Proceedings of COBEM 2005
18th International Congress of Mechanical Engineering
November 6-11, 2005, Ouro Preto, MG

DESIGN OF HIGH PRECISION POSITIONING AND MEASURING MACHINES USING VIRTUAL PROTOTYPING

Günter Höhne
Technische Universität Ilmenau, Germany,
D 98684 Ilmenau.P.O.Box 100565
Engineering Design Group
guenter. hoehne@tu-ilmenau.de

René Theska
Technische Universität Ilmenau, Germany,
D 98684 Ilmenau.P.O.Box 100565
Precision Engineering Group
rene.theska@tu-ilmenau.de

Torsten Brix
torsten.brix@tu-ilmenau.de

Thomas Frank
thomas.frank@tu-ilmenau.de

Markus Lotz
markus.lotz@tu-ilmenau.de

Thomas Hackel
thomas.hackel@tu-ilmenau.de

Abstract

Multi-coordinate positioning and measuring machines(NPM machines) of high accuracy in range of nanometres are enabeling equipment for a wide field of technological processes. The machinery makes use of a variety of tools to open up fields of application in micro-mechanics, nano-technology, genetic engineering and metrology. To reach this objective the construction of the machines has to meet in addition to the generalised properties the following main requirements:

- *flexible configurability in relation to the rquired technological process*
- *long-term stability of the construction and good dynamic behaviour*
- *realisation of wide moving areas in range of 200 mm x 200 mm and more*
- *high degree of communality for the different types of machines*

The equipment for this purpose will include mechanical, electrical, electronic and software components. Because of this design must be carried out as a mechatronics project.
By modularisation of the structure of such machines the resulting platform concept, the construction of machinery can be applied to a wide field of technological processes with extreme accuray. The function oriented configuration is supported by a collection of solution principles for the platform components. Virtual prototyping is used to test and evaluate different machine types and configurations.

Keywords*: mechatronics, modularization, virtual prototyping, positioning system*

1. Introduction

Multi coordinate positioning and measuring machines are automated machinery and equipment used in technical, experimental or manufacturing processes. This systems are being asked to meet the most stringent of specifications in certain fields of application, specifications in respect of accuracy, speed of movement, reproducibility and stability, all to be maintained in precise positioning over increasingly wide areas. One exampel is the processing and measurement of wafers for micro-electronics or micro-optical components. The equipment for this purpose will include mechanical, electrical, electronic and software components. Because of this design must be tackled as a mechatronics project. The machinery makes use of a variety of tools to open up flields of application in micro-mechanis, nano-technology, genetic engineering and metrology. Thus a whole new generation of machinery, with vast flexibility, is coming into existence. The current objective is to meet the specifications of the various fields of application by configuring and combining appropriate modules into different products for the respective fields. In particular, the questions are whether a platform concept can be applied in situations requiring such extreme accuracy. A further objective has to be the reaching of decision on the best possible design for the machinery in question by the use of virtual prototyping. The knowledge obtained form this research is intended to benefit the designers of such machinery of offering them design principles which habe been systematically expressed.

2. Process specification

The design of mechatronic systems should start with the specification of the technological process in which the system are to be made use of. A basic model supporting this consideration shows figure 1. For the analysis of the

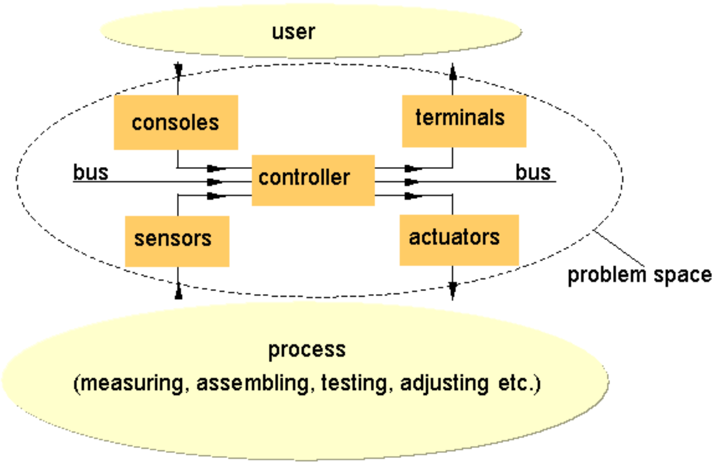


Figure 1. General model of mechatronic systems

Technological process it is necessary to describe first of all operations which must be carried out by nano-positioning and measuring machines in terms of the principles of inspection, measurement, testing, assembling, adjustment and processing involved (Table1). The system should provide the user with the enabling technology of nano-scale objects and macroscopic objects with high precision.

