

METHODICAL APPROACH FOR PERFORMANCE RATING DURING THE DESIGN PROCESS OF PRECISION MACHINES

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1 Introduction

The demands on the accuracy of mechanical devices for precision motion are rapidly raising in submicron and nanometer dimensions because of new applications in micro technology, mechatronics, genetic engineering etc.. For these fields of application state of the art machines either have high precision with little travel range or opposite [1, 2]. That means a position accuracy of less than 10 nm combined with an outstanding dynamic behavior and a large travel range of several 100 mm is required.

Though the performance of positioning machines can be enhanced by advanced control techniques and software methods it is principally limited by mechanical hardware design. It determines the influence of environmental disturbances and other sources of errors on accuracy and the reachable dynamics.

In the design process of superior precision machines it is necessary to identify and quantitatively determine performance parameters and possible error sources in the earliest stages to avoid them or minimize their impact.

This paper refers to the development of a 3-axis nanomeasuring and nanopositioning machine. To fulfil the demands of the standard setting semiconductor industry, a major field of application and other suitable tasks in industry the moving range of a new generation of ultra precise positioning machines has to be extended to 200 mm x 200 mm x 15 mm with the goal to reach a positioning uncertainty of about 10 nm.

Optimal machine performance can only be reached by consequent usage of advanced design principles in combination with high precision metrology and intelligent control [5]. Using virtual prototyping techniques helps to simulate the behaviour (e.g. mechanical, thermal, vibration behaviour) of crucial machine components, as it will be shown in selected examples. For validation the results of different FEA software will be compared.

2 Methods to Design High Precision Machines

The starting point for such a system design is the analysis of the technological processes and boundary conditions in which the high precision machines. For that purpose first of all it is necessary to describe the operations that must be carried out. These operations depend on the

application fields. Possible application fields are measuring and positioning tasks in biotechnology, optics or electronics.

For specifying a certain application case a generalised model is needed and used. It describes the overall function of the required machine by means of determination of its interactions with the expected environment, consisting of the operator, other technical systems and the surrounding atmosphere.

3 State of the Art

The current situation in the area of such ultra high precision positioning and measuring machines is characterised by special designs developed for a particular use. There is a variety of single-purpose machines individually designed as unique objects.

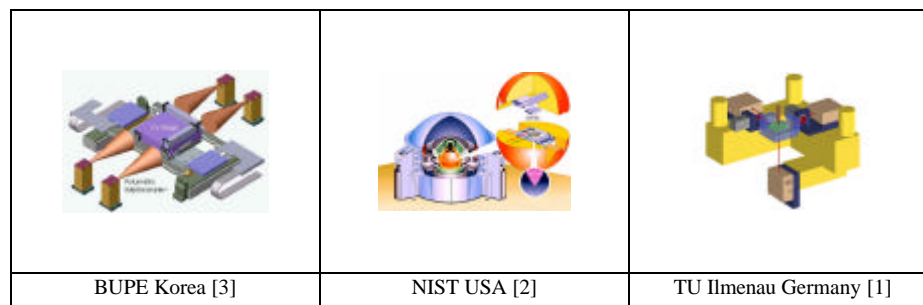


Figure 1. Multiple coordinate high precision machines (selection)

Analysing functions and structures of the existing systems following properties can be generalised:

- all systems realise a relative multiple-coordinate movement between an object and a tool,
- movements are controlled in a closed loop,
- high accuracy is realised by precision guides, prevented from disturbing influences,
- basis and frames have high stiffness, good long-term stability and minimised thermal deformations.

4 Design Process

As a result of the investigation of state of the art machines a general functional structure can be established. In consideration of the objective to serve technologies of the mentioned application fields this functional model forms a base for developing a new generation of high precision machines. It should provide the user with the enabling technology of measuring, handling, processing etc. of objects with high precision. To achieve this objective the design of the machines has to fulfil in addition to the generalised properties the following main requirements:

- flexible configurability in relation to the required technological process,
- long-term stability of the machine and good dynamic behaviour,
- large moving ranges of at least two axis with several hundred millimetres.

