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M. Lotz / G. Höhne

Design guideline for stage mirrors of ultra high precision measuring and positioning machines

Abstract

Applications of nanotechnology, optical and semiconductor industry need multi-axis positioning and measuring machines [8]. These machines are necessary to measure object properties like shape or dimensions with highest precision. For this purpose the object is moved relatively to a tool in two or three dimensions. Typical objects are lenses, mirrors or wafers as well as biological material. Thus these machines have to face demands for variability, large moving ranges, good dynamic behavior and accuracy in nanometer range. They are ultra high precision machines [4, 10]. Limiting factors for such machines are stiffness, mass and thermal as well as long term stability [12]. Functional components especially of the measuring circuit affect and limit dynamic and precision of the machines. Main elements of this circuit are measuring unit, object and tool. The position and orientation of the attached elements need to be ensured for example by a frame. Many common machines use three dimensional measuring systems with stationary laser interferometers and a moving stage mirror. The object is aligned to the mirror and relatively driven to the tool. Therefore a frame obtains an invariable position of tool and laser interferometers. In the described setup the stage mirror is moved, carries the object, reflects the laser beams and defines the measuring coordinate system. Thus it is the functional component of great interest because it influences dynamic and accuracy of the machine. State of the art stage mirrors have different disadvantages so improved designs are necessary.

The paper presents a guideline to design stage mirrors of ultra high precision measuring and positioning machines. It supports engineers during the design of these stage mirrors by describing a methodical procedure [6] and its application.

Using this guideline different stage mirrors were developed. Its successful application is demonstrated on three different stage mirror designs [9] and begins in the phase of task determination and leads up to the final technological realization. The guideline is structured as follows.

Method

Functional components like stage mirrors consist only of one or a few parts. Their design can be based on an iterative five stage process (Table 1). Thus it is possible to repeat every step 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.

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. Optimization of the embodiment design	Development, dimensioning and optimization of embodiment design based on the optimal solution variant	Optimized embodiment design
5. Detail design	Development of detail design and documentation	Documented detail design

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 behavior of the whole machine. The result is a *function plan* (Figure 1) with all input and output parameters including their admissible deviations, a *requirement chart* (Figure 2) representing layout conditions as well as connecting dimensions to the overall setup and a detailed *list of requirements* which are the base for the next steps.

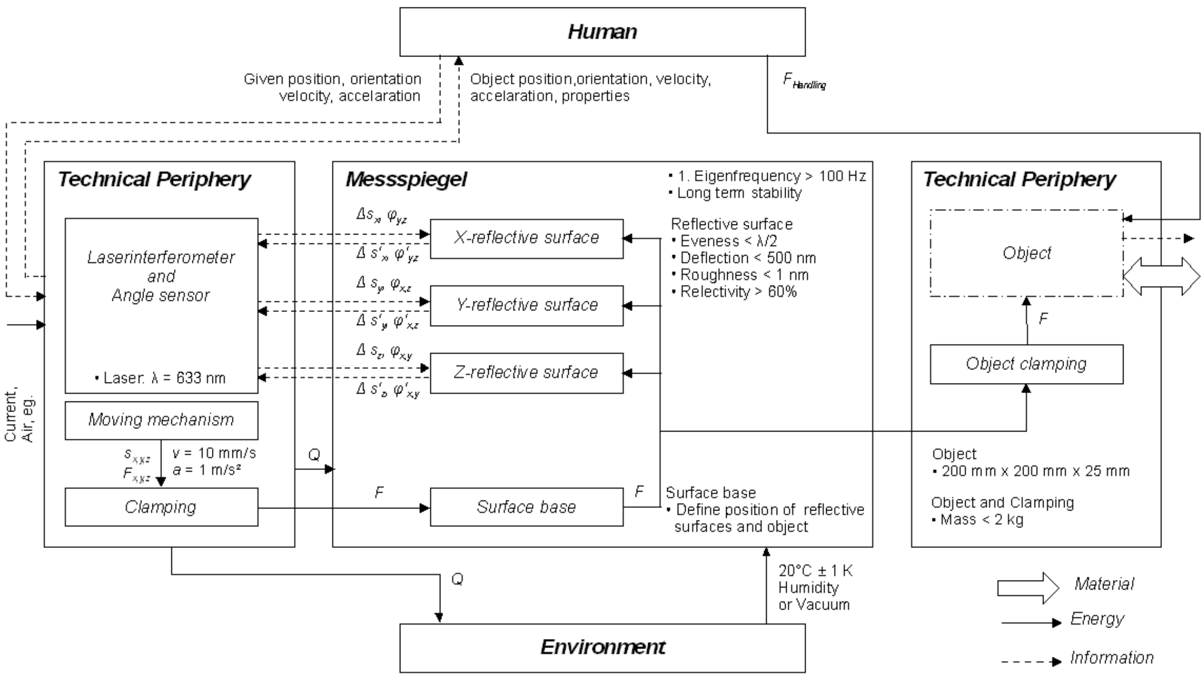


Figure 1. Function plan of a high precision measuring machine using laser interferometers and a stage mirror for measuring the position of an object in three dimensions

