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DESIGN METHOD FOR FUNCTIONAL COMPONENTS OF ULTRA HIGH PRECISION MACHINES

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ABSTRACT
Ultra high precision machines are defining the state of the art for measuring and positioning purposes. Thus they are a key technology in general but in particular to Micro- and Nanotechnologies. They have to meet increasingly tighter specifications to meet the growing needs to measure macroscopic objects with nanometre precision. Therefore the overall machine design as well as the design of the functional components need to be improved significantly. Application and further enhancement of design methods are strongly beneficial in this ongoing process. The developed design method for high accuracy will be demonstrated by the example of the design of a 3-plane mirror used in the metrology loop in combination with laser interferometers. As a result different new approaches of mirror designs are developed and realised as prototypes.

Keywords: design method, virtual prototyping, ultra high precision machines, stage mirror

1 INTRODUCTION
Many applications in nanotechnology, optical and semiconductor industry need multi-axis positioning and measuring machines. These machines have to face growing demands for large moving ranges and accuracy in the nanometre range. They are called ultra high precision machines [17] or nanomeasuring and nanopositioning machines [11]. For them special design methods for high accuracy are needed.

1.1 Ultra high precision machines
Ultra high precision machines have been identified as an enabling tool in the current developments in nanotechnology and other scientific fields (Figure 1). They are needed for positioning as well as for measuring tasks, have to realise multi-coordinate movements and have to meet the most stringent specifications in certain fields of application. Specifications are accuracy, speed of movement, reproducibility and stability all to be maintained in precise positioning over increasingly wide areas. One example is the processing and inspection of lithography masks in the semiconductor industry. There is a need for positioning systems with accuracy in the nanometre range.

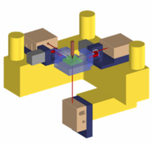
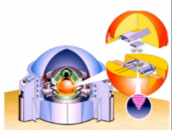
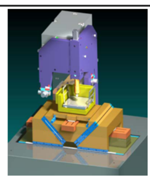
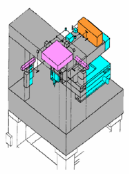
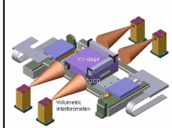
	Ultra high precision machines					
Name	NMM 1	Molecular Measuring Machine	Ultra Precision CMM	UA3P-5	Ultra Precision CMM	...
Design						...
Moving range	25 x 25 x 5 mm³	50 x 50 mm²	100 x 100 x 40 mm³	200 x 200 x 45 mm³	300 x 300 x 300 mm³	...
Designer	TU Ilmenau Germany	NIST USA	TU Eindhoven Netherlands	Panasonic Japan	BUPE Korea	...

Figure 1. State of the art ultra high precision machines [5, 13, 15, 21, 17]

A growing variety of tools are in use to open up fields of application in micro-mechanics, nanotechnology, genetic engineering, metrology and others like confocal microscopy, AFM or STM. Because ultra high precision machines are expensive, ease of adaptability for various applications is required. Thus a whole new generation of machinery with vast flexibility, is coming into existence. The study is focused on ultra high precision machines which are able to measure and position objects in three dimensions. [5, 8, 11, 12, 13, 15, 17, 22]

1.2 Functional components

Especially components of the metrology loop affect and limit the dynamic and precision of the machines (Figure 2). The machines considered here realise three dimensional movements. To fulfil the requirements of accuracy and measuring range a set-up of three fixed laser interferometers and a moving stage mirror with three reflective plane faces is used in most cases. The object is fixed to this mirror and driven relatively to a fixed tool (Figure 2). A metrology frame obtains an invariable position of tool and laser interferometers. Beside the laser interferometers themselves all elements in the measurement loop have to fulfil stringent specifications. Limiting factors for such functional components are stiffness, mass, geometrical tolerances and thermal behaviour as well as long term stability. [11, 12, 19, 22]

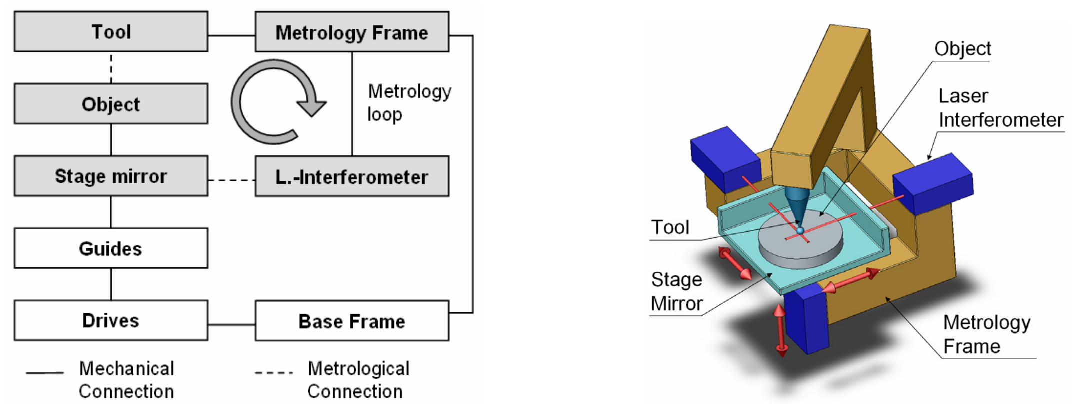


Figure 2. Functional structure (left) and metrology loop and its functional elements (right) (translational movements of the stage mirror are shown as arrows)