The goal is to develop high precision machines which meet the requirements of the applications fields based on only one type of machine to reduce development and product costs. In compliance with the well-known rules of modularisation [8], the consequence is to establish a platform consisting of the main subsystems which are shared by all variants of the product family. In the presented case the frame, the positioning systems consisting of actuator and guidance, the measuring system and the control system forms the platform elements.

Tools and objects vary according to the technology needs of the application. Therefore the tool and the mount of the object are so called non-platform elements designed or selected specially for each type of machine. A function-oriented configuration is indicated because the machines are produced in small numbers.

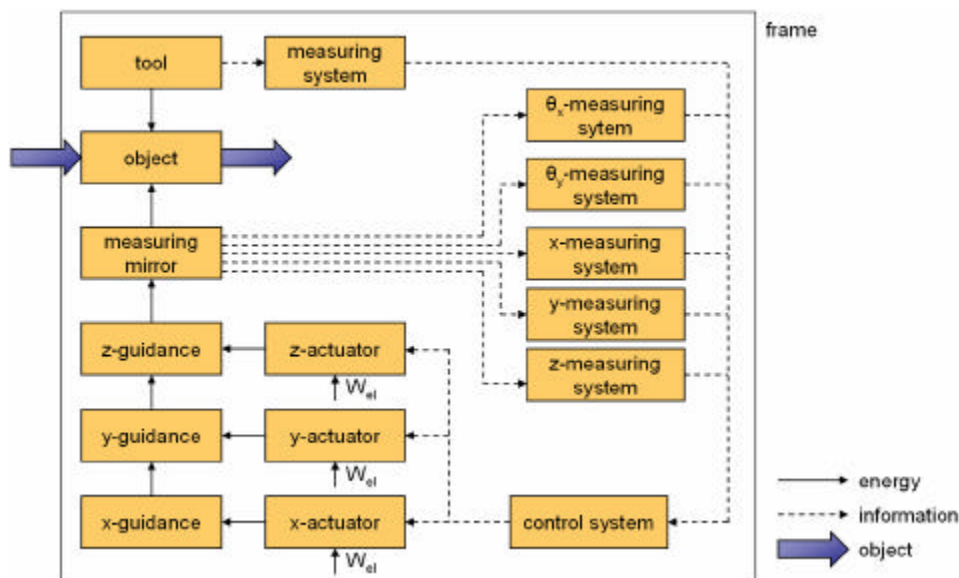


Figure 2. Functional structure of high precision machine

After specification of the task it is necessary to analyse and determine the technological operations which the machine has to carry out. The designer has to find and to describe the object and the tool(s) as well as the relative movements between them. This investigation specifies the overall function of the machine to be developed.

The third stage is the design of structures around the functions. Possible alternatives will either be to build up the structure from sub-functions to match the application or the reduction of an imaginary maximum structure. Considering the platform concept and the possibilities of virtual prototyping the second option is preferred. The designer can eliminate the not needed sub-functions and it is easy to store this structure by means of a computer.

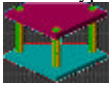








sub-system	variants			
frame	column type 	portal type 	pillar type 	...
guidance	roller bearing 	sliding bearing 	aerostatic bearing 	...
drive	moving coil 	piezo 	friction drive with motor 	...
...

Figure 3. Configuration matrix (section)

The specified functional structure and the determination of the movements are the basis to realise the function-oriented configuration of the machine. Figure 3 has in store solution principles for the platform components. This matrix can be expanded to include new potential solutions. The highlighted fields show the selected components of the machine which will be developed.

5 Design Principles for High Precision Machines

The design of the technical principle is crucial for the whole machine design. This phase allows to find the most critical error sources and crucial components of the whole machine and the measurement circle at this early design stage. Error calculations and the development of adjustment strategies can be carried out.