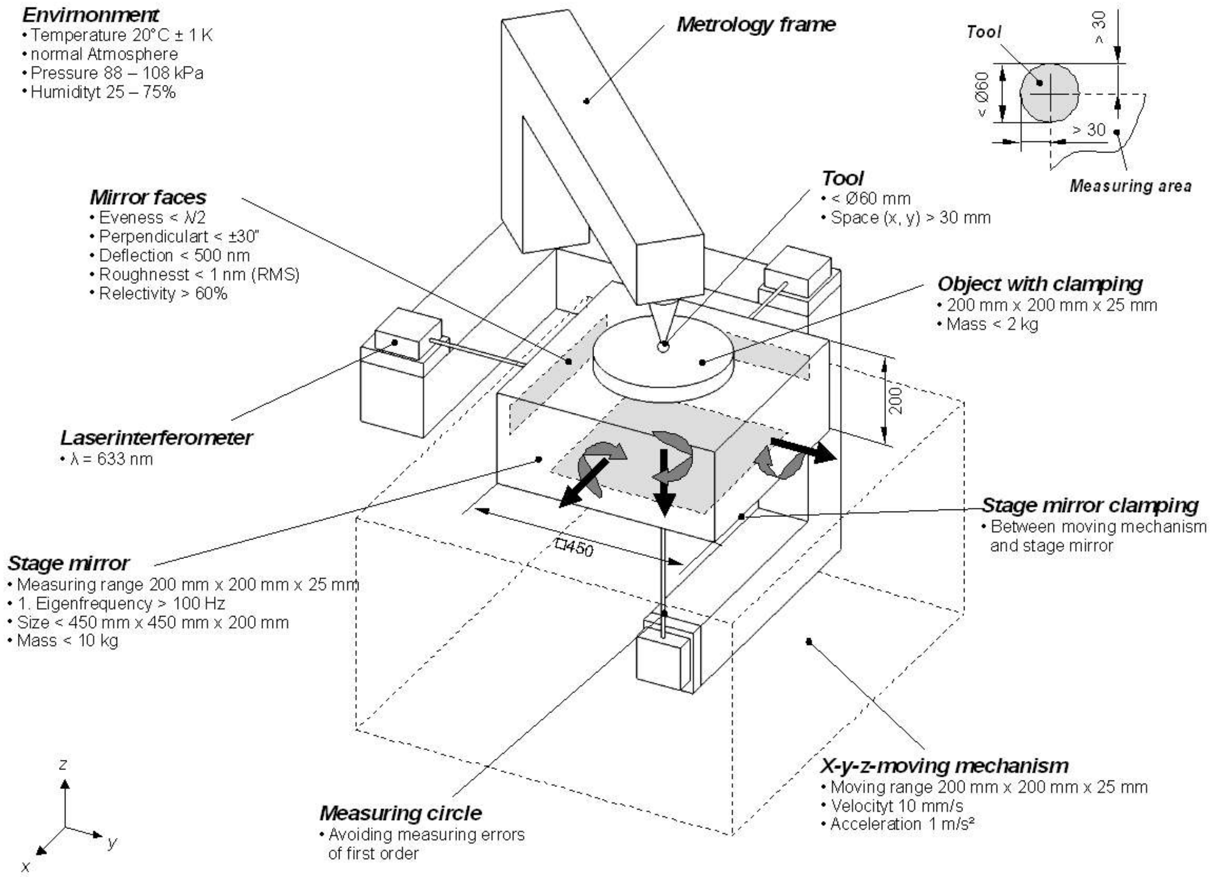


Figure 2. Requirement chart of a high precision measuring machine using laser interferometers and a stage mirror for measuring the position of an object in three dimensions

Development of solution variants

Functional structures evaluation and selection based methods can be used to find solutions. But iterative methods for varying parameters of the solution 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. Table 2 shows representative characteristics of stage mirrors and their differing variants. Combining these variants leads to different solution principles. These design alternatives need to be evaluated and the best one selected and further detailed. To compare solutions it is necessary to define criteria and to weight them depending on the given task.

Table 2. Morphological chart of stage mirrors

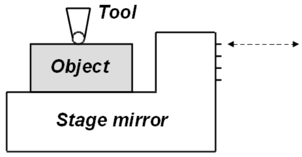
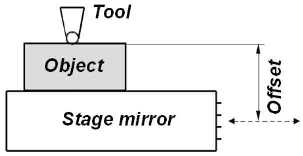
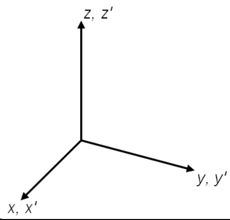
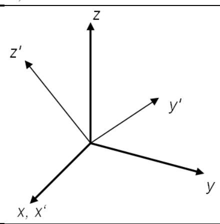
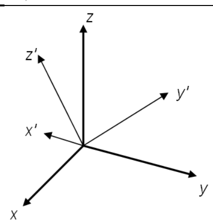
Characteristics	Variants	
1) position of reflecting surfaces to object and probing point	1.1) without offset	
	1.2) with offset	
2) position of reflecting surfaces to object coordinate system (angle between reflective face and coordinate)	2.1) 90°	
	2.2) 90° and unequal to 90°	
	2.3) unequal 90°	
3) number of reflecting surfaces	3.1) three	
	3.2) more than three	
4) size of reflecting surfaces	4.1) larger moving range	
	4.2) smaller moving range	

Figure 3 shows different design variants which result from the morphological chart shown in Table 2. Only two characteristics were diversified and lead to six possible solutions. The shape of the stage mirrors is influenced by these two characteristics very strong. Thus the designs of the stage mirror are very different. Variants V1 and V2 are designs which can be found in current high precision measuring and positioning machines. They use a plate with additional reflective faces on the side or on top of this plate. By contrast the other variants have shapes like prisms or tetrahedrons. They are a result of the variation of the position of the reflective surfaces to the object coordinate system. Thereby new designs were realized which are not used in existing high precision machines. Thus all variants need to be compared to find an optimal solution. Possible criteria are mass, size, stiffness and resulting measuring accuracy.

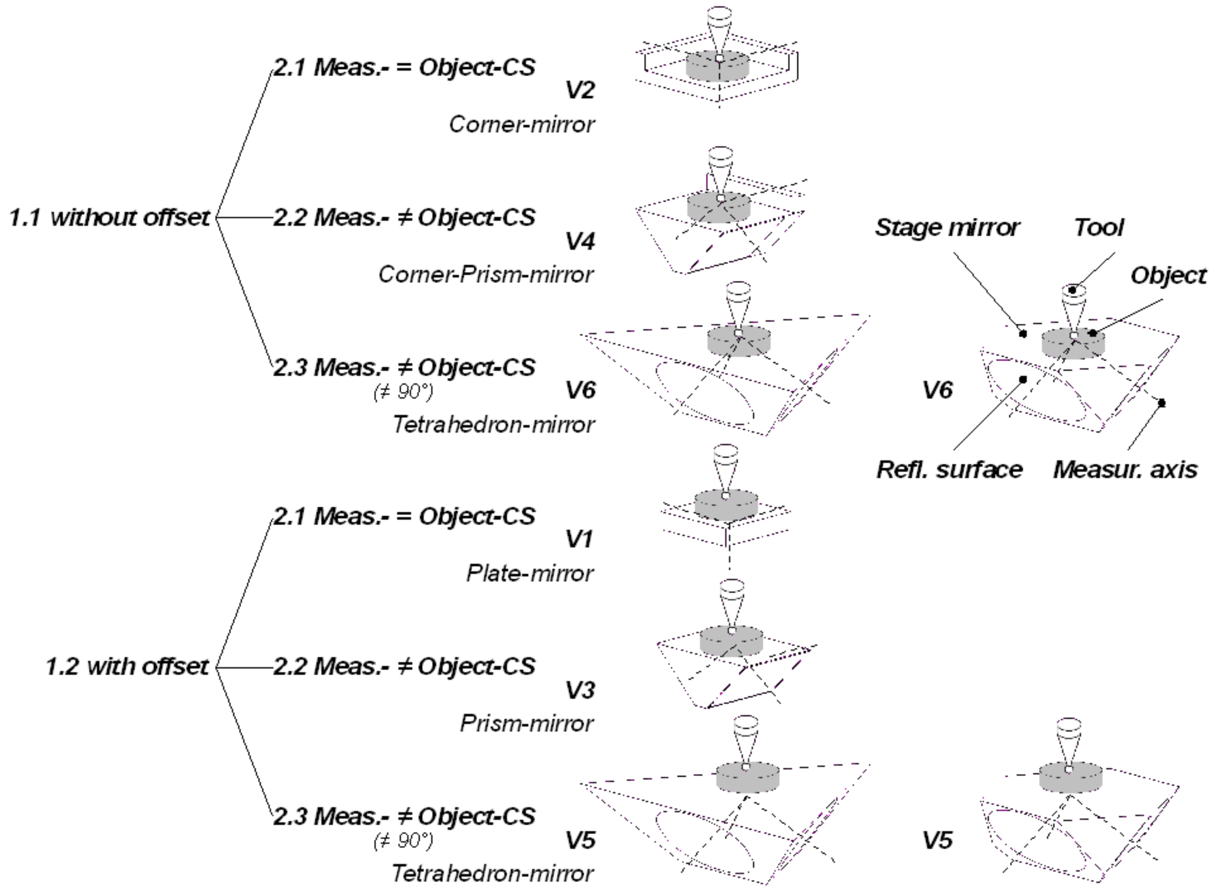


Figure 3. Variants of stage mirror designs (compare to Table 2)

Not all criteria can be used in this design phase because there are not enough information. For example stiffness depends on materials and detail design therefore it is only possible to make estimations. Design principles need to be considered in this step to improve and also compare solutions [19, 22]. These principles are fundamental possibilities of structuring technical components and their alignment. 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 realize the function as best as possible. Therefore they should be applied beginning in this early phase of the design process. But they can be also used to compare solutions. For example good solutions fulfill several design principles often.

