INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 03 STOCKHOLM, AUGUST 19-21, 2003

DEVELOPING A NEW GENERATION OF POSITIONING AND MEASURING MACHINES BY MEANS OF VIRTUAL PROTOTYPING

G. Höhne, M. Lotz, R. Theska, T. Brix, T. Frank and T. Hackel

Abstract

The configuration of a nano-positioning and measuring machine depends on its application fields. 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 accuracy. 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: Complexity, mechatronics, modularisation, virtual prototyping

1. Introduction

Ever increasing complexity is the mark of the automated machinery and equipment used in technical, experimental or manufacturing processes. Multi-coordinate positioning and measuring machines 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 example is the processing and measurement of wafers for micro-electronics. Before long there will be a need for positioning systems at a level of accuracy in the nanometer range. The equipment for this purpose will include mechanical, electrical, electronic and software components. Because of this the design must be tackled as a mechatronics project. The machinery makes use of a variety of tools to open up fields of application in micro-mechanics, 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 question is whether a platform concept can be applied in situations requiring such extreme accuracy. A further objective has to be the reaching of a decision on the best possible design for the machinery in question by the use of virtual prototyping. The knowledge obtained from this research is intended to benefit the designers of such machinery by offering them design principles which have been systematically expressed.

2. Specification of the technological requirements

The starting point for such system design is the analysis of the technological processes in which the nano-positioning and measuring machines (npm-machines) are to be made use of.

For that purpose it is necessary to describe first of all the operations that must be carried out by the machine in terms of the principles of inspection, measurement, probing, adjustment and processing involved (Table 1).

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

functions of npm- machines	application fields of npm-machines in nano-						
	electronics	optics	fabrication	materials	biotech-nology	metrology	…
calibrating	1.1	2.1	3.1	4.1	5.1	6.1 ■	…
measuring	1.2 ■	2.2 ■	3.2 ■	4.2 ■	5.2	6.2 ■	…
testing	1.3 ■	2.3 ■	3.3 ■	4.3 ■	5.3 ■	6.3	…
manipulating	1.4 ■	2.4	3.4 ■	4.4	5.4 ■	6.4	…
treatment	1.5 ■	2.5 ■	3.5 ■	4.5	5.5	6.5	…
structuring	1.6 ■	2.6 ■	3.6 ■	4.6 ■	5.6 ■	6.6	…
assembling	1.7	2.7	3.7 ■	4.7	5.7 ■	6.7	…
…	…	…	…	…	…	…	…

For specifying a certain application case a generalised model (Figure 1) is 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.

