NordDesign 2004 – Product Design in Changing Environment
18-20 August 2004, Tampere, Finland

VIRTUAL PROTOTYPING IN EARLY DESIGN PHASES TO DEVELOP ULTRA PRECISE MACHINES

Prof. Günter Höhne

Markus Lotz

Technische Universität Ilmenau
Faculty of Mechanical Engineering
Department of Engineering Design
P.O. Box 10 05 65
D-98684 Ilmenau
GERMANY
E-mail: guenter.hoehne@tu-ilmenau.de
E-mail: markus.lotz@tu-ilmenau.de

Prof. René Theska

Technische Universität Ilmenau
Faculty of Mechanical Engineering
Department of Precision Engineering
P.O. Box 10 05 65
D-98684 Ilmenau
GERMANY
E-mail: rene.theska@tu-ilmenau.de

Virtual Prototyping, Modularisation, Complexity, Innovation

Abstract

The paper presents an approach and innovative initial results of virtual prototyping for the development of ultra precise positioning and measuring machines in a changing market.
The basic concept is to apply the modularisation at all levels of abstraction during the design process. Thereby machines can be used for a wide range of applications. Virtual prototyping supports the development in all phases of design. The paper describes a fundamental contribution to improve the development process of positioning and measurement systems for highest precision applications.

1. Introduction

The product development process (Figure 1) is more and more driven by changing market conditions. This requires flexibility of the product structures and design procedures as well as the reduction of design cycles. Shifting important design decisions from the concrete to the conceptual design phase can be one possible approach to meet these requirements.

Important design decisions can only be made if the designer has enough information about behaviour and properties of the product to be developed. To get this information based on facts in the early design phases the designer needs special methods and tools. Therefore virtual prototyping is a very useful method and it can be applied even in early design phases.

For this purpose virtual prototyping should be used in an applied case study dealing with the development of ultra high precision positioning and measuring machines. These machines have to meet the most stringent specifications over increasing wide areas of movement for certain application fields in nano-, micro- and biotechnology. And there is an increasing demand for positioning machines at a level of accuracy in the nanometre range [Jäger,Manske& Hausotte01]. Machines for that purpose are so called nanopositioning and nanomeasuring machines (NPM-machines).

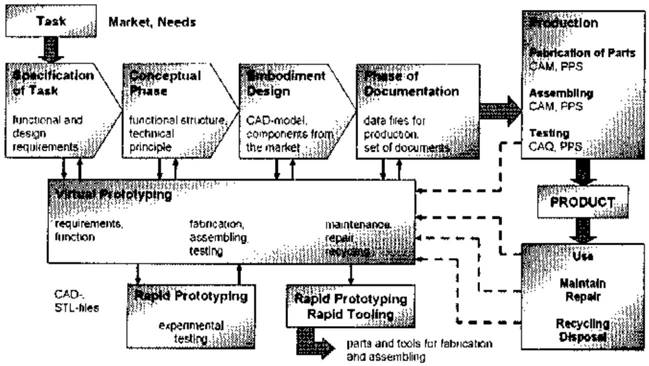


Figure 1. The product development process

Different tools are needed for application fields as mentioned above. But known positioning and measuring machines (Figure 2) are developed as unique systems for only one application and only few tools. To open up several fields of application a whole new generation of machinery with a huge flexibility has to be developed.

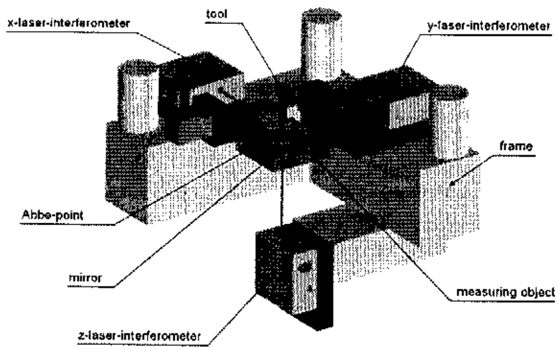


Figure 2. Principle of the NMM 1 [Hausotte02]

The current objective is to meet the specifications of the various fields of application by configuring and combining appropriate modules [Aarnio&Riitahuhta02] to different products for the respective fields. In particular, the question is whether a platform concept can be applied in situations requiring such extreme accuracy. For practical and financial reasons it is impossible to test each possible solution experimentally. Thus a further objective is to reach a decision on the best possible design for the ultra precise machine by the use of virtual prototyping.

