Design Principles

The field of Design Principles has an impressive list of Dutch pillars, such as A. Davidson, Wim van der Hoek and Rien Koster. But what is it that connects these people? Not only their passion for mechanics, revolutionary calculations and constructions, but, in my opinion, also how they created their mechanical designs. They stimulated creativity and out-of-the-box thinking. They showed that designing is about teamwork. They let designers solve design problems by asking the right questions. A design process full of brainstorming and collective reviewing. In this article I will explain that Design Principles is a Way of Working. "It is not only about the end result, but about how you get there."

• *Krijn Bustraan* •

A. Davidson was the authority in the field of high-precision mechanical engineering at Philips in the 1950s and 60s. He was the author of a handbook of precision engineering that formed the basis for the engineering community at Philips [1,2].
Wim van der Hoek made machines in the factory faster, more accurate and more silent by analyzing amongst others cam drive mechanisms. This led to a mechanical design that combined stiffness, dynamics, 'mechanical software' and input/output relations (mathematics) for converting actuator movement into end effector movements. He summarized his multi-disciplinary knowledge in lecture notes [3]. Later, one of his successors, Rien Koster, published the famous and widely taught book "Constructie-principes" [4], full of design choices often based on thinking in parameters such as the height/diameter values of hole flexures. Recently, Herman Soemers included dynamic aspects in his English-language lecture notes [5].

It is difficult to give an exact definition of Design Principles. My definition in one sentence is:
"Combining a fundamental understanding of mechanisms with a creative way of designing."

A multi-disciplinary technology field

'Mechanisms' not only includes mechanics but also physical principles such as wear, friction, hysteresis and damping. Design Principles is not only about mechanical design, but is a broad scope of disciplines including dynamics, actuation, control, metrology, physics, optics and thermomechanics. In my opinion the Way of Working that will be described in this article cannot be learned from a book or in a course, but only by working together in the design process with Design

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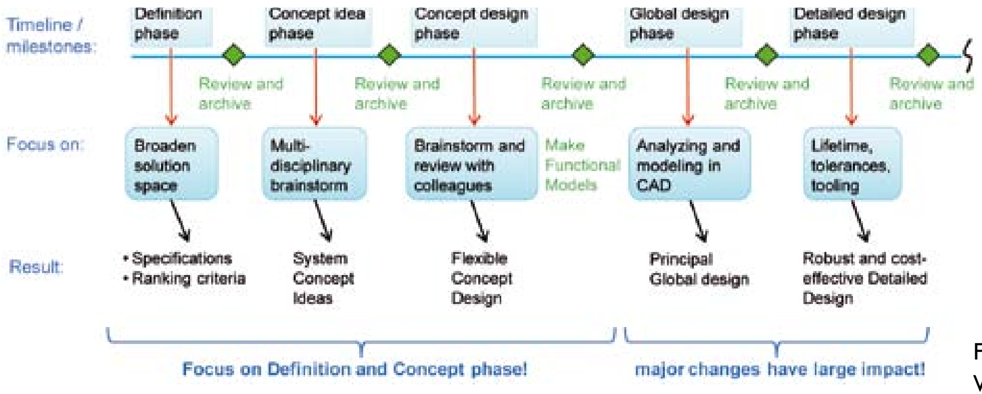


Figure 1. Proposed Way of Working in the design process.

Principles oriented engineers. Mechanical design is about teamwork. Use your colleagues as sparring partners to continuously reflect on your ideas and generate new ones. Designing together also means putting your ego aside. Stop the "not invented here" syndrome. In a brainstorm it does not matter who's idea it was!

Proposed Way of Working: include the right concepts by brainstorming

Mechanical designs are mostly not created by sudden brilliant ideas. Brainstorming can be used to stimulate creativity in a systematic way. Figure 1 shows the proposed systematic Way of Working for design projects with sufficient complexity. There are five phases in the design process that always have to be followed: definition, concept idea, concept design, global design and detailed design. The phases will be explained in the next section about the creation of an opto-mechanical design. Each phase ends with a review and archiving of the results.