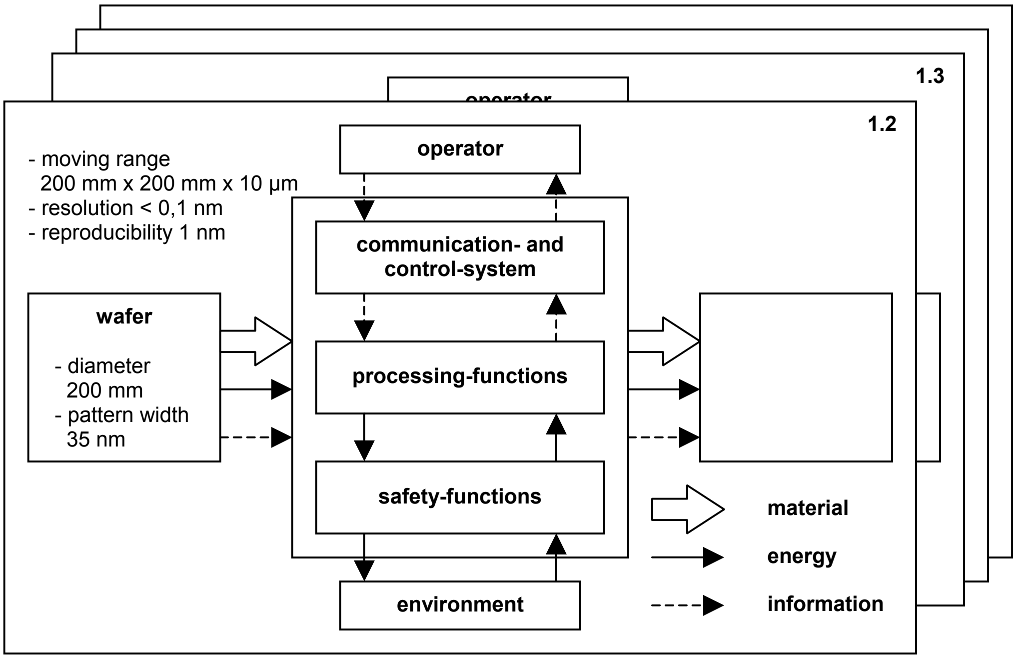


Figure 1. Overall function of a nano-positioning system.

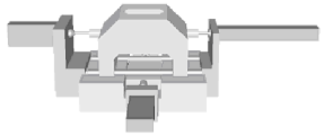
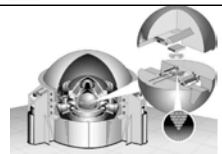
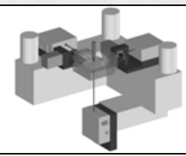
The objective to serve various technological processes by means of a small number of different technical equipments leads to the conception of modular systems.

The machine should be used for testing and measuring the surface quality of wafers for micro-electronic circuits. This exemplary specification of the fields 1.2 and 1.3 give the sample of the other application areas.

3. State of the art and systematic approach to a modular product structure

The actual situation in the area of ultra high precision positioning and measuring machines is characterised by special constructions developed for a particular use. There are a variety of single-purpose machines [1, 2, 3, 4] individually designed as unique objects. Table 2 presents a selection of such technical systems used for measuring of micro- and nano-scale structures.

Table 2. Multiple coordinate nano-measuring systems (selection).

type	technical specifications		structure
"Nano-CMM" [3]	arrangement: moving range: precision: reproducibility:	x-, y- and z-drive (y parallel) 10 mm x 10 mm x 10 mm resolution of scale 10 nm 20 nm	
"Parallel-CMM" [3]	arrangement: moving range: precision: reproducibility:	parallel; x-, y- and z-drive about 100 mm - 2 µm	
"M3" - Molecular Measuring Machine [4]	arrangement: moving range: precision: reproducibility:	serial; x- and y-drive 50 mm x 50 mm 10 nm -	
"NMM 1" Nano Measuring Machine 1 [2]	arrangement: moving range: precision: reproducibility:	serial; x-, y- and z-drive 25 mm x 25 mm x 5 mm resolution 1,24 nm 60 nm	
…	…	…	…

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

- all systems realise a relative multiple-coordinate movement between an object and a tool
- the movements are controlled in a closed loop
- the extremely high accuracy is realised by precision guides with special means to prevent them from disturbing influences
- the bases and frames have high stiffness, good long-term stability and they are optimised to minimise thermal deformations

As result of this investigation can be established a general functional structure of this type of machines (Figure 2). 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 nano-positioning machines. It should provide the user with the enabling technology of measuring, handling, processing etc. of nano-scale objects and macroscopic objects with high precision. To reach this objective the construction of the machines have to meet in addition to the generalised properties the following main requirements:

- flexible configurability in relation to the required 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