Nevertheless it is also important to consider adequate materials for example using 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 realized 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.

Selection of variants

The third step is characterized by the review and the selection of variants which are preferable. Therefore criteria for quantitative design are used. To review the developed 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 ambient conditions (temperature changes, vibrations, loads).

Not all variants have obvious advantages or disadvantages and most properties cannot be examined without tests. Therefore physical prototypes are needed which are expensive and require complex and time intensive tests. Thus methods of virtual prototyping like Finite Element Analysis are used offering precise and comparable results with less effort to select the optimal variant. [2, 8, 9]

In connection with virtual prototyping iterative methods of varying parameters are also usable 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.

Optimization of the embodiment design

In the fourth step further work is necessary to optimize the embodiment design of the chosen variant. This variant was the optimal one in the last step but it offers still different approaches for optimization. Here the method of virtual prototyping is useful too. The optimization of the design is focused on reduction of mass and improvement of manufacturing. Especially topology and shape optimization 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.

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.

Design Principles

Design principles are a preferred approach to support the review of concepts and the transfer to embodiment designs. Especially functional components with great influence to the desired function like stage mirrors should be designed using design principles. Important design principles are shown in Table 3.

Principle of Symmetry

Existing stage mirror designs are asymmetric. Therefore deformations by 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 stage mirrors of ultra high precision machines is necessary.

Table 3. Design Principles [11, 13, 14, 16, 17, 19, 21]

Design principles	**Explanation**
Principles of function	
Function separation	Independent structure realizes sub-function
Function integration	Structure realizes several different sub-functions
Principles of structure	
Structure separation	Structure is separated in several different elements
Structure integration	Several structures are integrated into one
Principles of material	
Functional material at function spot	Material of elements is selected to meet (mechanical, electrical, e.g.) requirements as best as possible for the given function
Principles of couplings	
Avoiding over constraints	Usage of well constraint couplings
Principles of small errors	
Error minimization	Minimizing error influence coefficients
Innocence	Function variable is influenced by disturbance variable of second order or higher
Invariant	Function variable does independent of disturbance variable
Compensation	Inadmissible deviations are eliminated using opposed parameters
Principles of self support	
Self balance	Supporting effect of auxiliary values to fulfill main function
Self intensify	Usage of a changing value to increase main function
Self protection	Additional force branch by overload
Principles of Force flow	
Direct and short force flow	Shortest and direct path to transmit forces and torques
Equal figure strength	Equal utilization of strength
Balanced deformations	Connection of parts is realized with no relative deformation between them
Force balance	Force / torque caused closed by short ways
Defined force branching	Branching of forces realized by static principle
Principles of Stability / Bi-Stability	
Stability	Disturbances cause reducing effect
Bi-stability	End state leads to different state or position
Principle of Symmetry	
Symmetry	Optimization of design depending on external/ environmental influences

The design of known stage mirrors is characterized 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 realized by changing the position of the interferometers and mirrors relative to the Cartesian moving directions (Figure 4). 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.

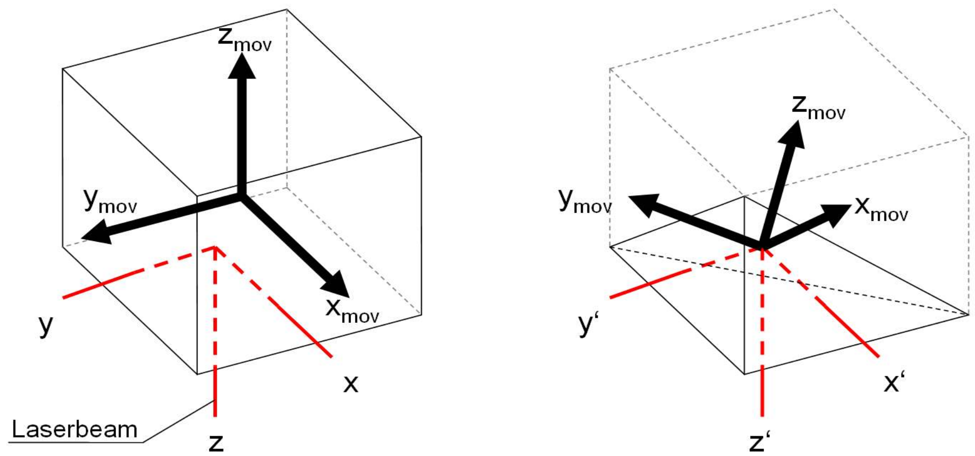


Figure 4. Alignment of moving directions relative to the mirror surfaces and laser beams (left: known mirror design, right: tetrahedron mirror design)

The resulting stage mirror is axial symmetric to the vertical axis (Figure 5). 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. This arrangement fulfills the comparator principle 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 and also its mass. This can be taken further if the mirror has a hole in its center which enables measurements under transmitted light.

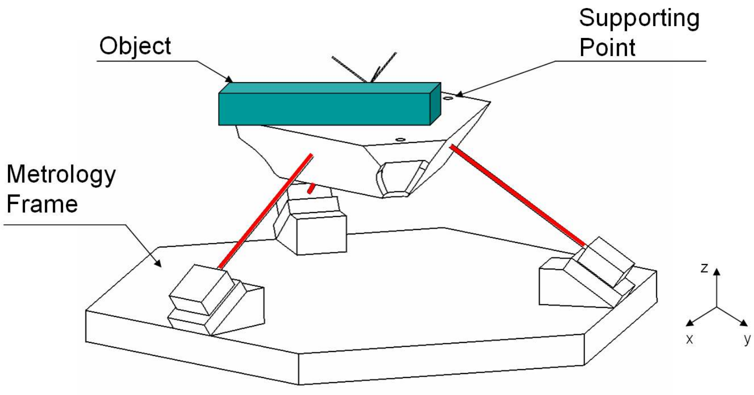


Figure 5. Design of metrology loop using tetrahedron stage mirror (consisting of metrology frame, laser interferometers, stage mirror and object)

Tetrahedron mirrors can be manufactured like common mirrors e.g. made of glass-ceramics using the same machining processes. The new design requires larger mirror faces but has 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 realization of the mirror are shown in Figure 6.