This includes also the development and evaluation of design guidelines for machines working at this high level of accuracy.

The knowledge obtained from this research is intended to support the designers of such machines by offering development principles and design guidelines which have been systematically expressed. Thus the work is contributing substantially to the design of complex technical systems.

2. The technological requirements

The starting point for such system design is the analysis of the technological processes in which the nanopositioning and nanomeasuring machines are used. For that purpose first of all it is necessary to describe the operations (e.g. testing, measuring, manipulating) that must be carried out by the machine (Table 1).

Table 1. Application fields and necessary functions of NPM-machines

functions of NPM-machines	application fields of NPM-machines in electronics	nano-optics	nano-fabrication	nano-materials	bio-technology	nano-metrology	...
calibrating						■	...
measuring	■	■	■	■		■	...
testing	■	■	■	■	■		...
manipulating	■		■		■		...
treatment	■	■	■				...
structuring	■	■	■	■	■		...
assembling			■		■		...
...	...	...	...	...	...	...	...

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

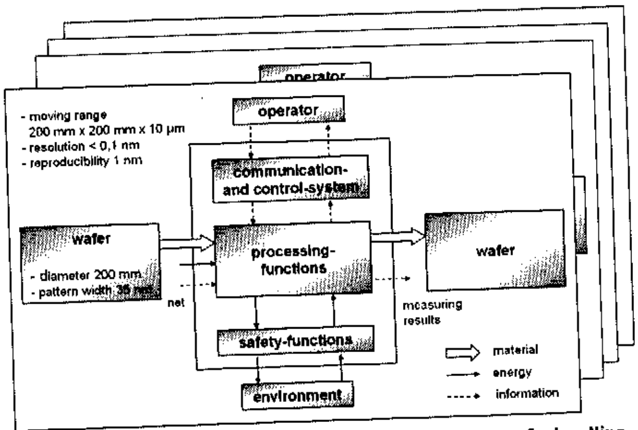


Figure 3. Overall function of a nano-positioning system for wafer handling

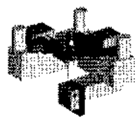
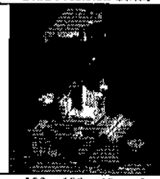
The objective to serve various technological processes by means of a small number of different technical equipments leads to the conception of modular systems.

For example the machine should be used for testing and measuring the surface quality of wafers with microelectronic circuits. This typical specification of the function measuring (Figure 3) gives the example of other application areas.

3. State of the art

The current situation in the area of 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. Table 2 presents a selection of such technical systems used for measuring of micro- and nanoscale structures.

Table 2. NPM-machines (selection)

	type			
name	NMM I	M^3	Ultra Precision CMM	Ultra Precision CMM
				
moving range	25 x 25 x 5 mm^3	50 x 50 mm^2	100 x 100 x 40 mm^3	300 x 300 x 300 mm^3
developer	TU Ilmenau [Hausotte02]	NIST [Kramar01]	TU Eindhoven [IBS04]	BUPE [KAIST03]

Analysing functions and structures of the existing systems the 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;
- extremely high accuracy is realised by precision guides with special means to isolate / separate them from disturbing influences;
- bases and frames have high stiffness, good long-term stability and they are optimised to minimal thermal deformations.

4. Systematic approach to a modular product structure

As a result of the state of the art investigation a general functional structure of this type of machines can be established (Figure 4). In consideration of the objective to serve technologies of the application fields presented in Table 1 this function model forms a base for developing a new generation of nanopositioning machines. It should provide enabling technologies of measuring, handling, processing etc. of nanoscale objects and macroscopic objects with high precision. To reach this objective the design of the machines has to meet the following main requirements in addition to the generalised properties:

- flexible configurability in relation to the required technological process;
- long-term stability of the machine and good dynamic behaviour;
- realisation of wide moving ranges of about 200 mm x 200 x 30 mm;
- high degree of communality for the different types of machines.

In compliance with the well-known rules of modularisation [Hofer&Gruenenfelder01], 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, the measuring system and the communication and control system form the platform elements (see Figure 4). Tools and objects vary according to the technology needs of the application. Therefore the tools and the fixtures of the objects are so called non-platform elements designed or selected especially for each type of machine. These machines are produced in small numbers, so that a function-oriented configuration is indicated.