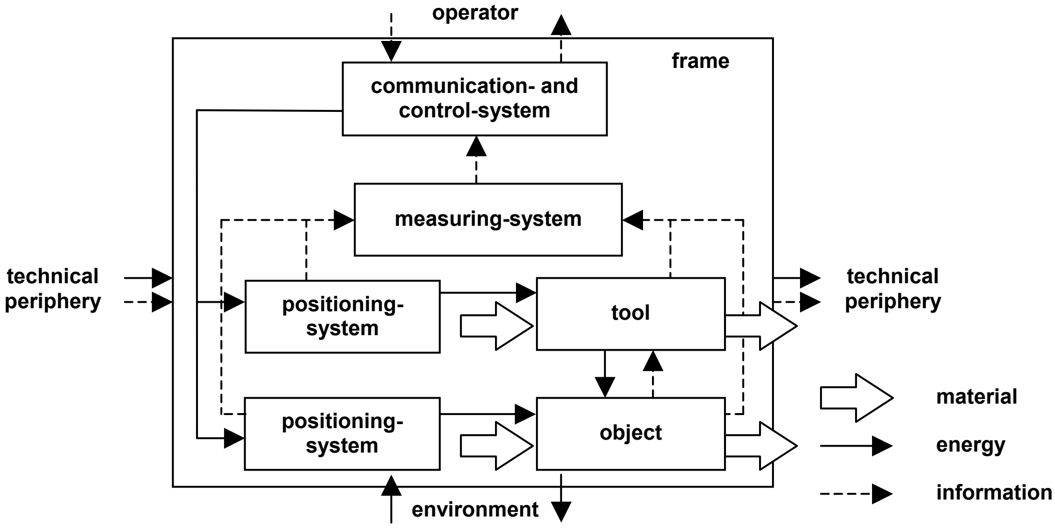


Figure 2. General function structure of nano-positioning machines.

In compliance with the well-known rules of modularisation [5, 6], 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 forms the platform elements (see Figure 2). Tools and objects varies 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 specially for each type of machine. These machines are produced in small numbers, so that a function-oriented configuration is indicated.

4. Function-oriented configuration of solution principles and preliminary layout

The sequence of activities required to run the design process of the described types of machines is presented in Figure 3.

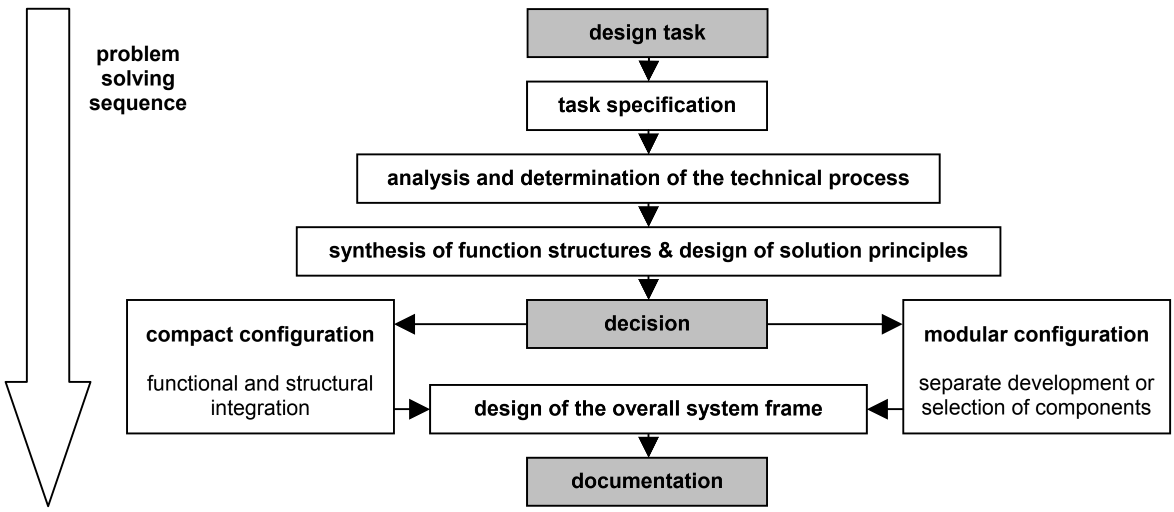


Figure 3. The design process for function-oriented configuration.

After specification of the task according Figure 2 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 and the states of the object (Figure 4).

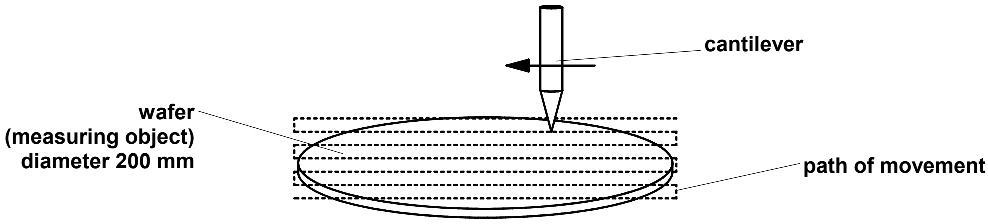


Figure 4. Measuring of an object and the path of relative movement (symbolic).