The stage mirror is one crucial component (Figure 3). In the examined machine setup it has to be moved so its mass influences the machine dynamic and can not be neglected. Because the object is fixed to the stage mirror all geometric object features (e.g. length, thickness) are measured relative to the mirror faces. Therefore the stage mirror is the measuring reference and has wide influence on the accuracy of the ultra high precision machine. Thus any deformation of the stage mirror and its mirrored faces e.g. caused by forces or temperature changes effect these properties. [19]

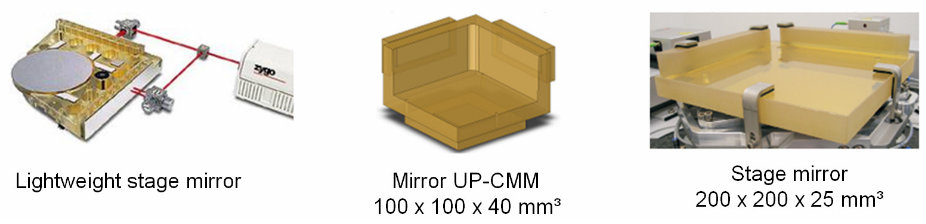


Figure 3. State of the art stage mirrors (left: [23], middle: [17])

State of the art stage mirrors have several disadvantages so improved designs are necessary. They are asymmetric and therefore difficult to mount. Because of their shape and tolerance requirements manufacturing is complex. The moving ranges of the ultra high precision machines are proportional to the dimensions of the stage mirror. Thus for larger moving ranges stage mirrors become heavy weighted (Figure 4). [4, 16]

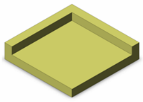
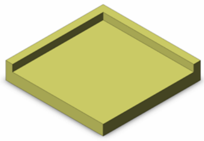
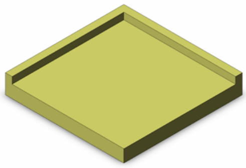
Measurement Range	200 x 200 x 5 mm³	350 x 350 x 5 mm³	450 x 450 x 5 mm³
Dimension of base plate	280 x 280 x 30 mm³	430 x 430 x 46 mm³	530 x 530 x 56 mm³
Mirror Mass	approx. 7 kg	approx. 23 kg	approx. 42 kg
			

Figure 4. Development of stage mirror mass depending on measurement range (monolithic designs with equal length to thickness ratio)

2 OBJECTIVES

Increased requirements in precision and moving range of ultra high precision machines lead to the need of improved overall machine designs and better functional components. With new demands in function and structure of functional components and increasing dependencies between them the common design process has its limitations. The methodology to design functional components of high precision products needs to be further developed.

This research is connected to the development of an ultra high precision positioning and measuring machine with a moving range of 200 x 200 x 25 mm³ (Figure 5). To reach highest measuring accuracy Abbe’s principle should be fulfilled in all measuring axes. As measuring systems three laser interferometers and a stage mirror are applied. [20]

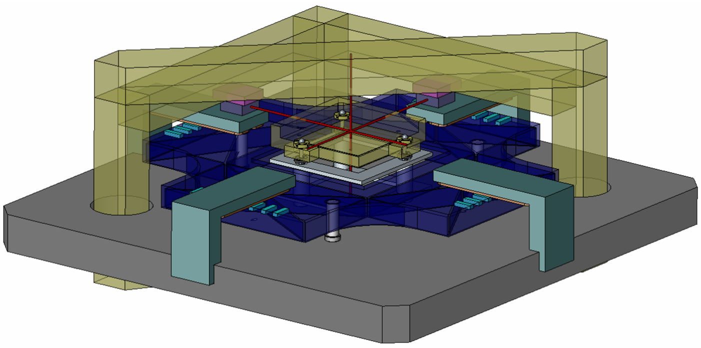


Figure 5. Design of an ultra high precision positioning and measuring machine [20]

Beside other functional elements in ultra high precision machines there is a great demand of advanced mirror and frame design. Therefore the stage mirror is the example on which the method should be applied.

3 METHODS

The design of functional components for ultra high precision machines is based on the overall machine design. Therefore the methods used for the machine design will be briefly described first.