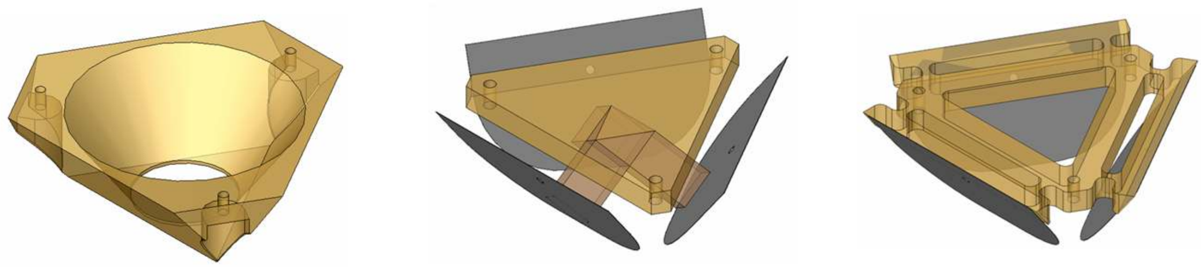


Figure 6. Design variants of a tetrahedron stage mirror (left: monolithic design, middle: prismatic frame, right: planar frame)

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 behavior.

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 realized by bonding. Compared to the others design variants it is less stiff but has also fewer connections.

Principles of Force Flow

The stiffness of stage mirror against deformation needs to be maximized to fulfill dynamic constraints. Therefore lightweight is one approach. But to realize a lightweight structure it is necessary to apply principles of force flow.

There are the following possibilities to reduce weight:

- material lightweight design – substitution of specific heavy materials through light and/or high-strength materials,
- condition lightweight design – reduction of constraints and requirements,
- shape and structural lightweight design – realizing of load and shape optimized structures.

The technology of light weight design can be divided into further lightweight construction (Figure 7). They are being defined depending on manufacturing, joining and material:

- differential construction – different parts are selective connected,
- integral construction – minimizing of separate parts (monolithic structure),
- integrating construction – organic unit of several stiff connected parts,
- composite construction – different materials are combined because of their specific properties.

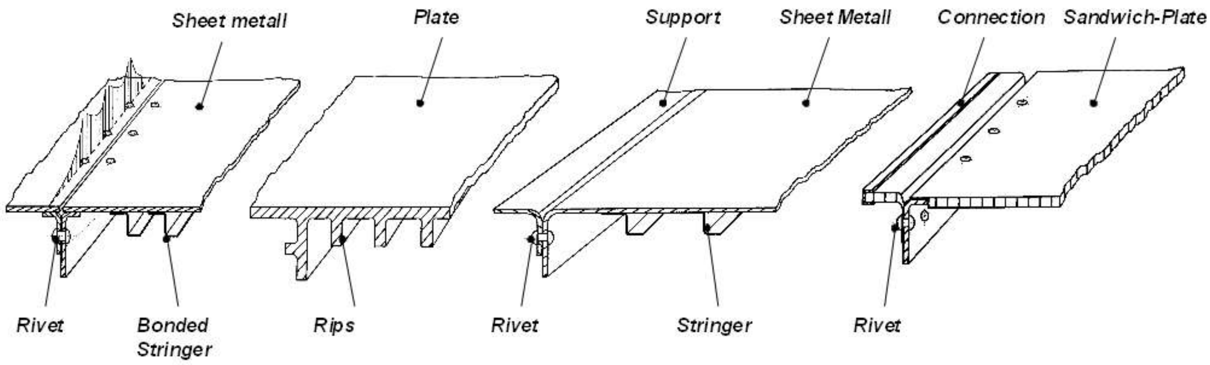


Figure 7. Technology of light weight design [12]

Lightweight structures can be compared by their efficiency. In this context efficiency is defined as relation between mass of a stage mirror and its deflection under self weight. Mirrors with sandwich structure have the highest efficiency. They can be realized by combining a honey comb structure with a top and a base plate. Also possible are drilling holes through not needed sides of the mirror (Figure 8). Nevertheless open back mirrors are very common because they can be manufactured easier and their thermal behavior is better because of their open design.

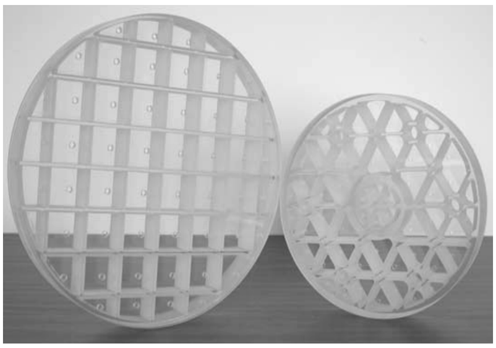
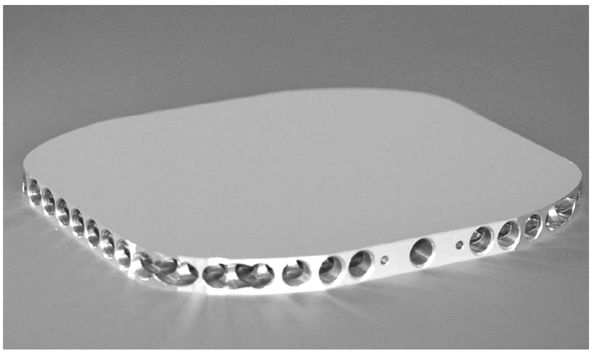
a)  b) 

Figure 8. Light weight design with sandwich structures a) joining of several parts [3], b) monolithic [5]

The application of lightweight design and principles of force flow can be seen on an existing corner mirror (variant V2 in Figure 3) for a measuring volume of 200 x 200 x 25 mm³ which was used as a starting point for optimizing. 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. 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 optimize the position of the supporting points. The aim is to minimize the mirror deformation under gravity. Because the material of the mirror is a glass-ceramic only little stress is allowed. Therefore variants with different shapes are developed (Figure 9). These variants are realized as virtual prototypes to simulate the mirror properties. The best variant is selected and needs further optimization. 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 modeled 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.

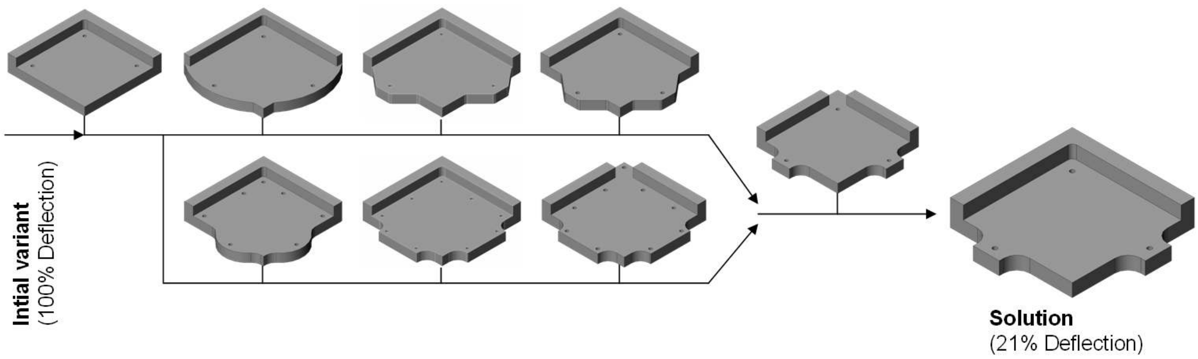


Figure 9. Variation of the supporting points (shape, count, position) of a stage mirror

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 10). As result the design of the stage mirror can be optimized by reducing the weight down to 45%. Force paths are also considered. They are very important to realize 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.