The definition phase is about getting the right specifications and ranking criteria by interviewing the client. What is important for the customer, determines the mindset in the design. This can be for example accuracy, CoGS (Cost of Goods Sold), reliability, lifetime (prediction) or easy assembly and maintenance. When the specifications and ranking criteria from the definition phase are clear, the concept phase can start.

An important step is to split the concept phase in a concept idea phase and a concept design phase. Figure 2 shows a way to come to a flexible concept design using brainstorming and ranking. This phase is about architecture and a multi-disciplinary team should be used. Brainstorming techniques such as mind mapping help to think out-of-the box and to enlarge the set of concepts. The large set of ideas should be filtered on feasibility and client's scope. It is recommended to compose two or three different system concepts from all the ideas: for example A, B and C. For each concept the design issues must be written down: α, β, γ. This gives insight in the complexity and design effort for each system concept idea.

After the concept ideas are ranked, one system concept can be chosen and the concept idea phase is finished. To give a generic example: for Lorentz actuation, moving coil (A) or moving magnet (B) can be chosen. System concept idea A has design issue water cooling on the moving world due to energy

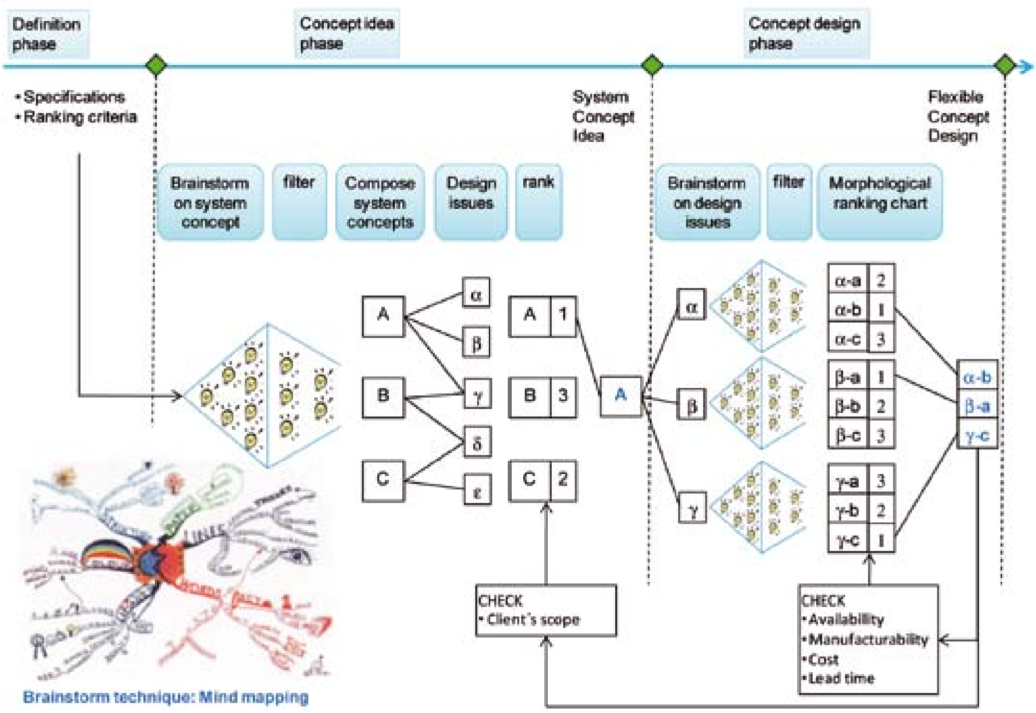


Figure 2. Concept phases with brainstorming and ranking towards a flexible concept design.