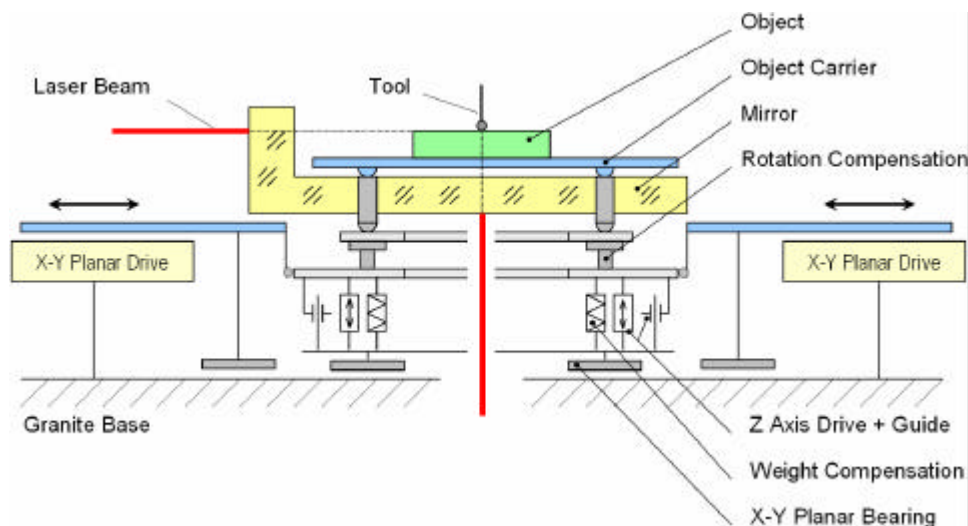


Figure 4. Technical principle of high precision machine

One possible solution for an ultra high precision machine is shown. Here, the mirror itself and its connection to the measuring object as well as the interferometers with their mountings are crucial components of the measurement circle.

If highest precision is desired it is necessary to apply design principles in all phases of the design process. The most important ones will be described the example of the technical principle.

5.1 General Metrology Concept – Principle of Small Error Arrangement

The stage position is measured by laser interferometers. First order position errors are eliminated by the arrangement of the interferometers. The position of a three-face mirror, which carries the measuring object is measured by three fixed laser interferometers. Abbe's principle will be respected in all three axes if the extensions of the three laser beams meet in a single point (so called Abbe point), which is in coincidence with the tool's working point.

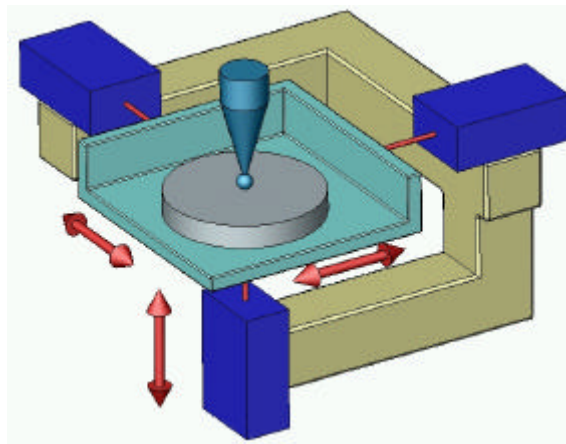


Figure 5. Measurement setup

Second order measurement errors of the mirror position are caused by rotational errors from the x-y-z guides. Therefore, these rotations of the mirror around x-, y- and z-axis are also measured in order to introduce a counter motion which is feedback controlled. So rotations of the mirror are kept considerably smaller than the existing guiding errors.

5.2 Principles of Function Separation and Integration

Depending on the level of abstraction, the overall function structure can be broken down into sub-functions. A function defines the desired output, which has to be fulfilled by the machine components, from the input.

For high precision and reliability it is inevitable to apply the principle of function separation. One component or subassembly has to fulfil a single defined function which reduces negative influences from interactions of several functions in one part. Also the adjustment as well as calculation of dimensions and tolerances is simplified. But this principle results in an increasing number of parts and interfaces which leads to an increased mass and volume.

One example is the separation of the metrological frame from the machine frame. This makes the metrological frame isolated from unwanted forces and vibrations. Another example is the separation of static (gravitational) and dynamic forces. A separate mechanism has to carry the weight of all components to be moved in z direction. The z actuator only generates dynamic forces to move the platform with highest resolution. To reach unidirectional forces, the weight is not compensated entirely. To fulfil dynamic requirements, the weight compensation should

not be a counterweight. Possible alternatives are spring mechanisms, pneumatic and magnetic devices that can provide a constant force over a certain area of motion.