3.1 Machine design

The overall machine design is based on a systematic design approach which consists of four stages (Figure 6). It starts with the detailed specification of the tasks which have to be fulfilled by the ultra high precision machine. [8]

The second step is the analysis of the required technical processes and the given boundary conditions. Therefore all operations which have to be carried out have to be described. It leads to a generalised model that describes the overall function of the machine as well as the interactions with the expected environment.

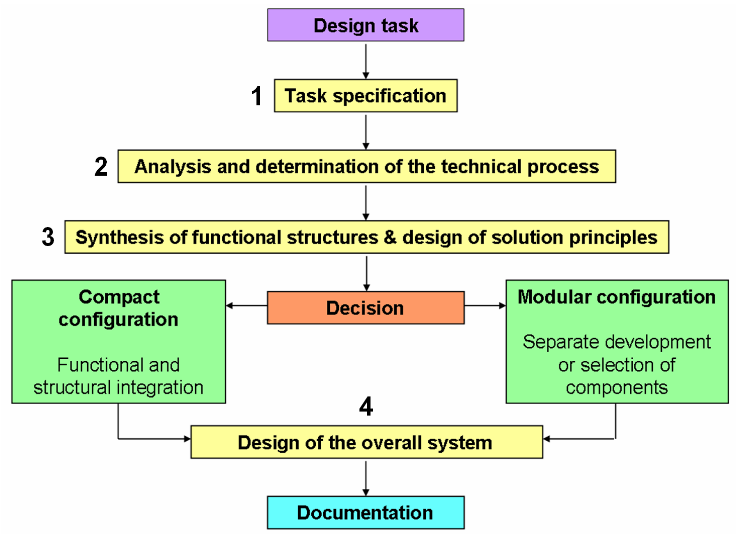


Figure 6. Design process of the machine design for function-oriented configuration [8]

In the third step a general functional structure will be established which is a basis for the whole design. All necessary functions are included and described. It is used as a maximum functional structure (Figure 7) this means it can be reduced if functions are not needed. The functional structure leads to the design of the solution principle. This principle is the base of the whole machine design. Design principles are applied to achieve an optimised design beginning in this early phase of development. [8]

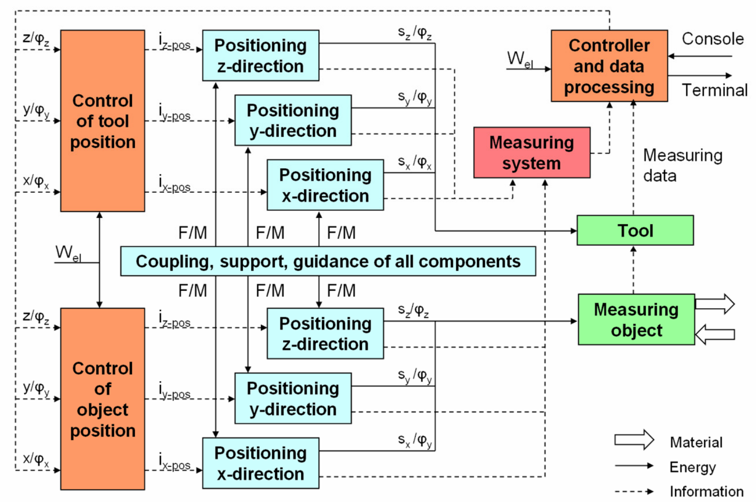


Figure 7. Maximum functional structure of an ultra high precision machine (rotations are used only to adjust errors in translation) [8]

The fourth step is the design of the whole machine. Due to the fact that ultra precision machines are often needed for different purposes a modular design approach based on the maximum functional structure is useful. Different modules can be combined depending on the application which needs to be addressed. Modules can be designed separately in several variants and collected in a configuration matrix. Thus it is possible to reuse existing designs for later on upcoming applications. This step ends with the detail design including all necessary documentations. [8, 9, 10]

If no appropriate components are available in the configuration matrix these components need to be designed or at least need to be adapted to the new requirements. This happens in a separate design process which will be described next.

3.2 Component design

Functional components like stage mirrors or metrology frames typically consist only of one or a few parts. Nevertheless there are also functional components like guides which consist of much more parts.

The design of functional components is based on an iterative five stage process (Table 1) and starts after the selection of appropriate modules in the machine design process. Every step can be repeated if its results or results of following steps are not sufficient. The designer should follow this process to identify new solution variants and to have the opportunity to evaluate and compare the properties of these variants as early as possible. Thus also complex functional components can be developed in a systematic manner.