Table 1. Application field of nano-positioning and measuring machines

Functions of NPM machines	Application fields of NPM machines in						
	Electronic	Nanooptics	Nano-fabrication	Nano-materials	Bio-technology	Nano-metrology	…
Calibrating						■	…
Measuring	■	■	■	■		■	…
Testing	■	■	■	■	■		…
Manipulating	■		■		■		…
Treatment	■	■	■				…
Structuring	■	■	■	■	■		…
Assembling			■		■		…
…	…	…	…	…	…	…	…

The objective to serve various technological processes by means of a small number of different technical equipments leads to the conception of an modular system. In our case the machine should be used for testing and measuring of wafers for micro-electronic circuits and micro-optical lenses. This exemplary specification of the fields 1.2, 1.3, 2.2 and 2.3 give the sample also for other application areas.

To realize this processes the construction of the machines have to meet the following main requirements:

- flexible configurability in relation to the required technological process
- long-term stability of the construction and good dynamic behaviour
- realization of wide moving areas of 200mm x 200mm x 5mm and more
- high communality for the different types of machines

3. Modular concept of nano-positioning and measuring machines

Anlalysing this requirements and existing systems a relative multiple-coordinate movement between the object to be measured or tested and a tool is necessary. The extreme high accuracy requires a control in a closed loop and special means to prevent the constraction from disturbing influences.

One fundamental concept to accomplish this objectives is the arangement and position measurement between object and tool corresponding the 3D-version of Abbe´s principle [1]. Figure 2 shows the Abbe´-point as virtual intersection point of three interferometer beams where is located the indicating tip. In this case the object carried be the 3D-mirror is moving in three directions. However other combinations of moving components are possible between object and tool.

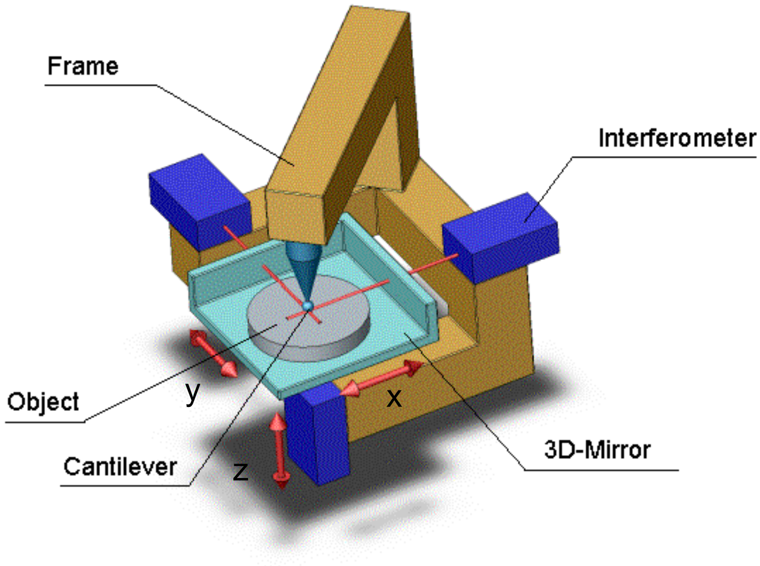


Figure 2: Principle of the measuring system

Following the rules of modularisation [2,3] a generalised function structure (Figure 3) forms a platform consisting of the main sub-functions which are shared by all variants of the product family. This maximum function structure can be specified according to the type of object, tool and to the technologic needs of the application. The positioning subsystems, the mesuring units, the frame the control and data processing components are the basic platform components.

