Three roles

It is clear that technology is important, but it is ill-advised to make a one-track-minded, technology-driven engineer the system architect in a design project. Communication skills and business sense are essential 'tools' for a system architect, as well as extensive experience. There is a training course, but system architecting is first and foremost learned in practice, hence a system architect is usually a senior professional.

To further outline the scope, Schoeber defines the three leading roles in a technically complex design project:

- the project leader, who is in charge of project planning and resources (people, money, tools, ...);
- the product manager, who is in charge of establishing market demand for a new product/system;
- the system architect, who is in charge of translating market demand into technical system requirements and making an estimation of the project resources required.

2 *Ger Schoeber is manager Innovation & Technology at Hotraco [4] and course leader of the "System architecting" training course. He is a board member of INCOSE-NL [5], the Dutch branch of the International Council on Systems Engineering, and a steering group member of the System Architecture Study Group (SASG) [6].*

In theory, one and the same person can fulfil these three roles, but it is best when three people each assume one role. Not only does this prevent work overload, also the tensions between potentially conflicting interests that are inherent to any complex project are explicitly represented. Each interest has its own representative and the discussions between them can lead to a well-balanced, optimal project result.

Responsibilities

From the above it is evident that the 'duties' of a system architect are numerous. Among them is requirements engineering, formulating the technical requirements in a 'smart' manner: specific, measurable, achievable, relevant and time-bound. This is the basis for any successful design project. Manufacturability is also the architect's responsibility; this concerns production technologies, materials, cost price, lead time, etc.; see also the article on Design for Manufacturing in this issue (page 26 ff).

Another important aspect of architecting is roadmapping. Choices made regarding the architecture have to be consistent with existing technological and business roadmaps for product (families). On the other hand, these choices can be guiding for new roadmap formulations, so the (future) roadmap always has to be at the back of the architect's mind.

Best of both worlds

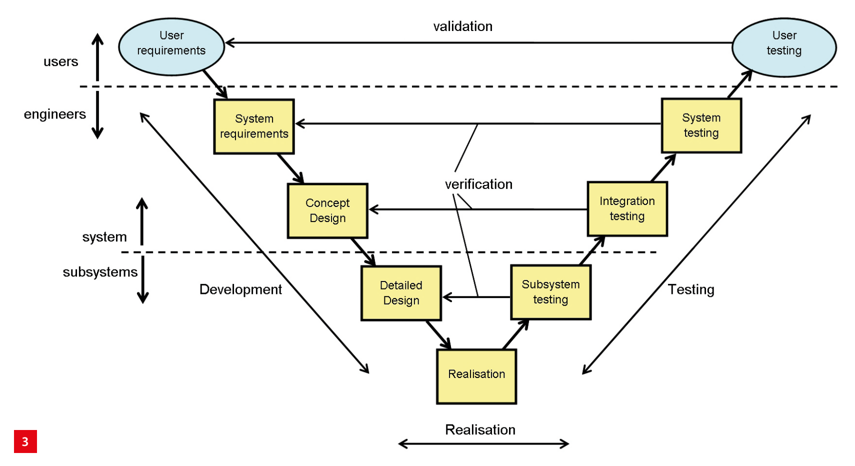
Whereas architecting is a common phrase in the high-tech domain system, other domains, such as civil engineering, work with system engineering. There are overlaps and differences between the two terms, related to the complexity of projects from either the technical, business or organisational perspective. In all cases, the ultimate challenge is the same: delivering a sound technical system that is of value to the company and the market.

In system engineering, the emphasis is often on process and stakeholder management. As a consequence, losing focus on the technical aspects may introduce risks in the final design. On the other hand, in the high-tech domain the main concerns are often technical complexity and time-to-market. This induces a pragmatic way of working in which the careful execution of the project plan receives less attention. According to Ger Schoeber, however, it is possible to merge the system engineering and system architecting approaches and combine the best of both worlds.