Table 1. Stages of component design

Stages	Design steps	Results
1. Specification of requirements	• Clarification of requirements • Examination of error budget • Examination of dynamic influence	List of requirements
2. Development of solution variants	• Development of functional structure, solution principle and if needed preliminary embodiment designs • Development of solution variants	Different solution variants
3. Selection of solution variants	• Definition of quantitative criteria for comparisons • Development and simulation of virtual prototypes based on solution variants • Comparison and selection of solution variants	Compared solution variants Optimal solution variant
4. Optimisation of the embodiment design	• Development and optimisation of embodiment design of the optimal solution variant	Optimised embodiment design
5. Detail design	• Development of detail design and documentation	Documented detail design

3.2.1 Specification of requirements

At first the requirements of the functional component have to be clarified. This step is based on the requirement definition for the whole machine. The different requirements of the machine need to be adapted to define the necessary properties, functions and structures of the component. It is important to examine the error budget of the component and its influence to the dynamic behaviour of the whole machine. The result is a detailed list of requirements which is the base for the next steps.

3.2.2 Development of solution variants

Functional structures and evaluation and selection based methods can be used to find solutions. But iterative methods for varying parameters of the principle or preliminary embodiment design can be used more efficiently in the second step. Especially the variation of size, shape, position, number and kind of structural elements of the component or the component itself is of interest.

In this step design principles need to be considered [18, 19]. These principles are fundamental possibilities of structuring technical components and their elements. They are given by the internal context and modification possibilities of the elements themselves. The aim is to find, adapt and improve the structure to realise the function as best as possible. Therefore they should be applied beginning in this early phase of the design process. Design principles which are of interest in the given case are:

- lightweight design,
- short and closed force loop,
- short and closed metrology loop,
- function separation,
- functional material at functional place,
- symmetric design.

Nevertheless it is also important to consider different materials for example with the selection method of Ashby [1]. Materials offer a great potential for new solutions and in this step the design can be adapted to them easily. But typically first solutions will be realised as principle designs. Thus consequences of different materials can not be compared because there is for example no volume. Therefore principle design solutions need to be further developed to preliminary embodiment designs in this step. As result different comparable variants are developed.

3.2.3 Selection of variants
The third step is characterised by the review and the selection of variants which are preferable. Therefore criteria for quantitative design are used. To review different variants it is important to calculate their properties as best as possible. Important properties of functional components for ultra high precision machines are mass, mechanical stability and especially deformation caused by different conditions (temperature changes, vibrations, loads).

Not all variants have obvious advantages or disadvantages and most properties cannot be examined by comparing designs without any tests. Therefore prototypes are needed but physical prototypes are expensive and need complex and time intensive tests. Thus methods of virtual prototyping like Finite Element Analysis are used offering precise and comparable statements with less effort to select the optimal variant. [2, 6, 7]

With virtual prototyping iterative methods of varying parameters are also useable all over the design process including embodiment and detail design. Therefore rebounds to the earlier step of solution development are reasonable and possible. The decisions to be taken are about starting point and length of rebounds, evaluation of obviousness to continue an iterative cycle as well as to manage results for comparisons. The design process has no obvious hard exit condition but with limiting parameters of the demanded function and by comparing the properties of the different solutions with the given requirements it is possible to finish this process successfully.

3.2.4 Optimisation of the embodiment design
In the fourth step further work is necessary to optimise the embodiment design of the chosen variant. This variant was the optimal one in the last step but it offers still different approaches for optimisation. Here the method of virtual prototyping is useful too. The optimisation of the design is focused on reduction of mass and improvement of manufacturing. Especially topology and shape optimisation can be used for this purpose. Thus it is possible to find designs which are not biased by the experience of the user but optimal for the given boundary conditions.

3.2.5 Detail design
The last step is the detail design of the functional component with all needed documentation. The developed component can be used as a module of the whole machine and stored in the configuration matrix if needed.

4 STAGE MIRROR DESIGN
In the following different examples of stage mirrors are described which were developed using the described five stage process of component design.

4.1 Optimisation of an existing design
An existing stage mirror design for a measuring volume of 200 x 200 x 25 mm³ is used as a starting point. It is mounted well constrained on three supporting points. These points are placed in the corners of the mirrors base. As a result there is a strong deformation of the used reflective faces is large. Another disadvantage of the existing design is the huge mass of the mirror. Thus this design needs to be improved to meet the expected properties of small deformation, high stiffness, lightweight and stable kinematic coupling.

For the given example it is important to optimise the position of the supporting points. The aim is to minimise the mirror deformation under gravity. Because the material of the mirror is a glass-ceramic only little stress is allowed. Therefore different variants with different shapes are developed (Figure 8).

These variants are realised as virtual prototypes to simulate the mirror properties. The best variant is selected and needs further optimisation. To solve this problem a parametric CAD-model is generated to change the position of the supporting points easily by few parameters. The supporting points themselves are modelled as a contact area to comply with the real system as best as possible. In an automatic loop different positions are calculated and their stress and deformation values compared. Thus the optimum design is found very fast.