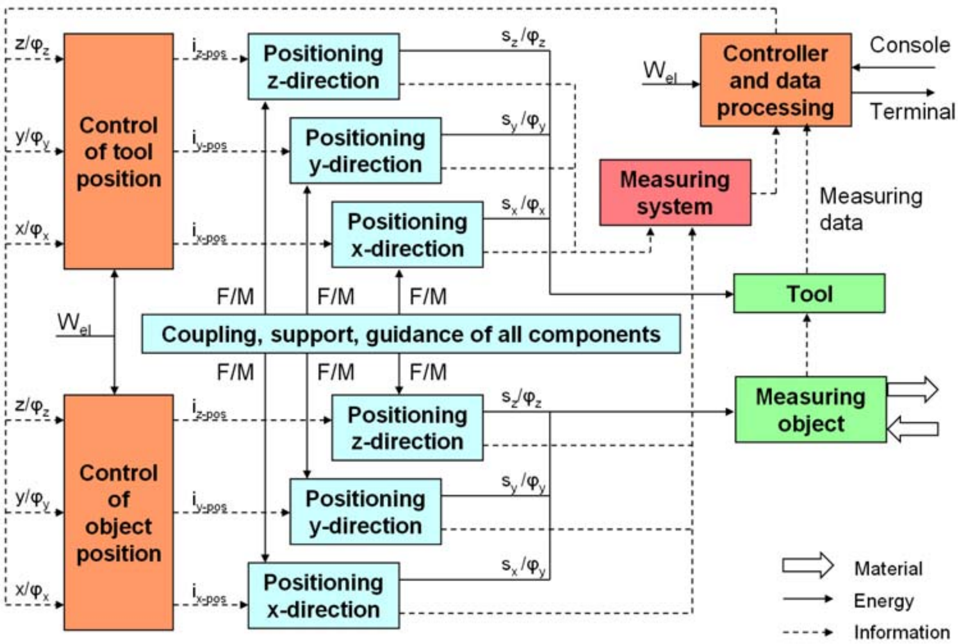
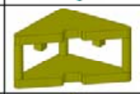
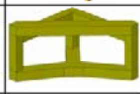
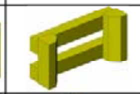
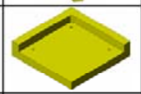
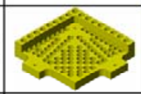
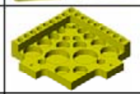
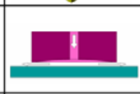
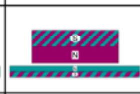
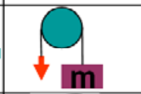
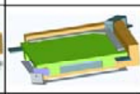
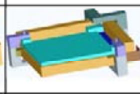


Figure 3: Maximum function structure of the machine

Tools and fixtures of objects are so called non platform components designed or selected for each typ of machine. With respect to the different application areas of such machines a function-oriented configuration ist indicated. The platform concept and the function structure are the base to apply this method. Each sub-function can be realised by a number of different variants. In this way is established a configuration matrix (Table 2).

The matrix contains solution principles and provides the configuration procedure with these virtually stored substructures.

Table 2 Configuration matrix for nano-positioning and measuring machines

Modules	Variants						
Frame						…	…
Metrology frame			…				…
Mirror					…		…
Guides			…				…
Gravity force compensation					…		…
Fixation elements			…				…
…	…	…	…	…	…	…	…

4. Virtual Prototyping

4.1 Function-oriented configuration

The layout of the machine is stepwise established as a virtual prototype by combination of selected components generating a number of variants (Figure 4).