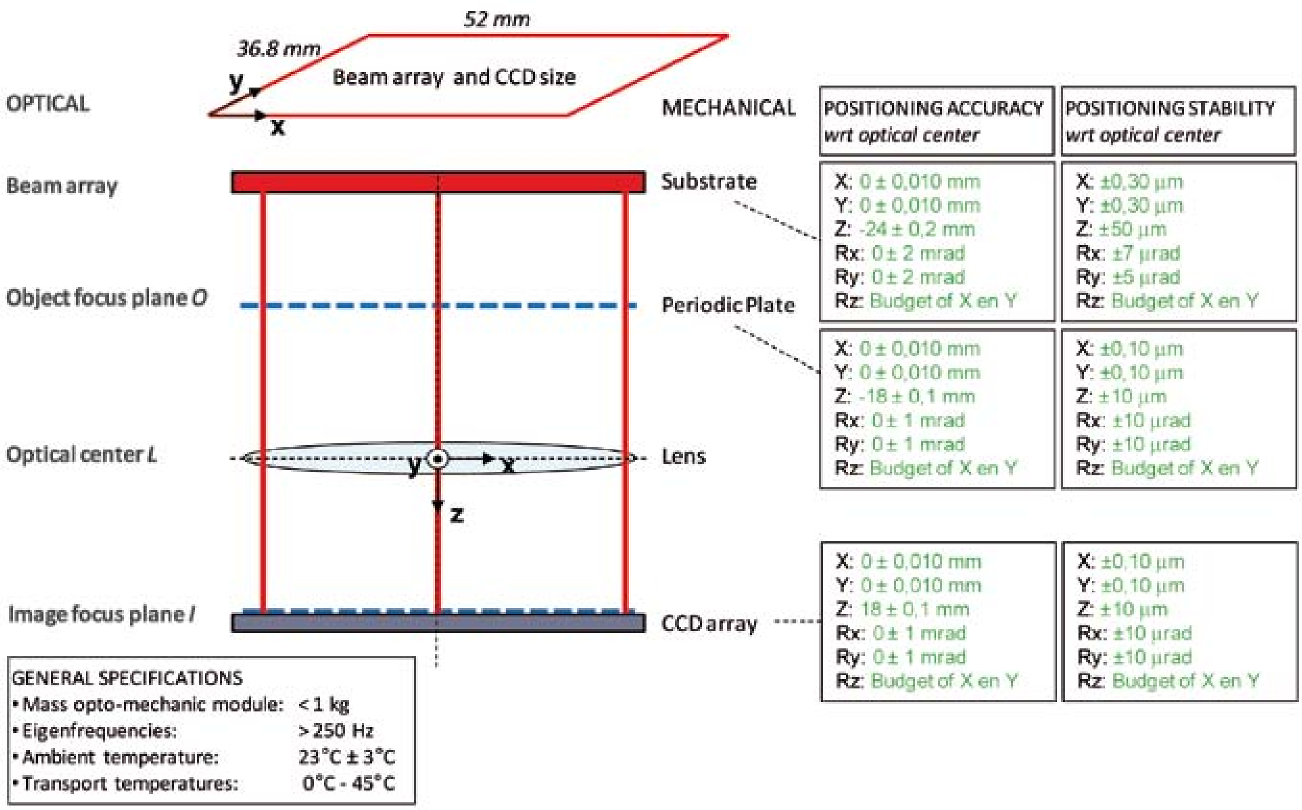


Figure 3. Specifications for an opto-mechanical module.

dissipation in the coils (α) and a cable slab with disturbance forces varying with stroke (β). System concept B has a design issue on reaching eigenfrequencies by large moving weight (δ). Both system concept ideas have a design issue on magnet stray field (γ).

The concept design phase is to solve the various design issues for the chosen system concept. The mechanical, electronical and software teams, for example, can solve their 'own' design issues. For each design issue, the set of ideas from the brainstorm must be filtered to two or three concepts (α-a,α-b,α-c). These concepts can be combined in a morphological chart and will be ranked. The proposed concept designs should be checked on, for example, availability, manufacturability, cost and lead time. If showstoppers arise, the next best concept design can be chosen without brainstorming again. All the best concept designs for all design issues together form the proposed concept design which is reflected to the customer to see if it is in line with his scope and expectations.

This proposed way of working with doing brainstorms, expanding the solution space and then narrowing the number of concepts, leads to a concept design with a large confidence that the *right* concept is chosen. Keeping two to three concepts alive leads to a flexible concept design that can easily be changed.