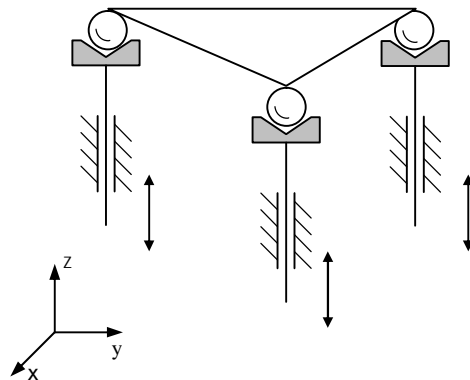


Figure 6. Setup of z-axis

On the opposite, the principle of function integration combines several functions in one component. It is applied for compact, miniaturised and lightweight design and less number of mechanical interfaces. Especially for auxiliary functions it is useful to apply this principle. But it is also possible to deliberately use auxiliary functionality, as shown in combination of z motion and tip-tilt-motion.

5.3 Principles of Force Transmission

A general principle of the precision machine design is to reach a short and direct force flow. To minimise deformations and to use part and material capacity in the best possible way the forces should preferably cause tensile or compressive stresses instead of bending and torsional stresses, which can be proven by finite element analysis (FEA).

In the machine concept, the gravitational forces of the measurement mirror and other component in z direction are led directly to the ground via a kinematic mount, the actuators and air bearings.

Being an example of function integration as well, the x-y planar drive generates the driving forces in only one plane, which is close to the centre of gravity of the moving parts. This minimises moments of tilt, which cause second order measurement errors. The height of the centre of gravity changes with motion in z direction, therefore this principle cannot be fulfilled entirely.

5.4 Principles of Symmetry

In order to average and to reach uniform systematic and random errors, precision machines should apply symmetric design not only for mechanical components and forces, but also for thermal design. All actuators, which are heat sources, are placed symmetrically to minimize temperature gradients in the machine. Combined with the principle of exact-constraint design symmetric 3-point supports are arranged at 120° angles, resulting in triangular shapes.

5.5 Principles of Exact Constraint Design

The entire machine can be seen as kinematic chains with rigid bodies and joints as elements. Either mechanical interfaces or elastic zones of a part serve as joints. Using exact constraint design, the kinematic chains or sub-chains must satisfy the desired and preliminarily specified degree of freedom. This can easily be calculated using Chebyshev's equation.

Overconstrained mechanisms require small geometrical tolerances that result in the need for high precision manufacturing or adjustment devices. Yet an over constrained mechanism is very sensitive regarding disturbing influences. Because of that, precision components should be based on a deterministic design.

6 Virtual Prototyping of High Precision Machines

The virtual prototyping method [9] is used, beginning in early phases of design, to check both – that the technical principles and the embodiment design consisting of parts and assemblies will work. For this purpose several different tools can be used.

MASP, a tool for constraint solving [4], is used to simulate movements, forces and tolerances of a principle solution. Following tools are that of simulation with multi-body systems and that of finite element method [10]. By means of simulation at the initial planning state at the level of principle and rough embodiment design it is possible to make important decisions on the optimum design.

The Virtual Prototyping Method is very useful especially for important machine components which are very complex and expansive. One typical component for high precision machines is the measuring mirror. It is used to measure the position of the object in three coordinates. On this component Virtual Prototyping with Finite Element Analysis is shown exemplary.

6.1 Modelling of Components with FE-Tools

The modelling of components or assemblies with FE-tools supports the designer during important phases of the design process. It is possible to make estimations of the object behaviour without any physical prototype. Nevertheless FEA is still a method which needs care during the phases of modelling, solution and post-processing as well as fundamental knowledge and experience of the designer.