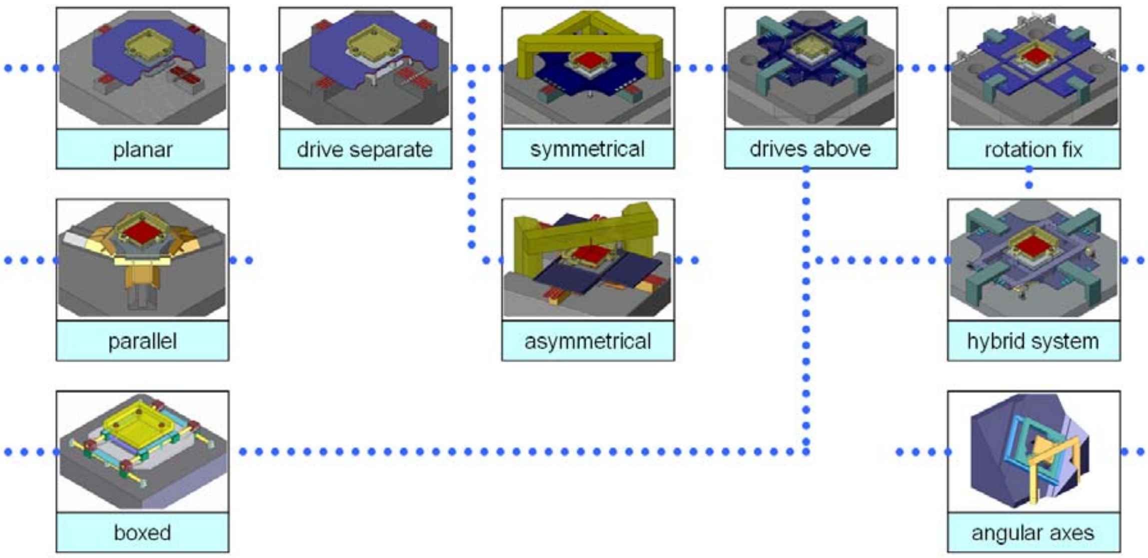


Figure 4: Variants of the overall structure

Realising the concept given in Fig. 2 two main structures are indicated to accomplish the requirements of moving areas and accuracy (Figure 5).

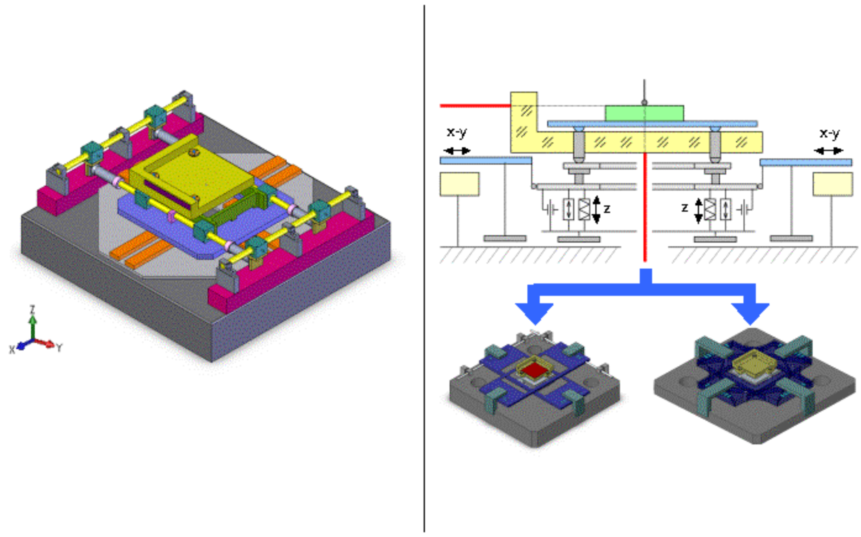


Figure 5 Seriell and parallel arrangement of x/y-positioning components

The serial arrangement uses linear guides and a planar drive system. Its dimensions are compact but the long force flow because of gravity and driving forces leads to bending and torsion. Therefore the parallel arrangement is prevered. The vertical moving axis is directly connected to the base through planar bearings. As a result the force flow is direct but the lateral dimensions are larger.

Analogous the moving system of the vertical axis z is modular designed. The results of this configuration process next must be checked and evaluated in relation to the requirements as accuracy, dynamic behavior, deformations under load etc. The objective is tho simulate this properties as erly as possible using virtual prototyps and optimize the dominatig parameters for saving time and effort in the concrete states of the design process and the bodily reatization.

4.2 Simulation of Solution Principles

Based on the favorised functional structure possible solution principles are developed by using configuration matrix (see section 3). The function elements of the solution principles are often described with idealized or symbolic elements. Series of calculations of the behaviors are possible on this level of abstraction (Table 3).

Table 3: Examples of possible calculations based on solution principles

Type of information	Possibilities for analysis, simulation and optimization
Qualitative described elements and relations ↓	characteristic of motion combination of solution elements classifications variation of the element number, form and position
Quantitative described elements and relations ↓	Variation of dimensions working space, overall and connecting dimension error and und tolerance analysis
Functional quantities	kinematics, static,...