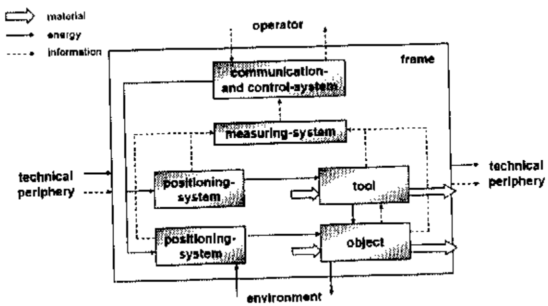


Figure 4. General functional structure of NPM-machines

5. Function-oriented configuration

The sequence of activities which is required to run the design process of the described types of machines is presented in Figure 5.

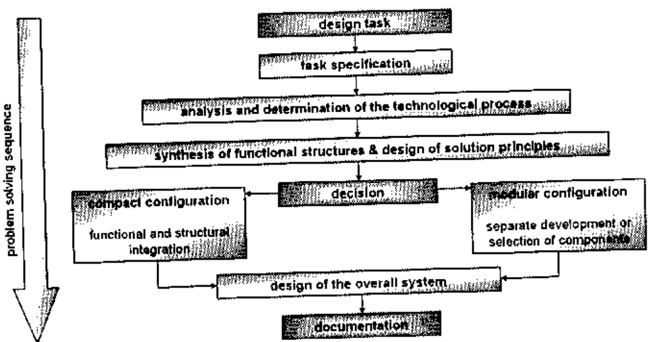


Figure 5. The design process for function-oriented configuration

The initial point of such a design is the analysis of the technological processes in which the nanopositioning machines are used. The first stage is finished, if the acquired specifications for each type of machine are listed. Any recurring operations will offer a potential basis for modularisation.

After specification of the task it is necessary to analyse and determine the technological operations which the machine has to carry out (e.g. inspection, measurement, probing, adjustment and processing). Following the designer has to find and describe the object and the tool(s) as well as the relative movements between them and the states of the object (Figure 6). This is an important step for the whole machine design. It is crucial for the dynamic and precision of the machine which movements have to be realised by the tool or by the object. Known NPM-machines use a serial mechanism with a movable object and a fixed tool. Often the so called Abbe-principle is realised which avoids first order measuring errors.

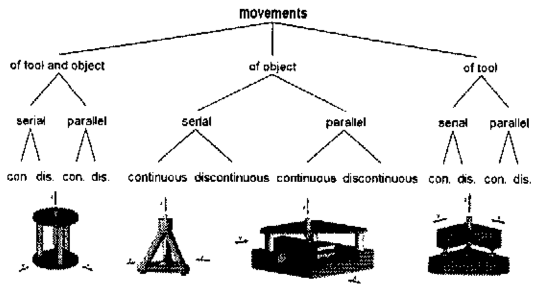


Figure 6. Decision tree for determination of the movement of object and tool

In the third stage the functional structure is the basis of the systematic determination of all principles to be applied in the design solution. This solution includes positioning units, measuring units, controller, tools and any further components.
The third stage starts with the design of structures around the functions. Possible alternatives are the design of the structure from sub-functions to match the application or the reduction of an imaginary maximum structure. To considerate the platform concept and the possibilities of virtual prototyping the second option is preferred (Figure 7). It is easy to store and present this structure by means of a computer.

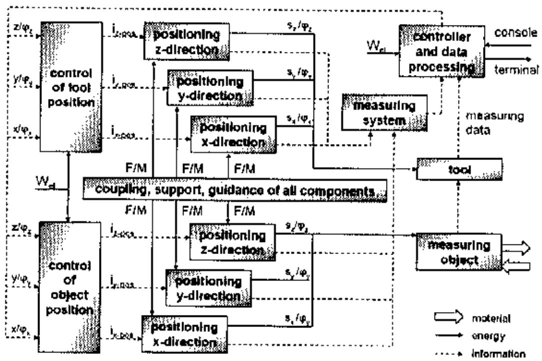


Figure 7. Maximum functional structure of a NPM-machine

The designer can eliminate the unneeded sub-functions. For example known NPM-machines have a fixed tool and a moved object. Because of this the tool control and the tool positioning systems are not needed and can be eliminated from the maximum functional structure (Figure 8). With this kind of functional structure it is possible to describe different variants and to realise which elements are needed. It is also possible to describe necessary interfaces between the elements.