Usually a large design effort and many costs are made after the concept choice: global design, detailed design, detailed calculations and tests. In my opinion, often too little time is planned for the concept phase. Choosing the right concept increases the probability that the global and detailed design phase can be executed in a straightforward and efficient way without further iterations.

Example of Way of Working: creating an opto-mechanical design

Definition phase:
towards specifications and ranking criteria

Figure 3 shows a generic opto-mechanical system consisting of a periodic plate with a beam array coming from a substrate as backlight, a lens and a CCD array. The lens is imaging the periodic plate onto the CCD array. The components have to be aligned and fixated with respect to each other with an accuracy of 10 µm. After calibration, the system has to be robust for (transport) accelerations and geometrically stable within 100 to 300 nm, see the positioning accuracy (initial alignment accuracy) and positioning stability (after calibration) in Figure 3. Other specifications are a maximum weight of 1 kg, minimum eigenfrequency of 250 Hz, an ambient temperature range of 6 °C and transport range temperature. The system will be made in series of about 100 each year.

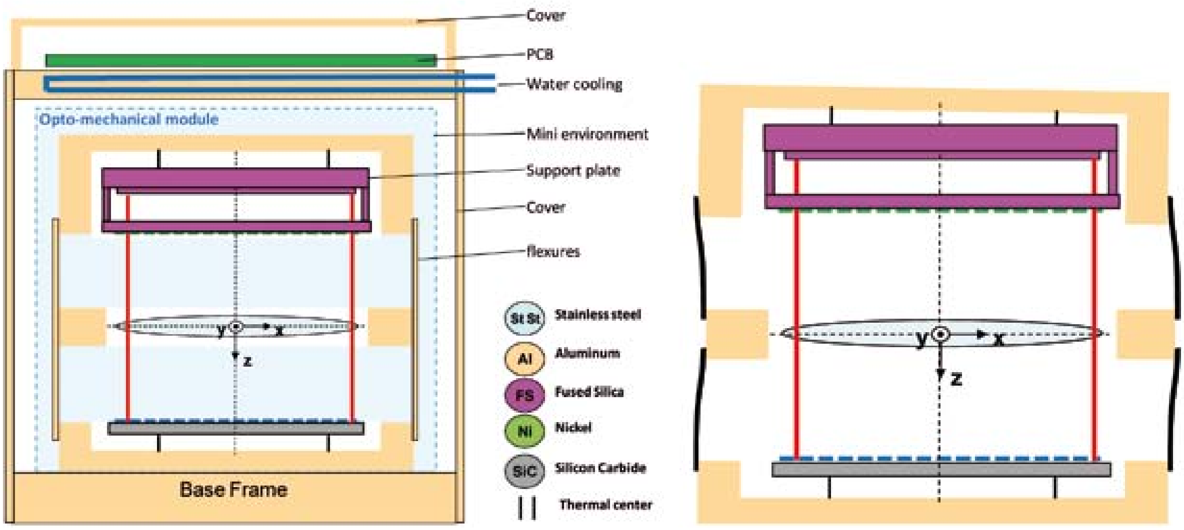


Figure 4. Concept idea phase.
(a) System concept idea.
(b) Opto-mechanical module with alignment principle.

The most important criteria for the customer in this case were: opto-mechanical quality, easy assembly, CoGS and design lead time. For the design team an added criterion was design flexibility, since the client had the alignment tolerances and alignment procedure not ready in this phase. These criteria were used to rank the concept ideas.

Concept idea phase: towards system concept ideas

The system concept idea is shown in Figure 4a. It was created by a multi-disciplinary team of mechanical, optical and electronical designers and reviewed by the client and manufacturing and assembly engineers as well. Alternative system concepts will not be discussed here. The concept idea is presented as a simple basic picture. In this phase no CAD design is needed.