The predominant question is the analysis, simulation and optimization of motion concepts to find preliminary layouts. The use of special software tools (like Matlab, SAM, WorkingModel, Watt) helps in finding a good solution principle and determines some basic embodiment design parameters. For the design of the NPM machine concept a new design tool with the name MASP (modeling and analysis of solution principles) is used. This design system enables the modeling and simulation of guide and drive concepts of the NPM machine. MASP uses a constraint-based method to describe kinematic geometries. The calculation of these geometries is carried out by a constraint solver, which is developed at the Technical University of Ilmenau. MASP enables the user to immediately test the functionality of the current design concept, for instance, by interaction with mouse drags or applying further calculations (e.g. kinematics or static calculations, error analysis) based on the evaluated constraint model [4]. The interactive modeling of solution principles is done by selecting symbols in the context of chosen instruction (e.g. create, delete, modify). For the first steps in embodiment design predefined form elements exist in the mentioned design system, which can be used for further calculations (e.g. working space, collision detection, dynamic calculations) and for the model transfer into a CAD system (Figure 6).

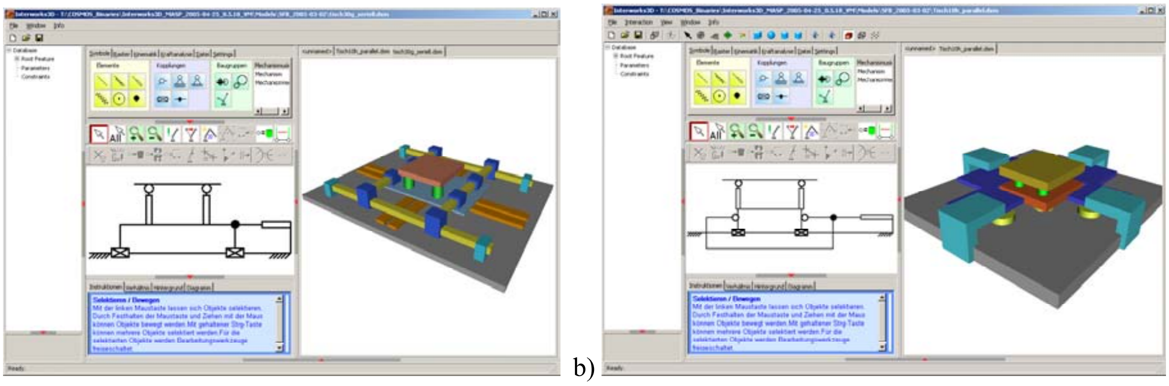

a) b)

Figure 6: Design system MASP with the motion concepts of
a) a serial layout and b) a parallel layout of a NPM machine

4.3 Multi-body simulation (MBS)

The basis for the dynamic simulation is the MBS model of the NPM machine. For the modeling it is important to understand the MPN machine as a coupled heterogeneous system. Following main problem areas must be considered for the modeling:

- positioning in a relative large workspace (200mmx200mmx5mm),
- nano-meter resolution and accuracy,
- high dynamic.

The developed MBS model contains information about the frame and rigid bodies, which are primarily interconnected with guides. Interdependences of the different NPM components are shown in Figure 7. For the conception of the MBS model it is necessary to consider the influence of the elasticity of some mechanical elements, in order to fulfill the precision requirements. Furthermore the concept of the MBS model allows the integration of additional functional elements like elasticity of the guides or voice coil drives.. Therefore the MBS model contain the following properties (Figure 8):

-mass and mass moment of inertia of the moved elements,
-elasticity of some mechanical elements,
-friction forces in the guides,
-forces introduced by cable tracks,
-forces of the drive elements.

It should consider that for the analysis of the MBS model the handling of extreme magnitudes of the MBS model parameters (The parameter range of motion space to the accuracy is 7 to the power of ten!) is necessity. For this reason adapted robust solving methods are required for the numerical calculations of the MBS model. The results of the MBS analysis show for example the influence of the couplings on the dynamic behavior of the NPM machine system and give a statement to the occurring deformation. This supports the selection of suitable components for the NPM machine.