A new stage mirror is realized based on the described analysis. It is used in a test device for ultra precision vertical movement. Because of its improved design the dynamic behavior of the whole device is improved too [15].

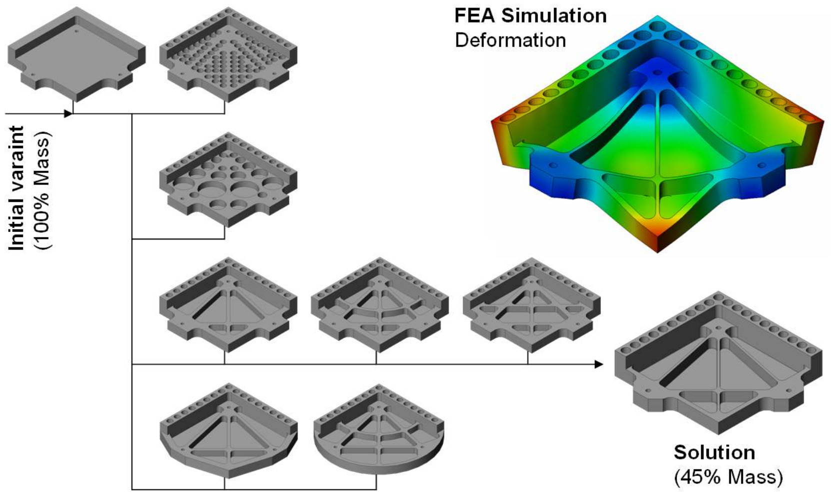


Figure 10. Variation of holes to minimize mass and optimize force paths of a stage mirror

Material Selection

Materials have great influence on functional properties like thermal stability and stiffness. Because of this the fourth part of the design guideline describes an approach to select materials for stage mirrors by formulating criteria and comparing materials using these criteria [1].

Further improvements of stage mirror design are needed to enable larger measuring volumes and moderate weight. This can be realized by function separation and function material at function place. One approach is the choice and combination of suitable materials for such a stage mirror (Table 4). 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.

The diagram Figure 11 shows the relation between specific stiffness and deformation caused by transient heat for typical materials used for mirrors. Both characteristic values are of great interest because with them it is possible to compare mechanical as well as thermal properties of materials. An optimal material should maximize both values.

Especially ceramics of SiC can fulfill the requirement. They have a high specific stiffness but deform under heat less. Thus they are preferable for high dynamic applications.

Table 4. Application conditions, requirements and needed material properties

Application conditions	**Requirements to the stage mirror**	**Needed material properties**
Mirror plane is used as reflector for optical distance and angle measurement	• Longterm stability of geometry	• isotrope homogene material • material does not change its structure
	• Mirror plane is polishable • reflexibility • flatness of mirror faces	• isotrope homogene material
Movement of stage mirror is realized with large accelerations	• Light weight	• Low density
	• High stiffness	• Low density • high modulus of elasticity
Stage mirror is used under different temperatures	• Minimal reproducible thermal expansion • no change in position nor shape of the mirror plane	• Small coefficient of thermal expansion • high heat conductivity • isotrope homogene material • material structure does not change under influence of temperature
Stage mirror is used at different times	• Longterm stability of geometry • Change in geometry is reproducible	• isotrope homogene material • material structure does not change

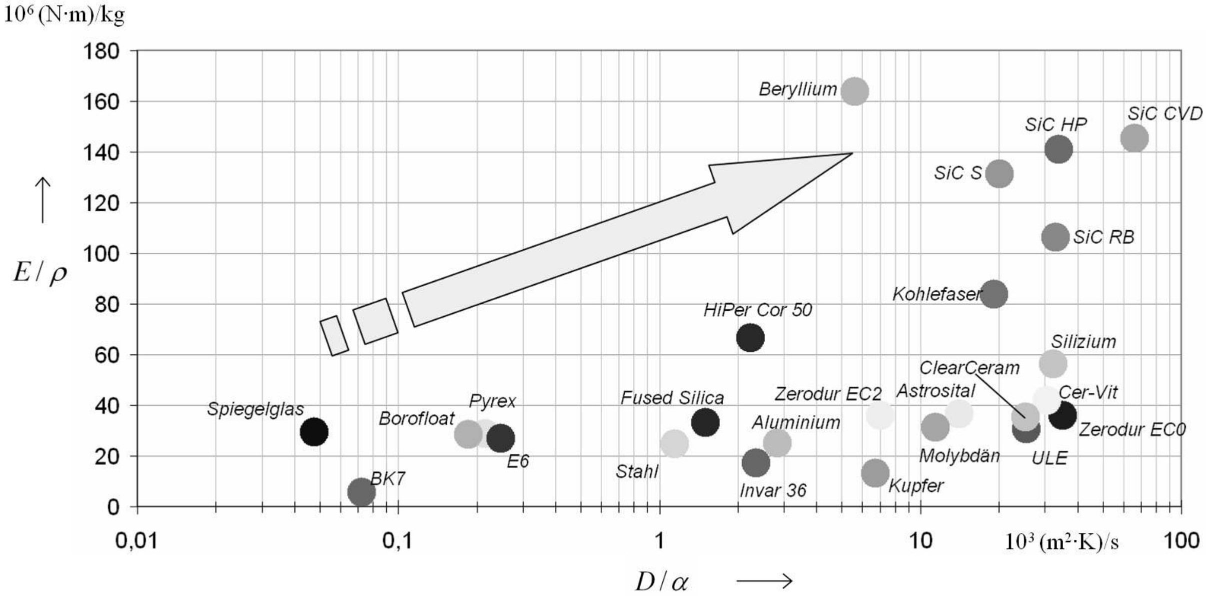


Figure 11. Specific stiffness over deformation caused by transient heat

Materials used for measuring mirrors in high precision measuring machines should have a very small coefficient of thermal expansion. Reasons are measuring stability during measurement. Figure 12 shows specific stiffness over coefficient of thermal expansion. The optimal material should also maximize both values. None of the materials fulfill this requirement. Glass ceramics like Zerodur or the glass ULE have very small coefficient of thermal expansion but specific stiffness is also small. Ceramics like SiC have high specific stiffness but only average coefficient of thermal expansion.