The material for three optical components was given: a fused silica substrate, a quartz lens and a SiC CCD. The substrate is mounted on a support plate of the same material to increase rigidity. The material of the periodic plate was selected as fused silica for thermal expansion matching. Each (group of) optical component(s) with the same CTE (Coefficient of Thermal Expansion) is mounted in an aluminum frame with a thermal center. The outcome of the system concept idea brainstorm was three possible materials for the frames: fused silica, stainless steel or aluminum. Aluminum was chosen for thermal stability, to obtain homogenous temperatures. Thermal gradients in the frames or flexures can disturb the positioning stability.

The periodic plate and backlight array were regarded as one optical component that will be pre-aligned. Then three frames (subassemblies) were created that have to be aligned with respect to each other. The frames can be aligned and fixated by aluminum flexures between the frames, see Figure 4b. A flexible and modular design was created from conventional frame materials to limit production lead times and CoGS. The alignment stroke could be designed in the frames using monolithic structures with adjustment screws, parallel guides and virtual rotation points by elastic hinges. However, in this phase the idea was born to use alignment tooling to reduce product complexity, cost and weight.

The opto-mechanical module of three subassemblies can be mounted into a water-cooled mini-environment. The beam array is activated by electronics on a PCB. From now on, only the opto-mechanical module will be discussed in detail as an example to explain the design process phases.

Concept design phase: towards flexible concept design

The concept design phase is to solve various design issues one by one by brainstorming in small (mono-disciplinary) teams. Exploring (hand) calculations can help ranking the concepts from the brainstorms and to estimate whether the specifications can be met.

Design issues for the opto-mechanical module were material choices for the frames, the mounting and material choice of the periodic plate and the alignment and fixation of the frames.

Starting with the first design issue, thermomechanical calculations showed that the temperature variations and gradients within the mini-environment were very small compared to ambient temperature fluctuations. Hence stainless steel seemed a better option than aluminum, since stainless steel flexures have a higher yield strength and no

MOUNTING PERIODIC PLATE	1. INTEGRATED PACKAGE WITH BEAM ARRAY	2. ON STEEL FRAME, WITHIN BACKLIGHT FRAME	3. ON STEEL FRAME SANDWICHED
Optical quality	☺	☺	☺
Risk of damaging parts	☹	☺	☺
Thermal stability	☺	☺	☹
Tolerance sensitivity	☺	☺	☹
Weight	☺	☺	☹
Ease of assembly	☹	☺	☺
Number of parts	☺	☺	☺
Tolerance range	☹	☺	☹
Complexity	☹	☺	☺
CTE Match -> thermal center	☺	☹	☺
Material cost	☹	☺	☺
Manufacturability	☹	☺	☺
Supplier can do alignment	☺	☺	☹
Manufacturing time	☹	☺	☺
Design flexibility	☹	☺	☺

Ranking Criteria				
	Opto-mechanical quality	5	4	3
	Ease of assembly	1	4	3
	Cost of BOM	1	5	4
	Lead Time	1	5	4
	Design flexibility	1	5	3
	RANKING	9	23	17

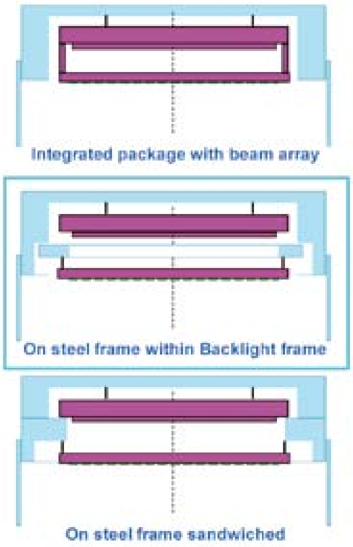
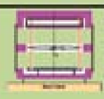
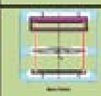
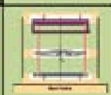
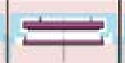


Figure 5. Brainstorm and ranking on mounting the periodic plate.