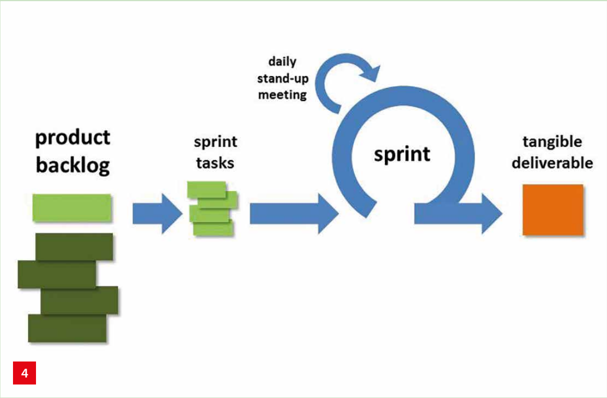
V-model vs Agile

The adage 'best of both worlds' also applies to the methods and tools used in system architecting [2], such as the above-mentioned CAFCR method. This is best illustrated by looking at two 'extremes', the V-model and Agile.

The V-model is a well-structured method, originally devised for hardware-dominated product development (Figure 3). A linear trajectory is followed from the upper left arm of the V (user requirements definition) through various (sub)system development stages to ultimately user testing. A forte of the V-model is that specification and verification are 'automatically' linked to one another at every development level, assuring a design that satisfies the requirements. However, this linear progression is a time-consuming procedure, especially if in later stages design problems or last-minute requirement changes necessitate a redesign in a previous stage.
Here the Agile method (Figure 4), originating from the domain of software development, [7] comes in with its project 'sprints'. A sprint is a short design iteration in which part of the functionality is developed, starting with the critical parts of the design, to create a so-called minimum viable product for which feasibility can be demonstrated at an early stage. This reduces the risk of extensive reiterations at later stages and in subsequent sprints new functionality can be added, building upon the proven core design.



3 *The V-model [2]; see the text for further explanation.*



4 *The sprint-based Agile method [7]; see the text for further explanation.*

Now it is the architect's mission to combine the two development 'cultures': the long-term goal orientation of the V-model with the short-term flexibility and development speed of Agile. Schoeber envisions a V-model in which at any given moment in time different parts of a design are each at different stages of their development trajectory: when some parts are still at the concept phase, other parts are already at the detailed design phase. Here the so-called student syndrome, i.e. doing the easy bits first to postpone a difficult assignment, should be avoided, Schoeber warns. It is essential to deal with the critical design challenges first.

Interface

Finally, talking about 'worlds', there is another cultural dimension at play. The high-tech community in the Netherlands is adept in system architecting, Ger Schoeber states, partly due to the Dutch 'polder' mentality, combining pragmatism and innovativity. Other countries/cultures, where for example hierarchy is held in high esteem, are better at process planning, sticking to the plan and delivering what was ordered, but have problems dealing with new insights or developments and adjusting plans. Here lies a real challenge for large multi-site, multinational projects and a new role for the system architect, that of cultural interface within a project team. ■

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ELEGANCE IN COMPLEXITY

For many years engineers have used basic geometrical shapes for various kinetic and kinematic purposes. We are very familiar with beam and tube geometries applied in flexure applications ranging from mechanisms to high-performance precision machines. There are however significantly more complex and intricate shapes in nature and mathematics that have yet to be utilised to their full potential. The challenge is to make them available for designers and make them as easy to design with as their conventional counterparts. This article introduces some principles and discusses the potential in engineering design.

JOEP NIJSSEN

AUTHOR'S NOTE

Joep P.A. Nijssen is a Ph.D. candidate in the Mechatronic System Design (MSD) research group of the Department of Precision and Microsystems Engineering at Delft University of Technology, the Netherlands. For this work he received a nomination for the 2017 Wim van der Hoek Award. The research presented is part of a collaborative research project together with Giuseppe Radaelli (Ph.D. candidate at MSD), Just L. Herder (chair of MSD research group) and Charles J. Kim (associate professor at Bucknell University, USA).

j.p.a.nijssen@tudelft.nl
www.pme.tudelft.nl

Leafspring flexures can be regarded as the most basic spatial elastic mechanism, having no curvature and having a small geometrical dimension in one direction compared to the others. Their importance in the design of mechanisms is not to be underestimated and their design principles are well known. Their kinematic behaviour is limited, however.