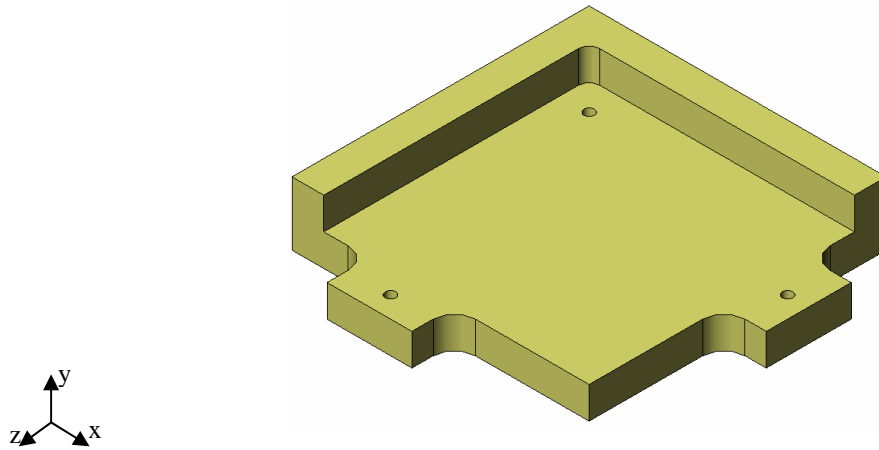


Figure 7. CAD-model of the measuring mirror

For the given example of the measuring mirror it is important to optimise the position of its supporting points. The aim is to minimise the mirror deformation under gravity. Because the material of the mirror is a ceramic glass only little stress is allowed.

To solve this problem a parametric CAD-model was generated to change the position of the supporting point easily by only one parameter. The supporting points themselves were modelled as a contact area to comply with the real system as best as possible.

The simulation of the measuring mirror is taken out with two different programs. One program is ANSYS 7.1 and the other program is COSMOSWorks 2003.

The modelling of the mirror is as far as possible equal in both programs. The element type is a 10 node tetrahedron. Also the constraints are equal. Only the mesh density varies depending on the mesher of the program.

Maximum von Mises stress and maximum resulting displacement are the values which will be compared. The aim is to minimize both.

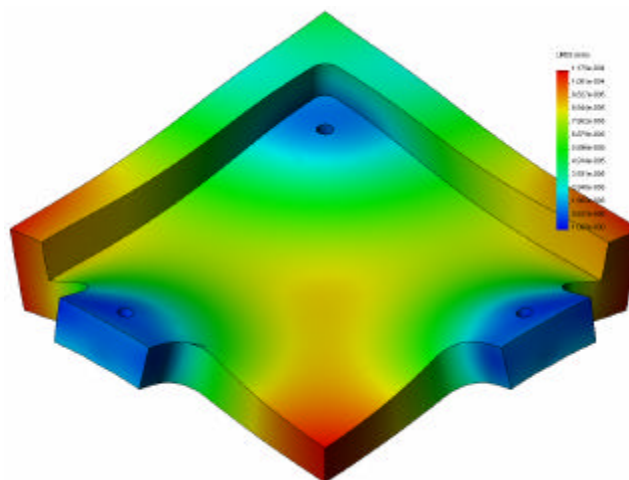


Figure 8. Displacement URES of the mirror

6.2 Results of the FEA

With both programs it was possible to find the optimal position of the supporting points. This position is equal in both programs.

Both programs showed almost the same values of the maximum displacement. There are only small differences with less than 1%. In the diagram it is also shown that the values converge.

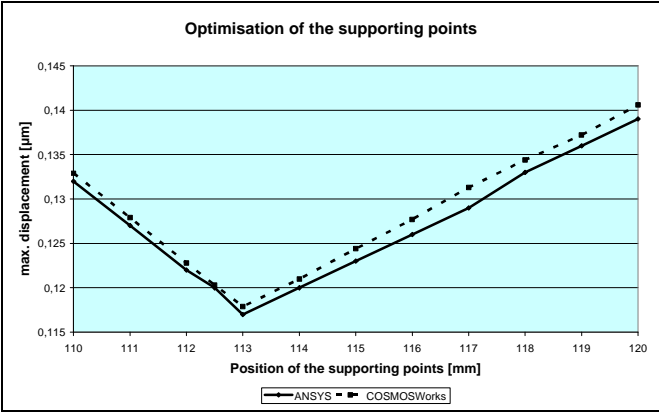


Figure 9. Maximum displacement

But both programs show differences in the results of the maximum stress up to 88%. In ANSYS there is almost the same maximum stress at different positions of the supporting points. In COSMOSWorks it is not.