	Design issues	Frame material choice			Mounting Periodic Plate			Periodic plate material			
	Concept options	FS	SST	AL	INTEGRATED FS PACKAGE WITH BEAM ARRAY	ON SST FRAME, WITHIN BACKLIGHT	ON SST FRAME SANDWICHED	FS	INV	SST	AL
	Concept options							With etched layer Ni	etched/lasered	etched/lasered	etched/lasered
Ranking Criteria	Opto-mechanical	4	4	3	5	4	3	5	N/A	N/A	N/A
	Ease of assembly	1	5	3	1	4	3	1	3	4	4
	Cost of BOM	1	5	4	1	5	4	1	3	5	5
	Lead Time	1	5	5	1	5	4	2	3	5	5
	Design flexibility	1	5	5	1	5	3	2	3	5	5
	Concept choice										
	Ranking	8	24	20	9	23	17	11	12	19	19

N/A: Not Applicable
FS: Fused Silica
INV: Invar
SST: Stainless Steel
AL: Aluminum
NI: Nickel

Figure 6. Morphological ranking chart.

inserts have to be used for screws. See also Figure 6, where the frame material choice is ranked with the ranking criteria.

The design issue of mounting the periodic plate was tackled with three colleagues and a whiteboard, filtered to three concepts and archived using simple basic pictures. The feasible concepts were ranked, see Figure 5: an integrated fused silica package with the beam array, mounted on a steel frame within the backlight frame, or sandwiched. The second concept design was chosen from the ranking.

The same way of working was followed to tackle all other design issues. The results were combined in a morphological ranking chart, see Figure 6. For the periodic plate material stainless steel or aluminum are not feasible due to thermal expansion outside the stability specification of 0.1 µm. Invar is stable enough but the manufacturing process is a showstopper: the holes cannot be etched or laser cut accurately enough regarding diameter and positioning. Hence, the only feasible option seemed fused silica with an etched metal (nickel) coating, although this option has the lowest ranking.

Figure 7 shows the concept design for the opto-mechanical module. Note the differences with the system concept in Figure 4.

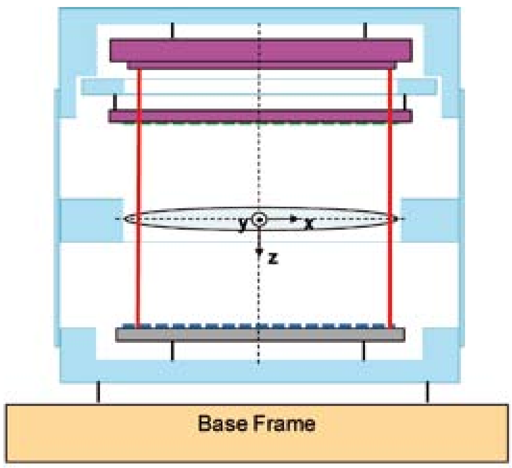


Figure 7. Concept design for the opto-mechanical module

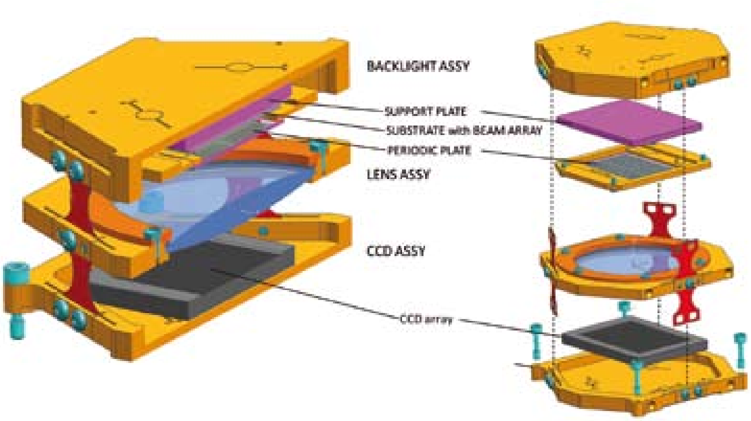


Figure 8. Global design of the opto-mechanical module.