This investigation specifies the overall function of the machine to be developed. The third stage will be to design structures around the functions; here the possible alternatives will be either to build up of the structure from sub-functions to match the application or the reduction of an imaginary maximum structure. Considerating the platform concept and the possibilities of virtual prototyping the second option is preferred. It is easy to store and present this structure by means of a computer. The designer can eliminate the not needed sub-functions (Figure 5).

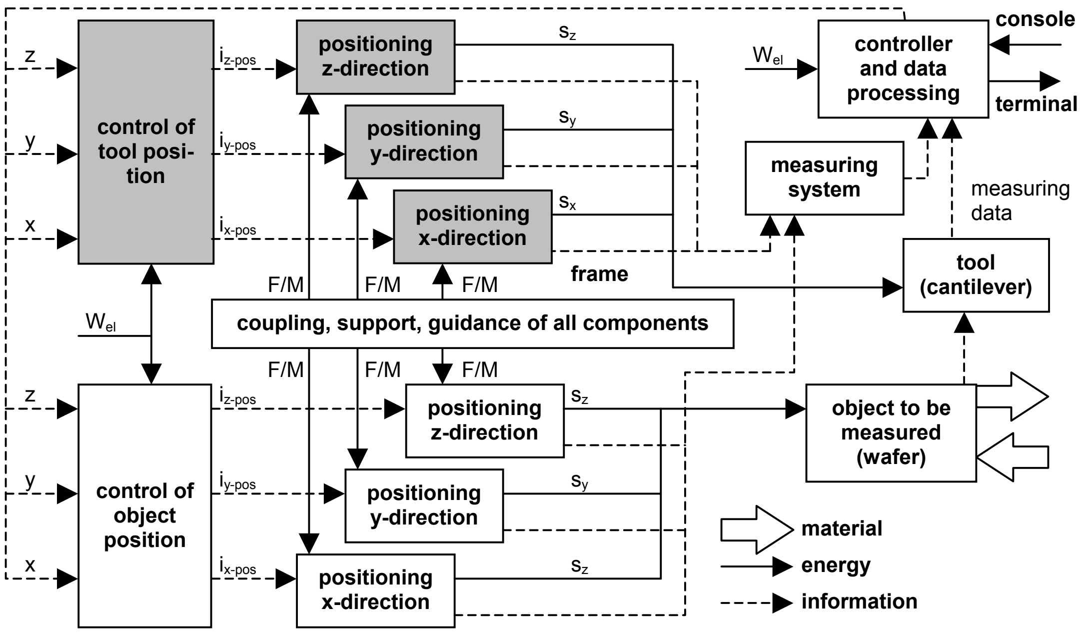


Figure 5. Maximum function structure specified for the wafer inspection by elimination of the shadowed sub-functions.

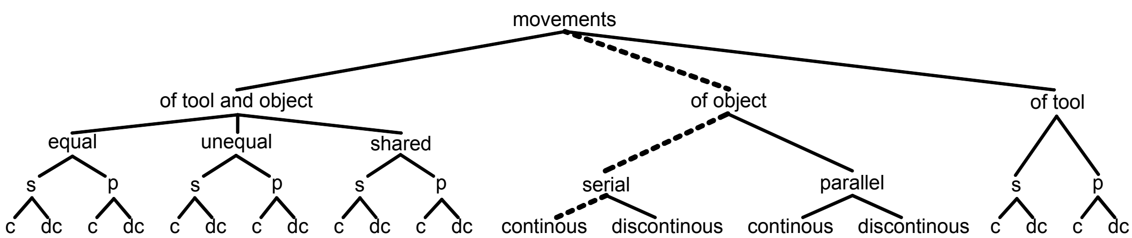


Figure 6. Decision tree for determination of the movements of object and tool (marked path of actual decision).

The selection of the adequate sub-functions can be supported by a decision tree (Figure 6). In the chosen case of wafer inspection high accuracy can be reached if the cantilever is fixed and the object moves in three coordinates continously in a serial arrangement of the positioning systems (meeting the Abbe principle).