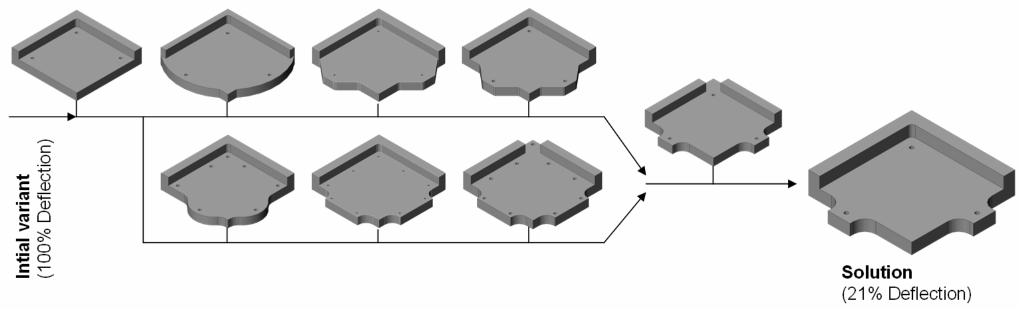


Figure 8. Variation of the supporting points (shape, count, position) of a stage mirror

In the second step the mass of the stage mirror needs be reduced. Holes and combs are used to reduce the mass. Different variants are developed and simulated for this purpose (Figure 9). As result the design of the stage mirror can be optimised by reducing the weight down to 45%. Force paths are also considered. They are very important to realise the necessary mechanical stiffness while reducing the mass with the aim to find an optimal ratio between mass and stiffness. To avoid over constraints a kinematic fixture consisting of three supporting points with V-groove and ball couplings have been used. An additional loop is then performed to review the existing design and to adept the supporting point position if necessary.

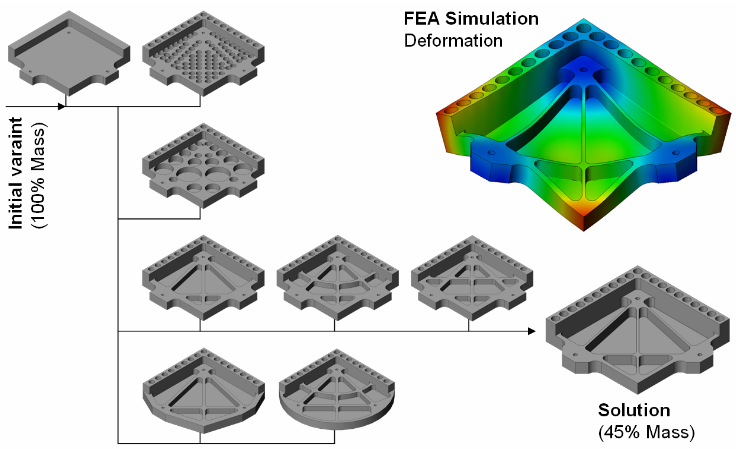


Figure 9. Variation of holes to minimise mass and optimise force paths of a stage mirror

A new stage mirror is realised based on the described analysis. It is used in a test device for ultra precision vertical movement. Because of its improved design the dynamic behaviour of the whole device is improved too.

4.2 Material driven design

Further improvements of stage mirror design are needed to enable larger measuring volumes and moderate weight. This can be realised by function separation and function material at function place. One approach is the choice and combination of suitable materials for such a stage mirror. In order to reach low weight and high stiffness a material with a large ratio of Young's modulus to density is required. Furthermore the ratio of the coefficient of thermal expansion to thermal conductivity should be low as well to address thermal influences. Using the method of material selection mentioned by Ashby different materials become interesting (Figure 10). [1]