A very logical step would be to add curvature to the flexure such that its kinematic behaviour changes. This can either greatly increase stiffness by creating dome-like structures or create a large source of potentially interesting geometries for (design) engineers to implement. As seen in Figure 1, by adding curvature the flexures can rapidly become complex, which makes understanding their behaviour significantly more difficult than that of the original flexure started with.

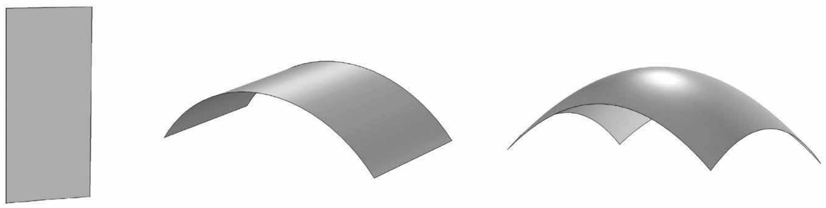
The question therefore arises: What kind of shapes will be of interest from an engineering perspective? And, if we have obtained a number of viable shapes, what is their behaviour and how can we use them in our design challenges?

Flexures as surfaces

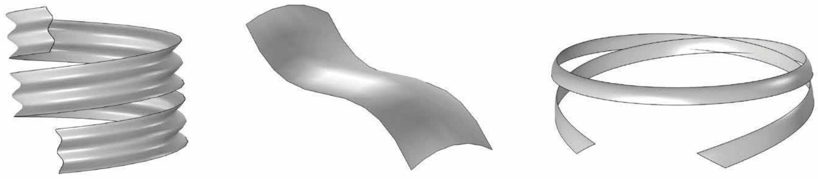
Flexures can be looked at as surfaces because they are generally very thin. Surfaces have been investigated in-depth in the field of mathematics. If we are interested in more complex flexure geometries, it therefore makes sense to look into the relevant mathematical surface libraries. These libraries can inspire mechanism designers to come up with flexure geometries that are increasingly more difficult in form and function. The advantage of these mathematical shapes is that compared to free-formed flexures, there is still a mathematical description that we can use in the modelling and eventual fabrication of the flexures. We can have very complex shapes, which can actually be described very elegantly by a set of surface equations [1]. Examples can be seen in Figure 2.

There are also more complex methods of modelling these geometries and sometimes the surface equations will provide a starting point for later optimisation. An example is the gravity balancer of Giuseppe Radaelli [2], seen in Figure 3. The shape of the mechanism is a highly unconventional geometry, which has been shape-optimised in order to exhibit a near-zero-stiffness behaviour over a large range of motion. This was made possible by describing the surface in NURBS (non-uniform rational B splines), which is a technique often used in computer graphics to describe complex surfaces.

A comparable method was used in other research where a geometry was chosen from one of these previously mentioned surface libraries. This hyperbolic paraboloid (hypar in short) was optimised using NURBS and shape optimisation to create a flexure capable of having a 40-N force capacity again over a large range of motion. The hypar seen in Figure 4 is used in an orthosis concept that makes



1 *Starting from the most basic leafspring flexure on the left, simply by adding additional curvature, we can change the behaviour. In some cases, as with the dome-like flexure on the right, this significantly increases stiffness.*



2 *Three complex flexure geometries (corrugated helix, shoe surface and crossed helix) that can all be described by a set of surface equations.*

3 *The gravity balancer designed by Giuseppe Radaelli [2], capable of balancing its own weight over a large range of motion.*

use of these force generators in order to provide spine correction [3].