Table 3. Configuration matrix for nano-positioning and measuring machines.

sub-system	variants					
frame	1.1 column type	1.2 portal type	1.3 pillar type	1.4 console type	1.5 bridge type	…
guidance	2.1 roller bearing	2.2 sliding bearing	2.3 aerostatic bearing	2.4 magnetic bearing	2.5 spring guidance	…
drive	3.1 moving coil	3.2 piezo	3.3 friction drive with motor	3.4 spindle drive with motor	3.5 linear step-motor	…
tool	4.1 AFM	4.2 STM	4.3 electron-beam	4.4 laser-beam	4.5 cantilever	...
measuring system	5.1 interfero-meter	5.2 incremental optical	5.3 inductive	5.4 capazitve	5.5. incremental inductive	…
…	…	…	…	…	…	…

The specified functional structure and the determination of the movements are the basis of the function-oriented configuartion of the machine. Table 3 has in store solution principles for the platform components. This matrix can be expanded to include new potential solutions.

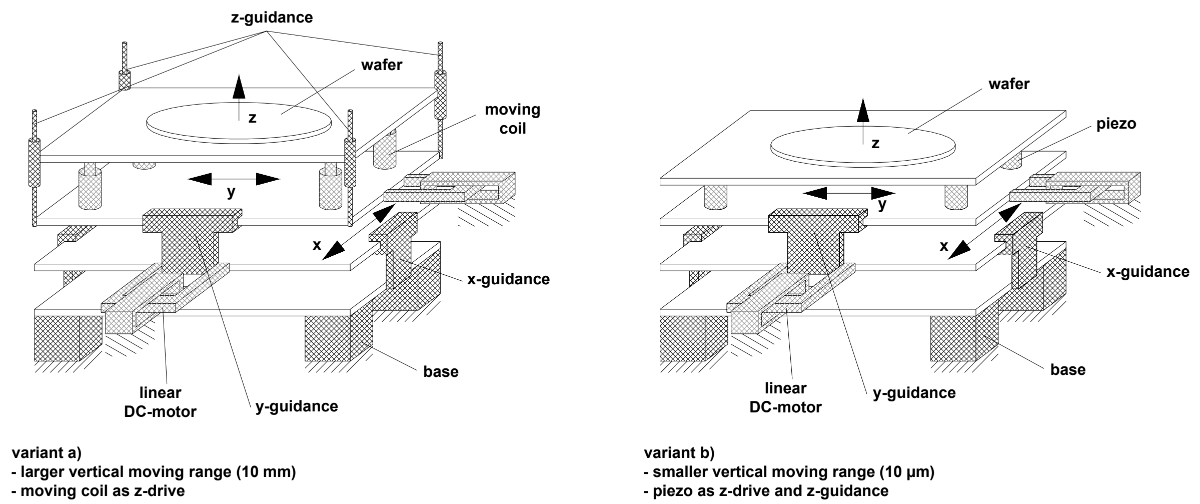


Figure 7. Three coordinate positioning units.

5. 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. Two examples of the positioning sub-system in Figure 7 are configurated from variants 2.1, 3.1 and 3.2 which will be used in the overall frame 1.1 together with a cantilever of 4.5 and a coordinate measuring system 5.1. The analysis and evaluation of the performance, accuracy and other properties of the configurated machine variants is supported by virtual prototyping.