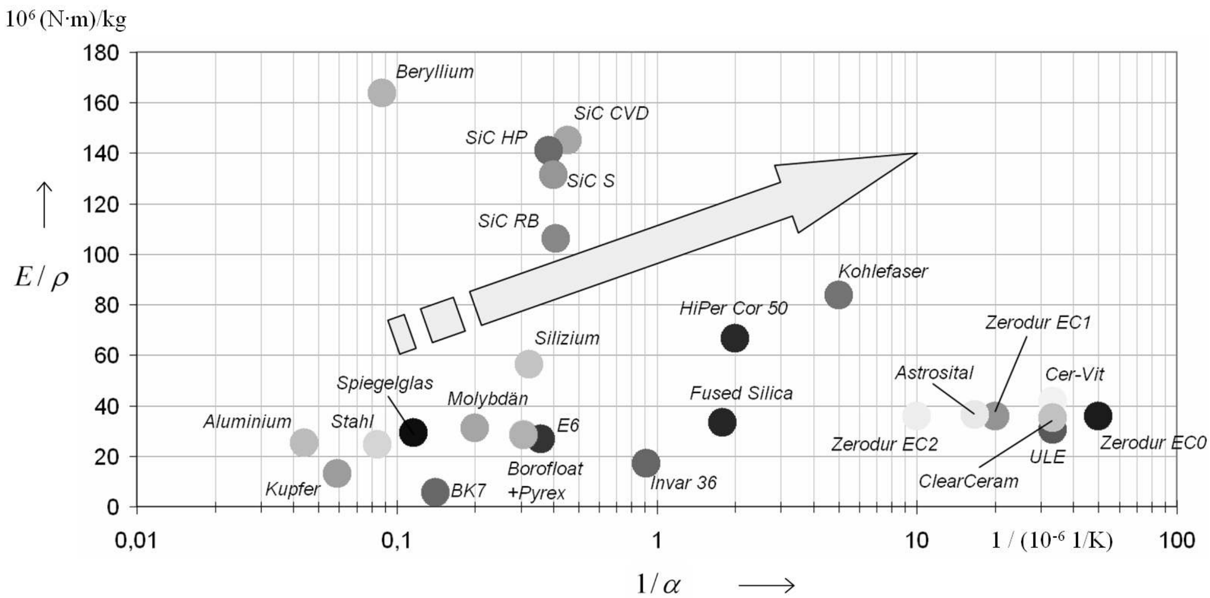


Figure 12. Specific stiffness over coefficient of thermal expansion

It can also be seen that metals and most common glasses play only a minor role. There is no optimal material. Therefore are compromise is necessary. Depending on the application characteristic values need to be weighted. In high precision measuring machines measuring uncertainty is more important than dynamic. Thus mirrors should be made of Zerodur or ULE. If long term stability is very important than glasses should be preferred over glass ceramics.

Another approach is the combination of materials. Besides Zerodur as a standard material for measurement and telescope mirrors silicon is well suited due to its extraordinary mechanical properties and its excellent thermal conductivity [5]. 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.

The relative high coefficient of thermal expansion is not useful to build a monolithic measurement mirror from silicon. But a combination of a base framemade of Zerodur and mirrors made of silicon uses the advantages of both materials (Figure 13). The base frame realizes a stable position of the silicon mirrors relative to one another.

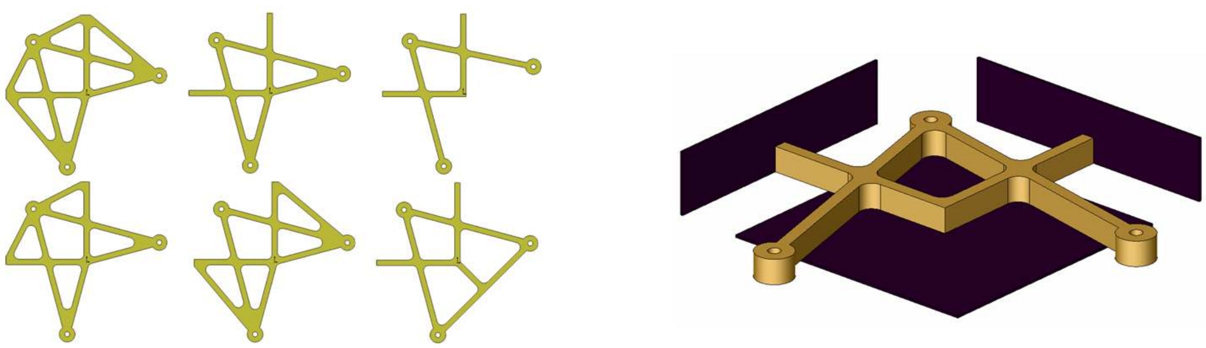


Figure 13. Frame variants and embodiment design of a lightweight stage mirror using different materials

One possible design is based on the idea to connect the silicon mirrors at its center 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.

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 minimized by optimal contact geometry of both components. A number of variants are developed (Figure 14) and examinated 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.

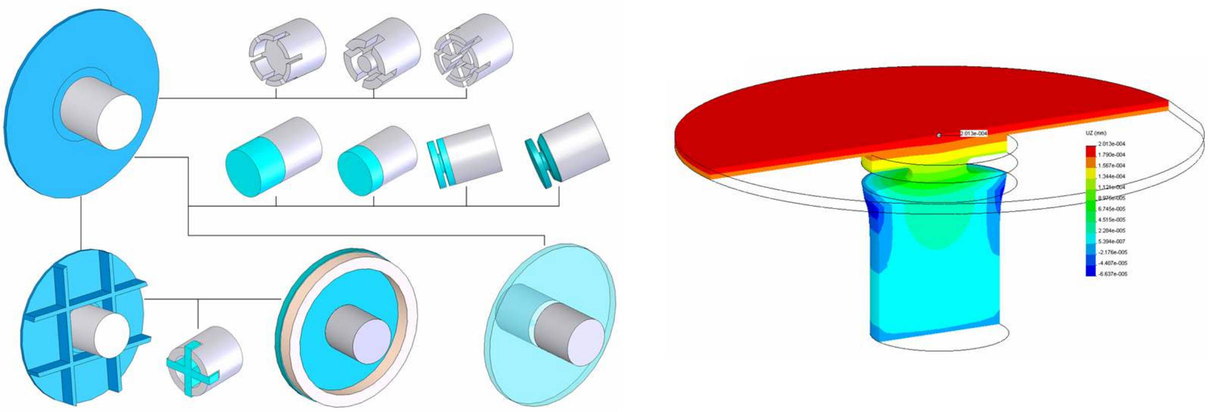


Figure 14. Variants of contact geometry (left) and FEA of one variant with minimized deformation (right: resulting deformation is shown)

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

Couplings

Besides stage mirrors shape its couplings are essential design features. They affect and ensure the function as well as the behavior of the mirror and realize the connection to the whole machine. Thus their design is described separately on different examples.

Couplings are needed to assure a mechanical and metrological stable connection between mirror and object as well as mirror and moving mechanism. Depending on their function they lock one or more degrees of freedom between to elements. For the connection between mirror and object or moving mechanism all degrees of freedom need to be locked.

Often different materials with different mechanical and thermal properties need to be combined and static and dynamic forces or torques have to be transmitted by the coupling. But no constrains should be applied to the mirror because they can cause not wanted and not reproducible measuring errors. A relative movement between mirror and object is not allowed too if both elements are in the measurement circle. Furthermore it is necessary touch the object at least on one side. All these requirements lead to couplings which constrains the mirror least possible. The achievement of these requirements depends on the mechanical realization of the couplings. Thereby deviations from the ideal shape because of manufacturing tolerances need to be considered.