Kinematics over kinetics

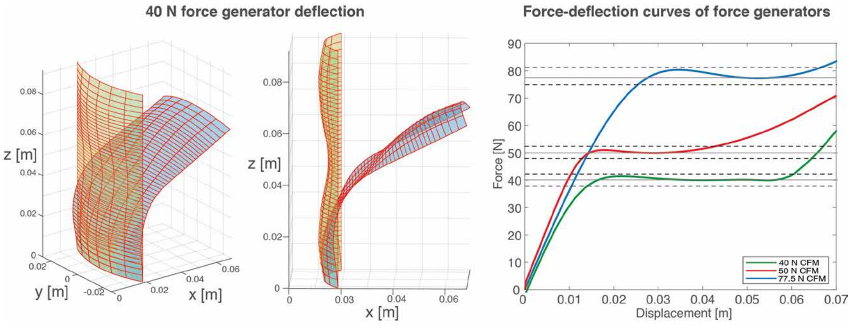
These types of flexures have a clear objective: create a certain force behaviour in a specific direction. Both the gravity balancer and the hypar are 1-DoF force generators (DoF = degree of freedom). Another important design objective that mechanisms are used for is to create a certain motion behaviour. Here another challenge arises: how do we describe the motion behaviour of complex flexures? Having this library of potential flexure shapes is not worth much if an engineer cannot describe how the flexures behave. We preferably want these shapes to be as intuitive as conventional leafspring flexures during concept design.

Another challenge is that DoFs at some point lack the information to properly describe the motion behaviour of certain shapes. What works for a leafspring flexure or a set of leafspring flexures might for instance not work for a crossed helix (seen in Figure 5). And what happens if we want to describe the motion behaviour of a set of these complex shapes in a certain configuration?

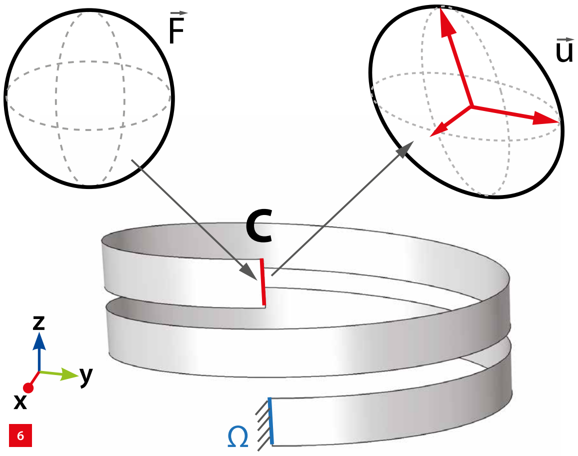
5 *A wide range of complex flexures and serial and parallel combinations of them. How can we describe the behaviour of these kinds of mechanisms without it becoming too complex? These flexures are all made from polyethylene using thermoforming.*

A possible approach that can be followed is looking at the flexures as separate building blocks and describing the motion of the blocks separately. In the building-block-type synthesis approach, Charles Kim [4] presents the use of so-called compliance ellipsoids. A compliance ellipsoid creates a visual representation of the relative DoFs in three dimensions. By constraining a flexure on one side and actuating it on the other, we can transform a unit force sphere into a displacement ellipsoid. Two ellipsoids are thus needed to describe a three-dimensional mechanism in all its DoFs, one for the rotations and one for the translations. The semi-axes of the ellipsoids present the ratio of motion, which is a more elaborate description of the DoFs.

The ellipsoid of the helix in Figure 6 for instance shows that its largest motion direction is roughly in the *z*- and *y*-direction, whereas the allowable motion in the *x*-direction is more restricted. Two ellipsoids (one rotation and one translation) can thus describe – by means of a visual representation – the linear relative DoFs exhibited by these complex geometries. Especially by having a visual representation, it becomes much more intuitive to use complex flexures in initial concept design. The ellipsoids can also be used to determine the motion profile of serial and parallel conjugated mechanisms, but additional theory is needed to describe the resulting behaviour; it can be found in the work of Charles Kim [4].



4 *The optimised hypar which is capable of having a constant-force characteristic over a significant range compared to its own length. The hypar has zero stiffness in the x-direction. The corresponding zero-stiffness behaviour for this flexure is equal to the 40-N curve seen in the force-deflection plot.*



6 *The ellipsoid describing the translational freedom range of a helix is seen on the right. The input force sphere F (left) is transformed into the output compliance ellipsoid describing the motion behaviour. The visual representation of the freedom range of the complex shape makes understanding it more tangible.*