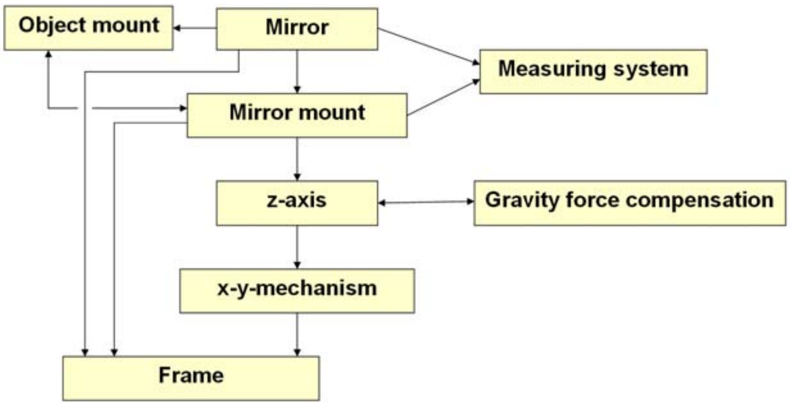


Figure 7:Interdependences of the NPM machine components

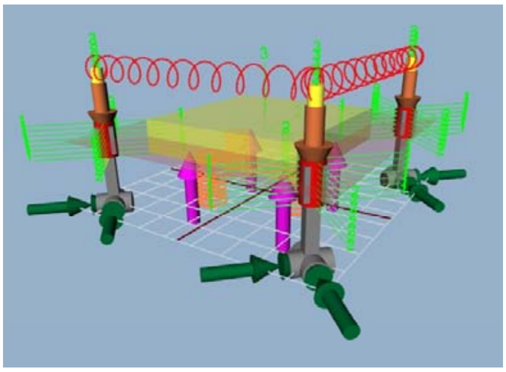


Figure 8:MBS model (program alaska) of the z positioning unit

Important for the validation of the dynamic model is the quality of the dynamic parameters. The values of parameters are proofed and optimized with self developed test benches to determine Young’s modulus, Poisson’s ratio etc.

Relevant design recommendations are derived from the MBS and support the design of optimized systems with stable system behaviors, which are necessary for the easier development of machine controls.

4.4 Finite elemente analysis (FEA)

One of the fundamentals in the development of NPM machines is the design of dynamically and statically stiff components. Especially the mirror of a NPM machine, which is used for three dimensional interferometric measurements, has a great influence to the system performance. For the identification of weak solutions and the optimisation of components and the whole machine design FEA is used (Figure 9).

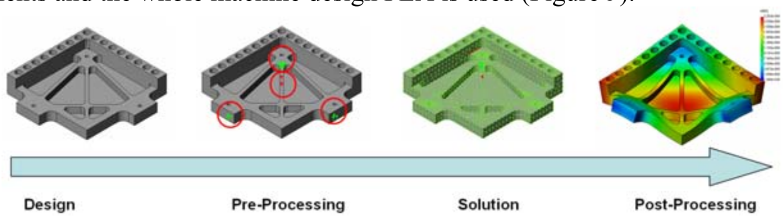


Figure 9: Operations of the FEA processing

The use of FEA is shown on the measuring mirror of a NPM machine. It is important to minimise its deflection and its mass. Because of this the first approach was to find the optimum count and position of the needed supporting points. Starting point of the research was the existing solid body mirror made of the glass-ceramic Zerodur. Using FEA it was possible to find an optimal design using three supporting points and to reduce the deflection by 79% (Figure 10a). After this it was necessary to reduce the mass to improve dynamic behaviour of the machine which can be simulated using MBS. FEA and design principles like short and direct force flow were used to find an optimal design of holes and combs. Thus the mirror mass was reduced down to 45% (Figure 10b).

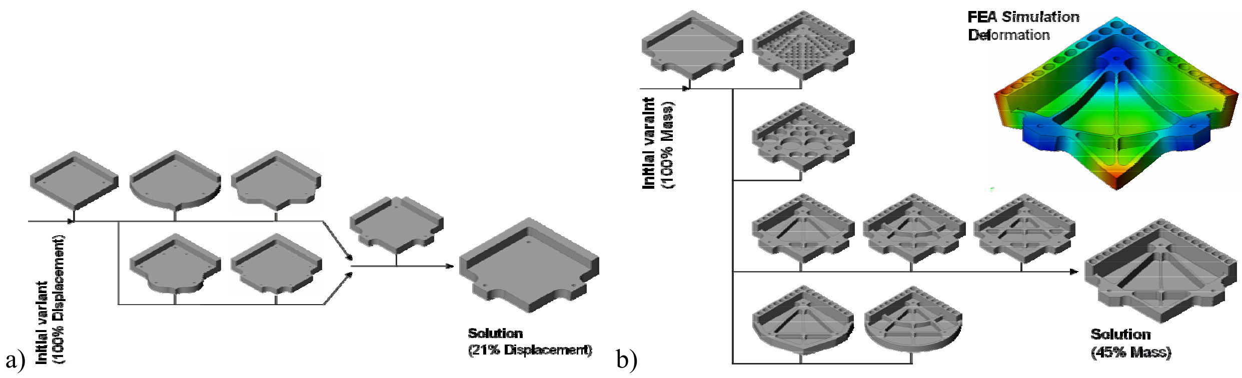


Figure 10: FEA on the measuring mirror of a NPM machine
a) positioning of the supporting points and reducing the deflection and b)reducing of the mirror mass