Couplings between mirror and moving mechanism as well as object can be realized by material-, form- or force-fit (Figure 15). Material-fit can not be separated without destruction. Furthermore it leads to strain. Thus it is not usable for the connection of mirror and object. Couplings with form-fit are directly between two elements. All movements perpendicular to the joining direction are locked. Depending on tolerances between the elements is clearance or press-fit. This disadvantage can be reduced if the couplings are elastic. Nevertheless couplings with force-fit are preferable. They use external forces and friction between coupled elements. Thus this kind of couplings are free of clearance. To avoid movements friction forces need to larger than the occurring forces for example realized by movements.

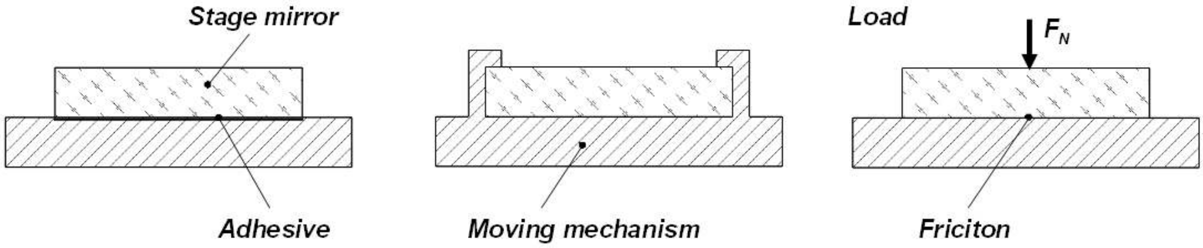


Figure 15. Different kinds of couplings (left to right) material-fit, form-fit, force-fit

A coupling between stage mirror and object can be realized directly or indirectly (Figure 16). If a direct coupling is used both elements are connected and no degree of freedom between them is left. In contrast degrees of freedom of the object need to be locked if both elements have an indirect coupling. Additional couplings are needed using supporting elements. To realize a short measurement circle and direct force flow between mirror and object a direct coupling is preferred.

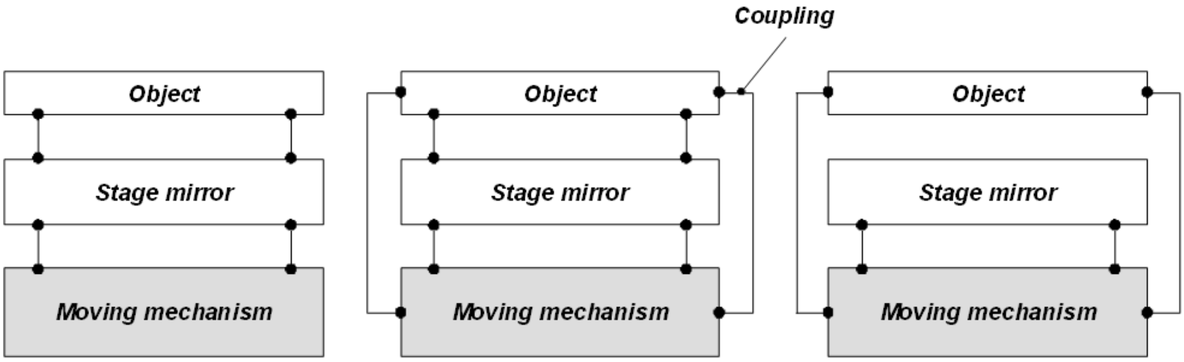


Figure 16. Coupling between stage mirror, object and moving mechanism (left to right) direct, and indirect

The stage mirror needs to be connected to a moving mechanism or a frame. This task is realized with a mount. To fulfill the given requirements the design of this mount should follow design principles with the aim to minimize moments, forces and resulting deformations. Design principles can be summarized to:

- well constraint coupling of stage mirror and object to realize a reproducible and defined fixation;
- short and direct force flow to minimize deformations and strain by transmitting forces directly through supporting points (Figure 17);
- defined force branch out using supporting points with equal distance to the center of gravity to minimize deformations with the aim of equal loads on every supporting point.

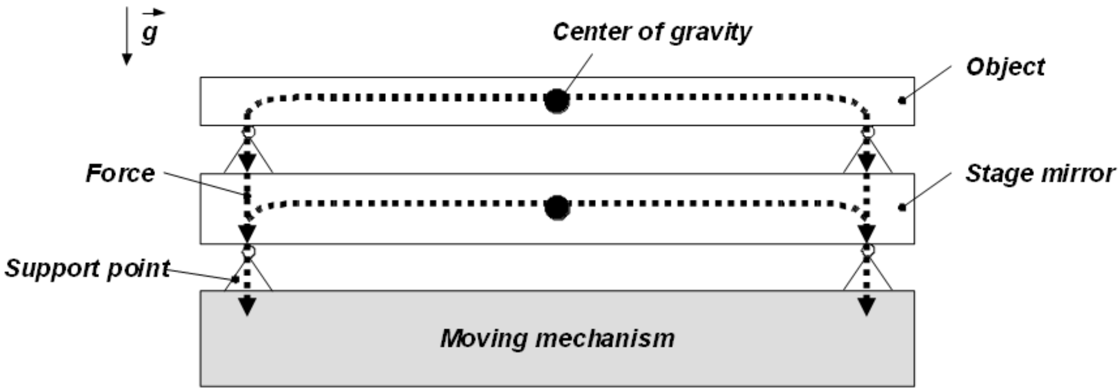


Figure 17. Transmitting forces caused by the object mass through supporting points of the stage mirror

The realization of the coupling should be based on the given approaches. Especially the selection of appropriate matchings to fix exactly six degrees of freedom is important. Three ball v-groove couplings comply with this requirement very well (Figure 18). Thus they are used in many high precision applications. Their advantages and disadvantages are shown in Table 5. Using them a mirror symmetric around the vector of gravity is preferable to realize equal forces at every coupling.