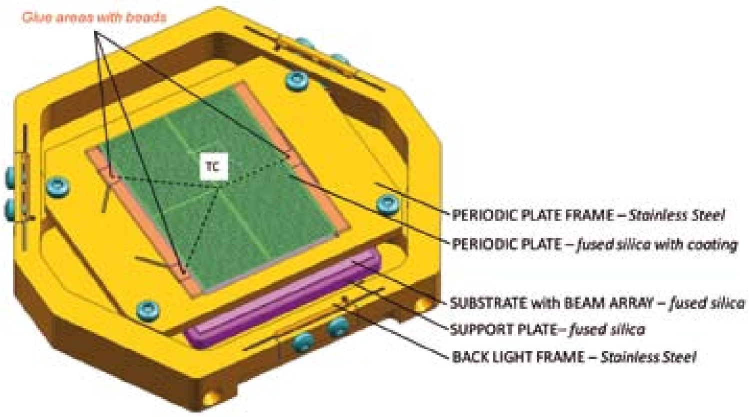


Figure 9. Backlight assy with periodic plate.

Global design phase: towards a principal global design

The global design phase is where the CAD design starts to fit all parts and functions in the required volume. Geometry is optimized to balance low weight, high stiffness and eigenfrequencies on one side, with decoupling for thermal expansion differences and low alignment stroke forces on the other side.

Figure 8 shows the global design consisting of three frames: a backlight assy with the periodic plate mounted on a separate stainless steel frame and the beam array as backlight, a lens assy and a CCD assy.

The periodic plate can be glued with beads as spacers onto the periodic plate frame using a spark-eroded Thermal Center (TC), see Figure 9.

The backlight assy has to be aligned in three Degrees of Freedom (DoFs) to the object plane of the lens. The CCD assy has to be aligned to the image plane of the lens (z, Rx, Ry) and to the periodic plate (x, y, Rz), a total of six DoFs to align. Figure 10 shows the statically determined tooling interface for alignment in six DoFs. Each frame has three conical holes that serve as interface for the tooling. The tooling consists of an external manipulator that is coupled to the upper and lower frame by three pins with a spherical front surface. Pin 1 constrains three DoFs, pin 2 constrains two DoFs by decoupling the horizontal positions for manufacturing tolerances by an elastic hinge. Pin 3 is retractable (play-free) and constrains only the z-direction by using an elastic hinge and radial preload. The six DoFs alignment can be performed by many different manipulators, either sourced or by dedicated design.

After alignment the position has to be fixated. Figure 11 shows the three sheet flexures that are used to provide alignment stroke and exactly constrained fixation after clamping the flexures using screws.

Three possible phenomena can cause fixation errors:

1. Reaction forces of the flexures in bent position will cause small elastic movements after removing the alignment tooling.
2. Tool clamping forces can deform the frames, which will cause small elastic movements after removing the alignment tooling.
3. Disturbing moments on the frame by screw fixation torque. When fixating the first of six screws that clamp the flexures, the screw torque can be led into the frame and can lead to elastic deformation by finite stiffness of the tooling.

Ad 1) Fixation errors by flexure reaction forces are minimized by a high compliance of the flexures, see Figure 11. For the chosen configuration of three flexures at 120 degrees, a uniform horizontal stiffness is obtained of 1.5 times C_y. This implies that the frame on the flexures will have an alignment stroke dependent fixation error of 0.8 μm per mm.
Ad 2) The flexures are 'cut' to reduce the radial stiffness to a minimum: 6 N/mm. For 1 mm alignment stroke, pin 3 has to be preloaded with 9 N only.
Ad 3) Screw fixation torque is prevented to be led into the tooling stiffness by shorting the moment directly into the flexure. The flexures are clamped into a monolithic spark-eroded slot. The hold moment between flexure and frame (on two sides) is always larger than the disturbance moment between screw head and frame, even for varying friction coefficients. This way, the frames with optical components can be constrained in a stress-free and hysteresis-free way.

Detailed design phase: towards a robust and cost-effective detailed design

The detailed design is amongst others about robust tolerance trains and stretching the tolerances. In this case, for example, the frames holding the optical components can be water-cut and milled with tolerances of ±0.1 mm.