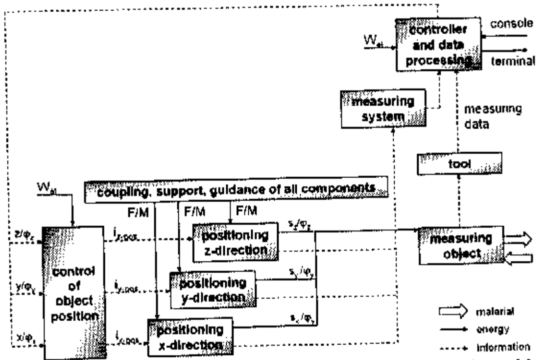


Figure 8. Reduced maximum functional structure of a NPM-machine

The fourth stage in the methodology concerns the design of the embodiment and ends with the detail design including all necessary documentations.
The specified functional structure and the determination of the movements are the basis of the function-oriented configuration of the machine. Figure 9 has in store solution principles for the platform components. This matrix can be expanded to include new potential solutions. For example weight compensation mechanisms or control systems can be included as new subsystems with their different variants.

subsystem	variants					
frame	column type	portal type	pillar type	console type	bridge type	...
guidance	roller bearing	sliding bearing	aerostatic bearing	magnetic bearing	spring guidance	...
drive	moving coil	piezo	friction drive with motor	spindle drive with motor	linear step-motor	...
measuring system	interferometer	incremental optical	capacitive	inductive	incremental inductive	...
tool	AFM	STM	electron-beam	laser-beam	cantilever	...
...	...	...	...	...	...	...

Figure 9. Configuration matrix for NPM-machines

It is possible to store this matrix as a computer based database. Known information like parameters and properties of the variants can be included. This database can also store functional structures and design rules to assist the designers in their choice. Because of this the configuration matrix can be a powerful tool for the whole design process.

Figure 10 shows two possible design variants of a NPM-machine. Both have a serial design with a moved object. To realise different vertical moving ranges the configuration matrix is used. As a result the variants use the same base, x- and y-guidance and drives. Only the z-drive and guidance are different.

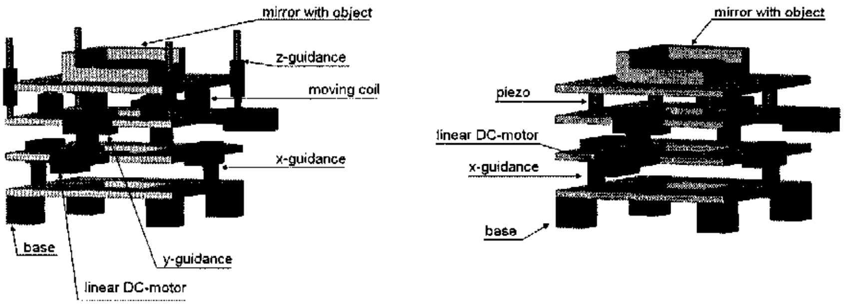


Figure 10. Design variants of a NPM-machine with large and small vertical moving range

6. Virtual prototyping of main design steps

The complete layout of the machine is established as a virtual prototype by combination of selected components so that a number of design variants are generated. Figure 11 shows as an example the design of a z-axis of a NPM-machine. It consists of a mirror, fixation elements, guidance, drives and weight compensation. Because it is a virtual prototype different variants can be tested easily. For example the fixation of the mirror or the two different weight compensation mechanisms can be tested to determine their possible position in the designed space.

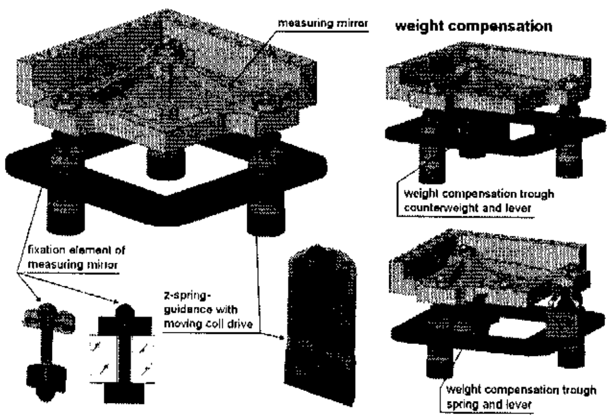


Figure 11. Z-axis of a NPM-machine with weight compensation

Furthermore the analysis and evaluation of the performance, accuracy and other properties of the configured machine variants is supported by virtual prototyping. The virtual prototyping method [Kunz&Meier01, Spur&Krause97] is used to check both – that the principles will work and that the general form is sound.