Nevertheless the application of FEA shows that for larger moving ranges the mirror mass will be too big for the needed dynamic performance of the NPM machine. Therefore new solutions with extreme light weight design using alternative materials and joining technologies are necessary. One possible approach is shown in Figure 11.

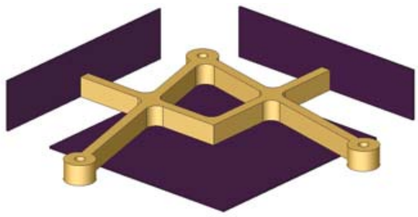


Figure 11: Extreme light weight design of a new measuring mirror

5. Conclusion

The paper presents a design approach of a new generation of multi-coordinate positioning and measuring machines with high accuracy in range of nanometers in the early design phases. The high requirements on accuracy and dynamic of such machines demand the strong use of suitable software tools. Furthermore it is shown, how the software tools are performed to determine the NPM machine behaviours based on the well known design process (Figure 12). Due to the consequent application of the described software tools virtual prototyping can be successful applied for the development of new NPM machines and other high technology products. Several examples are given to explain the design approach.

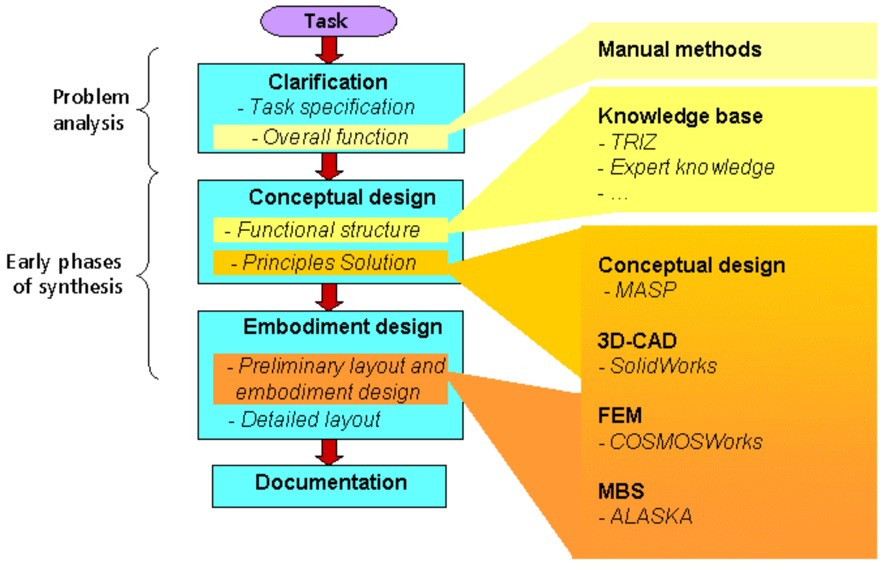


Figure 12: The main stepts of the design Process with the means of virtual prototyping

6. Acknowledgement

[1] Jäger, G.; Manske, E.; Hausotte, T.: Nanopositioning and measuring machine, Proceedings of EUSPEN 2001, Vol.1, Turin, 2001, pp. 290-293.

[2] Hofer, A.P.; Gruenfelder, M.: Product family management based on platform concepts“, Proceedings of ICED ´01, Vol3, Glasgow, 2001, pp. C 586/631.

[3] Aarnio, J. P; Riitahuhta, A.O.; Modularisation by integration (MBI) a means to modularise a mechatronics product”, Proceedings of NordDesign 2002, Trondheim 2002, pp.1-8

[4] T. Brix, U. Döring, M. Reeßing: Constraint-based Computational Kinematics. Proceedings of CK2005, International Workshop on Computational Kinematics. Cassino May 4-6, 2005.