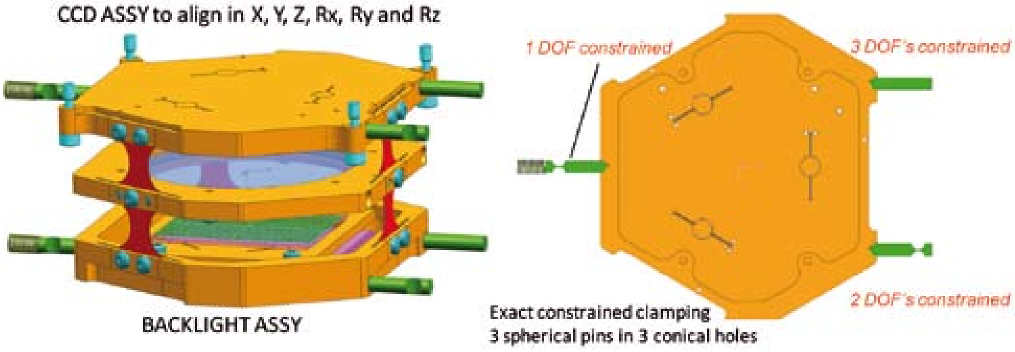


Figure 10. Exact constrained tooling interface for alignment in six DoFs.

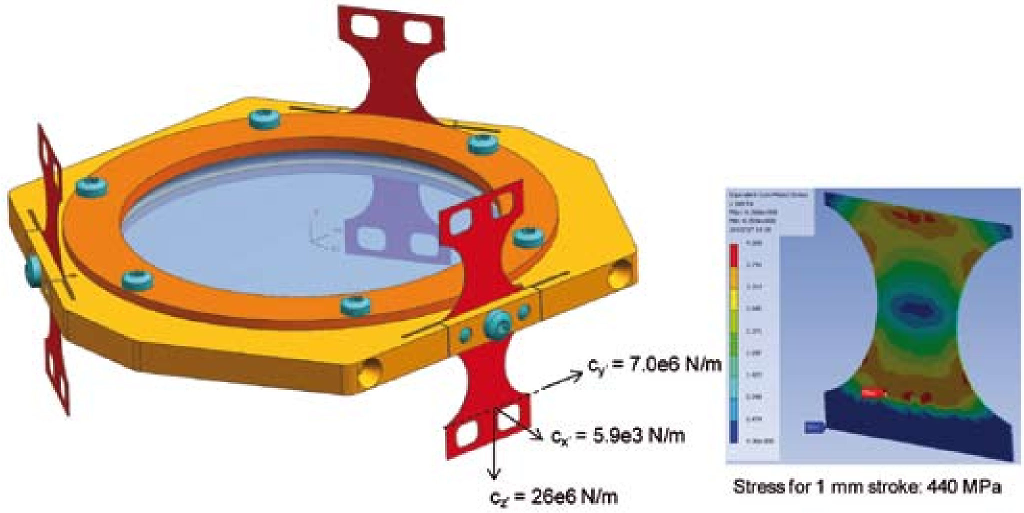


Figure 11. Flexure stiffness ratio $C_{y'}/C_{x'}$ = 1 : 1,200; stress level for 1 mm deflection: 440 Mpa.

The only accurate features are the spark-eroded thermal centers and the flexure clamping blocks. This results in relatively cost-effective parts.

Summary

Design Principles is about thinking in Degrees of Freedom, thinking in functions and parameters, and being creative and analytical. Design Principles is also about a Way of Working using brainstorms and continuously reviewing design ideas with colleagues. It is not only about the end result, but about how you get there. A Way of Working was proposed consisting of five phases with the focus on concept design. This proposed Way of Working leads to a concept design with a large confidence that the *right* concept is included. Keeping two to three concepts alive and creating a modular design leads to a flexible design that can easily be changed if showstoppers arise or if the client's scope changes. Choosing the right concept design accelerates the global and detailed design phase without further iterations. It leads to a relatively short and straightforward design process. Ultimately, it may result in improved customer satisfaction because of shorter time-to-market and cost-effective and robust products.

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