MASP, a design tool for constraint solving [Brix,Döring&Reeßing03], is used to simulate movements, forces and tolerances of a principle solution. Its application is shown in Figure 12. Here a weight compensation mechanism is described as a functional structure in MASP. It is possible to simulate the transfer function of the spring mechanism. To simulate its dynamic behaviour the functional structure has to be transferred in an embodiment design as shown in the picture.

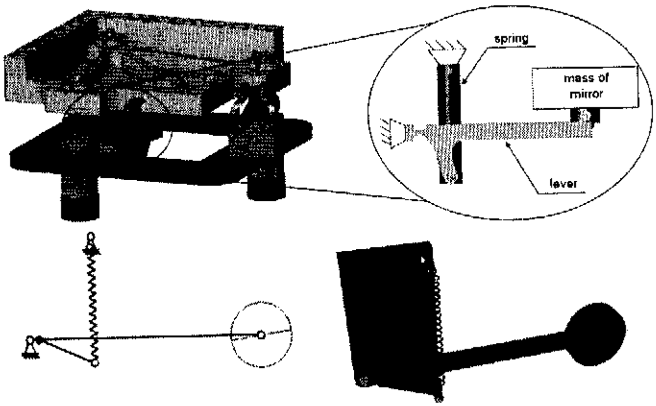


Figure 12. Virtual prototyping of a weight compensation mechanism

Following tools are simulation with multi-body systems and finite element analysis [Hochmuth&Meerkamm01]. It is likewise essential to make estimates for tolerances and faults in the designed modules and in the overall system and, where necessary, to minimise them by means of regulatory or compensatory mechanisms. By means of simulation starting at the initial planning state, at the level of principle and rough embodiment design it is possible to make fundamental decisions on the optimum design.

7. Conclusion

The paper presents concepts for a virtual design starting in early design phases to develop ultra precise positioning and measuring machines. A consistent description of the model at various levels of abstraction (functional structure, technical principle, rough design) is shown. Using a four-stage process of synthesis which can be used to design complex systems leads to interim results. These results are described as virtual prototypes. Thus it is possible to make fundamental decisions on the optimum design even at the initial planning stage. The simulations are carried out with assistance of constraint solving, multi-body systems and finite element analysis.

As a result of the research the designer will be equipped with:

- a plan of the sequence and guidelines for the design of the machines;
- a modular concept on which to base the design;
- a matrix of the modules which would be possible to use;
- a list of the various means of regulation, simulation and evaluation.

The presented methods are very useful for the design of complex systems especially for systems which consist of modules or many different variants. It is possible to test complex structures like moving parts and assemblies virtually before physical prototypes exist. Because of this time and money can be saved.
All methods should be applicable also to other areas of mechanical engineering. Further research has to be done to evaluate them on other examples.

Acknowledgement

The authors would like to thank for the support provided by the Deutsche Forschungsgemeinschaft and the members of the collaborative research centre 622 "Nanopositionier- und Nanomessmaschinen" at the Technische Universität Ilmenau.

References

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.

Brix, T.; Döring, U.; Reeßing N., "Multi-stage modelling in early phases of design", Proceedings of ICED 03, Stockholm, 2003, pp 279-280.

Hausotte, T., "Nanopositionier- und Nanomessmaschine", Dissertation, Isle, Ilmenau, 2002.

Hochmuth, R.; Meerkamm, H., "Approach to evaluate the precision of technical systems", Proceedings of ICED '01, Vol. 3, Glasgow, 2001, pp.C586/031.

Hofer, A. P.; Gruenenfelder, M., "Product family management based on platform concepts", Proceedings of ICED '01, Vol. 3, Glasgow, 2001, pp.C586/631.

IBS Precision bv, "UP CMM – Ultra Precision Coordiante Measuring Machine", http://www.ibspe.com/main/news/Poster%20UP-CMM%20A4.pdf (2004-04-15)

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

KAIST, "BUPE: Annual Report 2003", http://pem.kaist.ac.kr/bupe/Annual%20Accomplishments%20for%20FY%202003.htm (2003-11-05)

Kramar, J., "Molecular measuring machine research and development", NIST Manufacturing Engineering Laboratory, USA, 2001.

Kunz, A.; Meier, M., "Innovation at the digital product - the use of virtual product development process", Proceedings of ICED '01, Vol. 1, Glasgow, 2001, pp.693-700.

Spur, G.; Krause, F.-L., "Das virtuelle Produkt: Management der CAD Technik", Hanser, München, 1997.