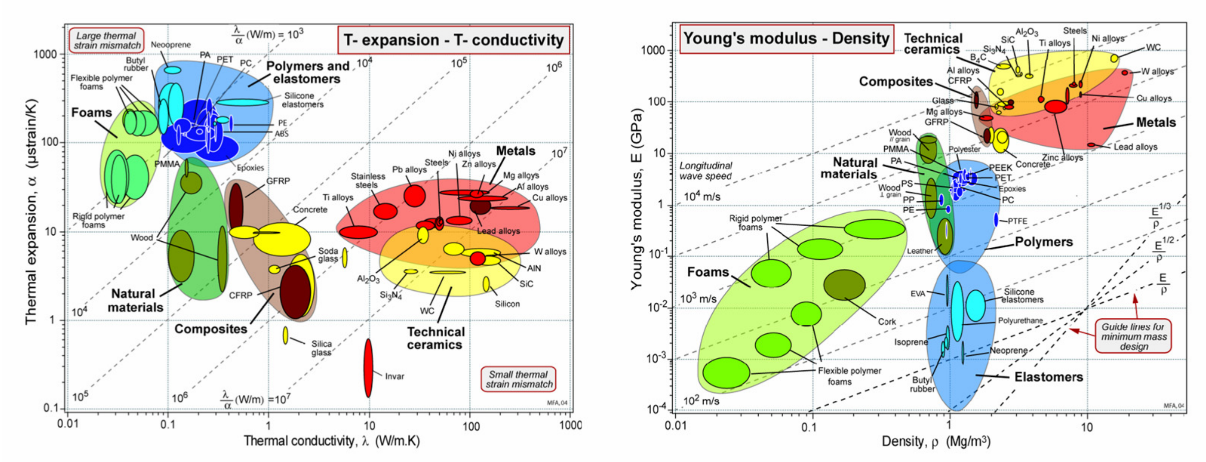


Figure 10. Ashby charts of materials [1]
(left: thermal expansion over thermal conductivity, right: Young's modulus over density)

Besides Zerodur® as a standard material for measurement and telescope mirrors silicon is well suited because of its extraordinary mechanical properties and its excellent thermal conductivity [3]. Nevertheless the coefficient of thermal expansion is two orders of magnitude worse than Zerodur®. Because of the excellent thermal conductivity the expected temperature gradients in a mirror made of silicon are small. So the thermal expansion may be derived from a temperature measurement. With this approach it is also possible to add more functionality to a stage mirror, e.g. integrated temperature sensors can be used for a dynamic online shape correction. Also active shape compensation would be possible.

Because of the relative high coefficient of thermal expansion it is not useful to build a monolithic measurement mirror from silicon. But with a combination of a base frame, which is made of Zerodur® and mirrors made of silicon the advantages of both materials can be used (Figure 11). The base frame realises a stable position of the silicon mirrors relative to one another. One possible design is based on the idea to connect the silicon mirrors at its centre on a temperature stable Zerodur® frame to avoid deformation due to different coefficients of thermal expansion. It is also necessary to support the base frame at three points. Therefore several variants of the base frame, which has to hold the three mirrors and the three supporting points, need to be developed and tested using methods of virtual prototyping.

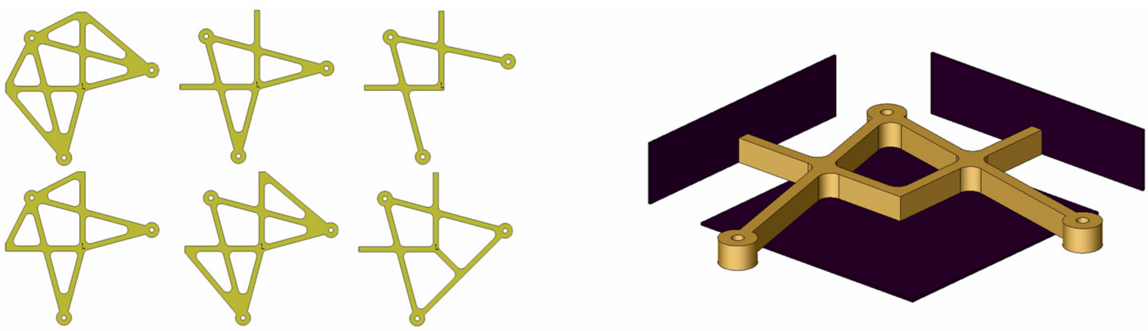


Figure 11. Frame variants and embodiment design of a lightweight stage mirror using different materials

It is necessary to connect silicon and Zerodur® in a proper way. Because of the different coefficient of thermal expansion of both materials deformation of the silicon mirror due to temperature changes occurs. This deformation can be minimised with optimal contact geometry of both components. Therefore different variants are developed using the described design method (Figure 12). Examinations have been carried out using the Finite Elements Analysis. As a result it is shown that the deformation of direct joining can be reduced down to approximately 1% by introducing an intermediate body of silicon.

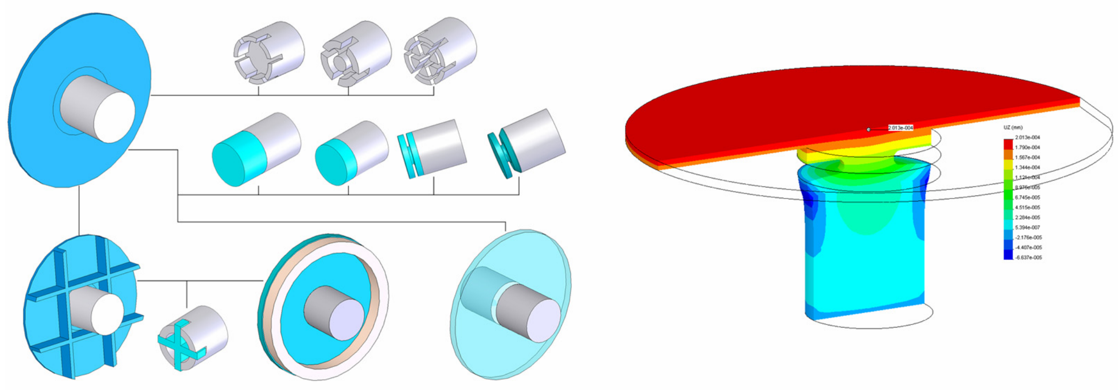


Figure 12. Variants of contact geometry (left) and FEA of one variant with minimised deformation (right: resulting deformation is shown)

Different physical prototypes to test the contact geometry are realised. Tests at different temperatures show good correlation between the simulated and measured behaviour. Ongoing work is focused on the realisation of a stage mirror consisting of the two materials Zerodur® and silicon.