Table 5. Advantages and disadvantages of ball v-groove couplings

Advantages	**Disadvantages**
Realization economically	High stress cause by point contact
Reliable	Gliding friction at contact place
Reproducible	Wear possible
Deterministic properties	

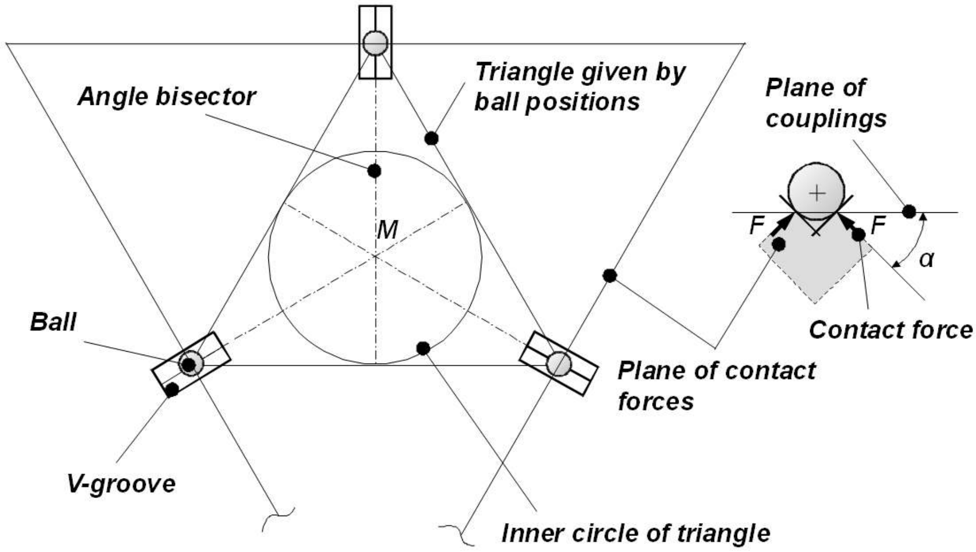


Figure 18. Scheme of a ball -v-groove coupling [20]

This kind of coupling is limited by Hertzian stress between ball and grooves as well as friction and wear. To avoid this also monolithic hinges can be used (Figure 19). They are frictionless and have no wear. But under deformation they act like springs thus counter forces need to be considered. It is difficult to realize more than one rotational degree of freedom when the axis of rotation should cross ideal in one point. Therefore it is more difficult to avoid forces and torque compared to ball v-groove coupling. Nevertheless they can be used for applications in the micron range.

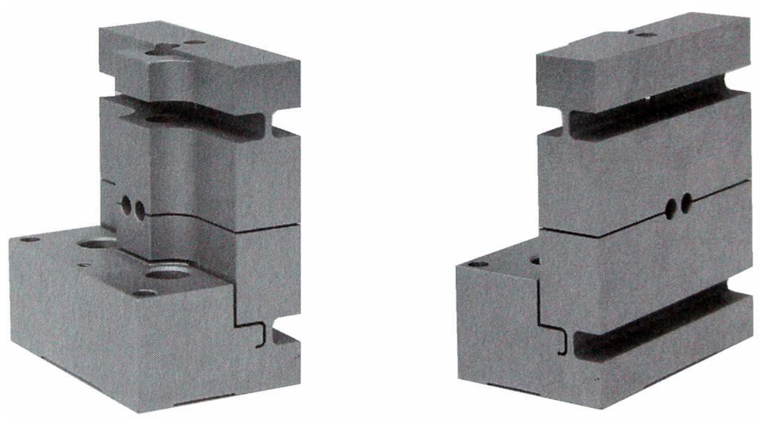


Figure 19. Monolithic hinges as coupling [18]

Independent from the selected coupling the connection to the mirror is typically realized by a friction-fit (Figure 20). Therefore it is possible to reduce stress in the stage mirror by larger contact areas. Further on an adjustment between coupling and mirror is possible. The coupling itself can consist of another material than the mirror and so the design principle of function material at function spot can be applied. To realize a direct force flow from object to moving mechanism or frame with minimized deformation of the mirror all couplings should be directly aligned to the supporting points of object and stage mirror.

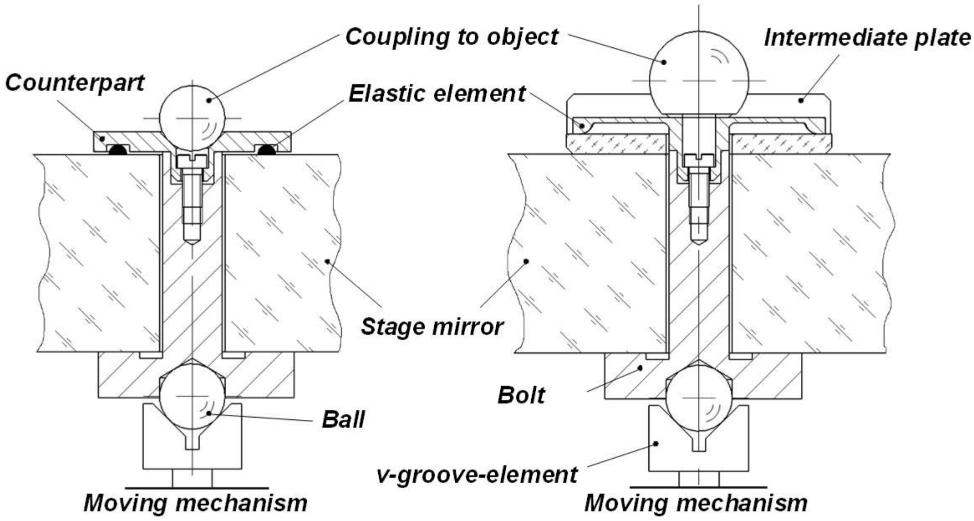


Figure 20. Connection between coupling and stage mirror

Virtual Prototyping

Further on methods of virtual prototyping which are usable during the design of stage mirrors are shown [7]. They afford to simulate and compare the behavior of design variants and to optimize selected ones.

In all design steps and approaches a number of variants are developed. These variants are compared under the use of FEA. As result it can be shown that the 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 by means of 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 realized (Figure 21).

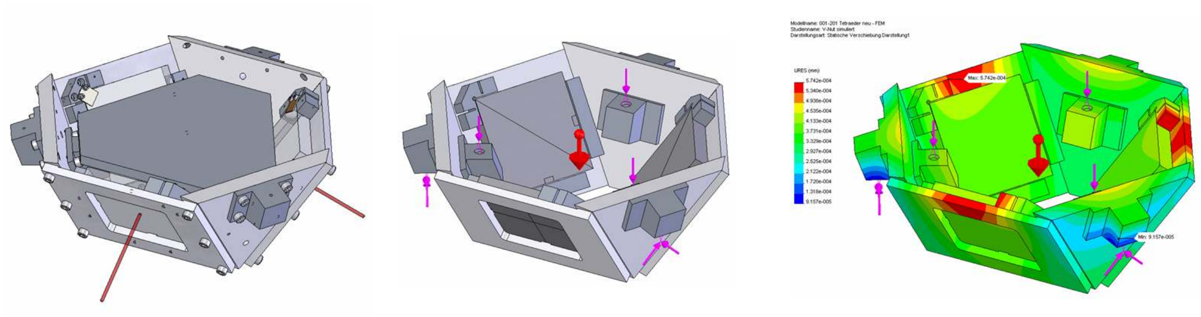


Figure 21. Design of the prototype tetrahedron stage mirror, FEA model and simulation (left: CAD model, middle: FEA model with boundary conditions, right: deformations)

Results

The paper presents a guideline to design stage mirrors of ultra high precision machines. By using this method novel designs of a stage mirror are developed for an ultra high precision positioning and measuring machine. One design of a tetrahedron mirror is patented and is realized as a physical prototype. A second design leads to a new material combination whose test is in progress.

Conclusions

The design of stage mirrors 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 realize 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 is necessary between the desired and the reached properties and the decision if the difference is acceptable. 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 behavior can be integrated in the whole system design earlier. The aim is to make 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 minimized and also better prepared.

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