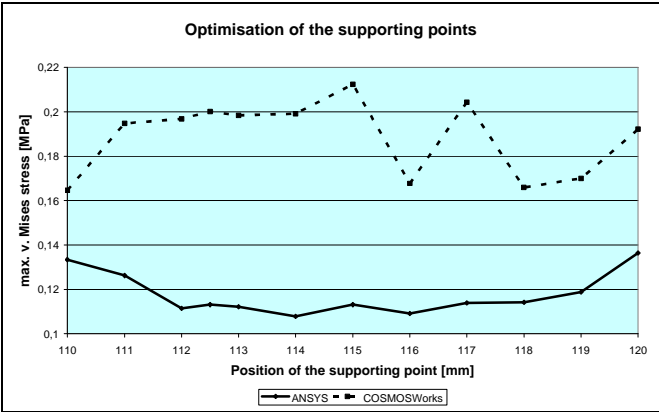


Figure 10. Maximum von Mises stress

Nevertheless it was possible to find the optimal position of the supporting points and to make estimations about the maximum stress in the measuring mirror.

7 Conclusions

The design of a high precision machine should be as simple and reliable as possible, and exactly determined. To achieve this goal, the persistent use of the design methodology and principles is a powerful tool in the design process of ultra-precision instruments with extreme

accuracy, repeatability and stability requirements. Already at the earliest stages of the design process, they are a great help to elaborate a machine concept on a more deterministic and comprehensible way.

Design principles are not only limited to the mechanical system, they can also be applied to thermal, magnetic, electrical, material and other problems. One general method of high precision machine design is to avoid or minimise systematic and random errors due to various kinds of disturbances. This is achieved by the machine structure itself or geometrical constraints. The remaining errors have to be compensated or corrected afterwards by means of sensors, actuators and control algorithms. This could be a step towards the further enhancement of design principles, which is also in the centre of current research work.

By using virtual prototyping techniques it is possible to optimise the arrangement and the shape of the machine components. Because a high precision machine is an extremely complex system it is useful to treat the components separately but also the interaction of the components must be considered.

Further research has to be done to experimentally test the design principles and evaluate the results of the virtual prototyping. So it will be possible to get a feedback for the current development of methods and tools.

References

- [1] G. Jäger E. Manske, T. Hausotte, W. Schott, "Operation and Analysis of a Nanomeasuring and Nanopositioning Machine", Proceedings 17th Annual Meeting, ASPE, St. Louis, 2002, 299-304
- [2] Kramar, J., "Molecular measuring machine research and development", NIST Manufacturing Engineering Laboratory, 2001
- [3] KAIST; BUPE: "Annual Report 2003", <http://pem.kaist.ac.kr/bupe> (2003-11-05)
- [4] T. Brix et. al., Multi-stage Modelling in the early Phases of Design, Proceedings of ICED 2003, Stockholm, 2003, 279-280
- [5] R. Theska, T. Frank, M. Lotz, T. Hackel, G. Hoehne, S. Frank, Advanced Design Principles to Develop Nanopositioning Machines, Proceedings of euspen 4th conference, Glasgow, 2004, 440-441
- [6] G. Höhne, R. Theska et al., Developing a New Generation of Positioning and Measuring Machines by Means of Virtual Prototyping, Proceedings of ICED 2003, Stockholm, 2003, 279-280
- [7] Ruijl, T., "Ultra Precision CMM: Design, Calibration and Error Compensation", Ponsen & Looijen, 2002
- [8] Hofer, A. P. et al., "Product family management based on platform concepts", Proceedings of ICED 01, Vol. 3, Glasgow, 2001, pp.C586/631
- [9] Kunz, A. et al., "Innovation at the digital product - the use of virtual product development process", Proceedings of ICED 01, Vol. 1, Glasgow, 2001, pp.693-700
- [10] Hochmuth, R. et al., "Approach to evaluate the precision of technical systems", Proceedings of ICED 01, Vol. 3, Glasgow, 2001, pp.C586/031

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