4.3 Tetrahedron design

Existing stage mirror designs are asymmetric. Therefore deformations trough its own mass and the object load lead to asymmetric bending of the mirror faces. The supporting points have unequal loads. Thus it is difficult to mount the mirror because it tends to tilt. The driving forces of the vertical drive system are different for each supporting point. Another problem is that the objects to be measured or positioned are laterally limited by the vertical mirror faces of the horizontal axes. For these reasons a completely new design approach for measuring mirrors of ultra high precision machines is necessary.

The design of known measuring mirrors is characterised by plane reflective faces which are perpendicular to the moving and measuring directions. The mirrors themselves are rectangular to each other defining a Cartesian coordinate system. A completely new design can be realised by changing the position of the interferometers and mirrors relative to the Cartesian moving directions (Figure 13). By rotating them relatively to the coordinate system of the moving directions the Cartesian coordinate systems still exist but the resulting geometry of the mirror can be reduced to a tetrahedron.

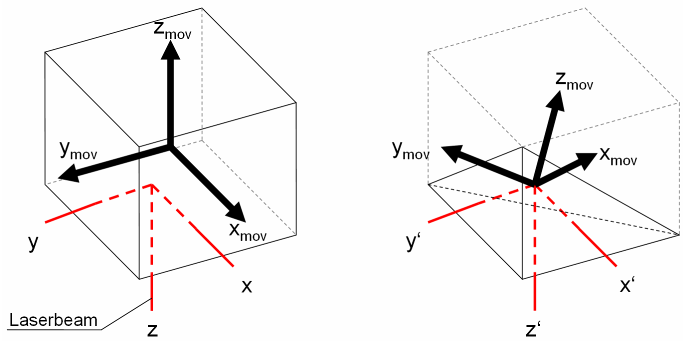


Figure 13. Alignment of moving directions relative to the mirror surfaces and laser beams (left: known mirror design, right: tetrahedron mirror design)

The resulting measuring mirror is axial symmetric to the vertical axis (Figure 14). All of its reflective faces have equal shapes. If the supporting points are situated at the corners of the tetrahedron's base all have equal loads. Thus the resulting deformations of the mirror faces through gravity are symmetric. The laser beams intersect in one point, the so called Abbe-point, above the tetrahedron's base. Through this arrangement the comparator principle can be fulfilled for all three measuring axes. The object to be measured or positioned is laterally not limited. Now it is possible to measure objects with larger dimensions than the mirror. The calculated mirror body is much bigger than necessary. But it is possible and useful to remove the edges of the tetrahedron to reduce its volume. Therefore the mirror mass can also be reduced. This can be taken further if the mirror has a hole in its centre. Thus it is also possible to measure objects using backlight.

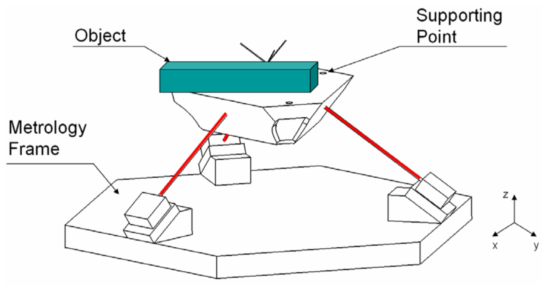


Figure 14. Design of the metrology loop using the tetrahedron stage mirror (consisting of metrology frame, laser interferometers, stage mirror and object)

Tetrahedron mirrors can be manufactured like common mirrors e.g. made of glass-ceramics using the same machining processes. Through the new design the mirror faces are larger but have the equal size and shape. Thus the mirror is heavier than common mirrors. Therefore ways to further reduce the mass are needed. Three different approaches of the realisation of the mirror are shown in Figure 15.

One way is to manufacture the mirror monolithic. For this purpose it is imaginable to machine a cubic element down to a tetrahedron. A disadvantage is the size of the original part. Because of this the mirror should be machined beginning with a smaller element. Here the challenge is the machining of the mirror faces under the given angle. Nevertheless this design is interesting because applications using transmitted light are possible now. These applications are useful especially for optical measurement setups.

Another approach of manufacturing is the application of prismatic parts which connect special mirror faces. Here the design principles of function separation and functional material at functional spot are used. A thermal stiff frame holds special mirror plates. The prismatic frame parts and the flat mirror plates are less complex in high precision machining. Nevertheless one small tetrahedron part is necessary. All parts need to be connected for example by bonding. Thus several connections exist which can effect the dynamic as well the measurement behaviour.

The third approach consists of a plate made of thermal stiff material which holds three mirror plates. This design uses also the mentioned design principles and is light but less stiff. Also the manufacturing of the necessary connection surfaces and their angles is complex. The necessary angles of the mirror faces need to be manufactured directly on the plate. The connection between the parts can be realised by bonding. Compared to the others design variants it is less stiff but has also fewer connections.

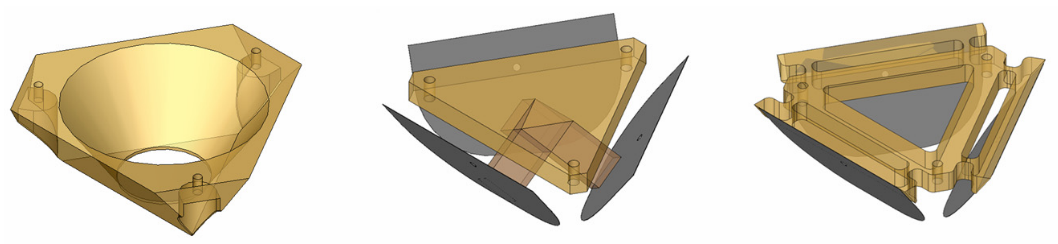


Figure 15. Design variants of a tetrahedron stage mirror (left: monolithic design, middle: prismatic frame, right: planar frame)

For all design steps and approaches different variants are developed. These variants are compared under the use of FEA. As result it can be shown that the resulting deformations of the mirror through gravity are symmetric and small for all mirror surfaces. This is a big advantage in comparison to the existing mirrors. Also the twisting of the mirror surfaces is much smaller. The overall stiffness is higher and all supporting points have the same load. Further more with this method design variants of mass reduction are simulated and their advantages and disadvantages compared. Based on this research a first simplified prototype consisting of metal plates made of Invar® is realised (Figure 16).

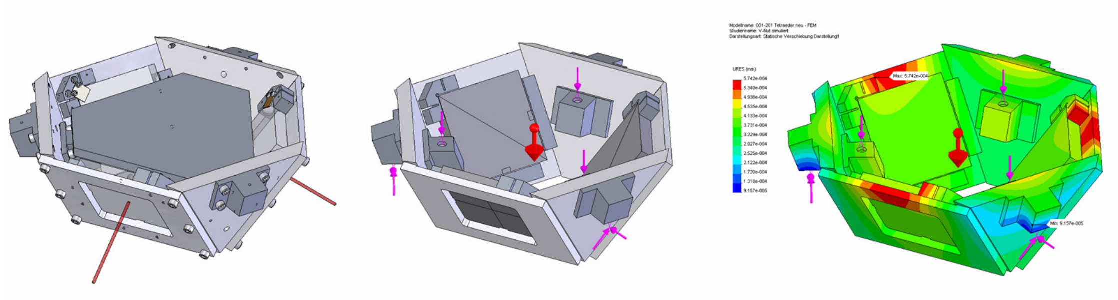


Figure 16. Design of the prototype tetrahedron stage mirror, FEA model and simulation (left: CAD model, middle: FEA model with boundary conditions, right: deformations)

5 RESULTS

The paper presents an approach to design functional components of ultra high precision machines. By using this method novel designs of a stage mirror are developed based on the development of an ultra high precision positioning and measuring machine. One design of a tetrahedron mirror is patented and is realised as a physical prototype. A second design leads to a new material combination whose test is in progress.

6 CONCLUSIONS

The design of functional components for ultra high precision machines needs special approaches to find optimal solutions. The basic concept is to extensively use methods of variation in early phases of the design process to generate a variety of solutions target oriented and to review and compare these variants by using methods of virtual prototyping in an iterative process. Therefore it is necessary to realise these variants as embodiment designs. Iteration loops between different steps of the design process are needed to vary existing solutions and find new ones. Virtual prototyping is used to determine properties of the developed variants. This leads to precise and comparable statements. These statements are used as exit criteria of the iteration loop. At every loop a comparison between the desired and the reached properties and the decision if the difference is acceptable is necessary. Virtual prototyping is also used to optimize the selected variant.

Virtual Prototyping is useful and necessary especially for crucial machine components which are often very complex and expensive. They can be tested in early design phases without physical prototypes. Therefore results of the simulations and knowledge of the future behaviour can be integrated in the whole system design earlier. The aim is to make take decisions on the optimum design in early phases of design. Later on physical prototypes are still necessary to evaluate the simulated properties. But the number of physical tests can be minimised and also better prepared.

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