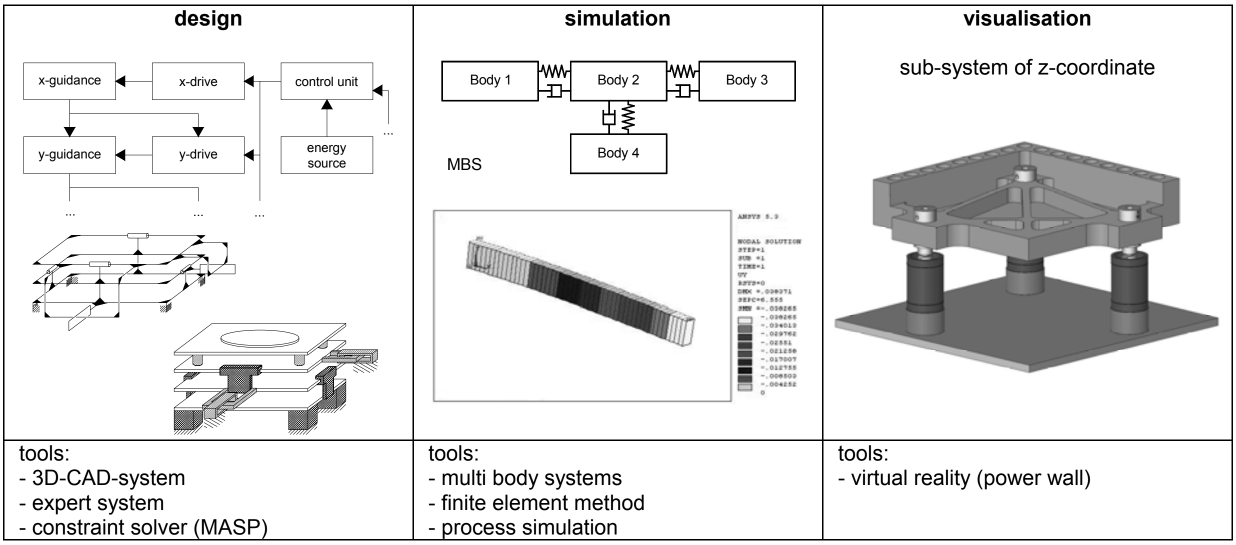


Figure 8. Virtual prototyping in function oriented configuration.

The virtual prototyping method [7, 8] is used to check both – that the principles will work and that the general form is sound (Figure 8). MASP, a new design tool for constraint solving [9, 10], 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 [11]. It is likewise essential to make estimates for tolerances and faults in the modules designed and in the overall system and, where necessary, to minimise them by means of regulatory or compensatory mechanisms. By means of simulation at the initial planning state at the level of principle and rough embodiment design it is possible to make vital decisions on the optimum construction.

6. Conclusion

The paper reflects the concerns of ICED 03, offering a plan and innovative initial results for the development of a new generation of positioning and measuring machines working at ultra precise accuracy. By modularising the structure of the product, the construction of machinery can be made relevant to a wide range of fields of application. It is apparent that parameters must be set even in the earliest stages of development, and for this the virtual prototyping method and the use of simulation of functions make a vital contribution to improved development. The designer will be equipped with:

- a modular concept on which to base the construction
- a plan of the sequence for designing the machinery
- a matrix of the modules it would be possible to use, i.e. a range of virtual prototypes
- a list of the various means of regulation, simulation and evaluation

to assist with the complex task of development.

7. Acknowledgement

The authors would like to thank for the support provided by the Deutsche Forschungsgesellschaft and the members of the SFB 622 at the TU Ilmenau.

References

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

[2] Hausotte, T., “Nanopositionier- und Nanomessmaschine”, Dissertation, Isle, Ilmenau, 2002.

[3] Takamasu, K.; Hiraki, M.; Enami, K.; Ozono, S., “Development of nano-CMM and parallel-CMM – CMM in the 21th century”, Proceedings of International Dimensional Metrology Workshop 1999, Tennesse, 1999.

[4] Kramar, J., “Molecular measuring machine research and development”, NIST Manufacturing Engineering Laboratory, USA, 2001.

[5] Hofer, A. P.; Gruenenfelder, M., “Product family management based on platform concepts”, Proceedings of ICED ’01, Vol. 3, Glasgow, 2001, pp.C586/631.

[6] 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.

[7] Spur, G.; Krause, F.-L., “Das virtuelle Produkt: Management der CAD Technik”, Hanser, München, 1997.

[8] 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.

[9] Brix, T.; Brüderlin, B.; Döring, U.; Höhne, G., “Feature- and constraint-based design of solution principles”, Proceedings of ICED ‘01, Vol. 1, Glasgow, 2001, pp.613-6200.

[10] Brix, T.; Döring, U.; Reeßing N., “Multi-stage modeling in early phases of design”, Proceedings of ICED ‘03, Stockholm, 2003.

[11] Hochmuth, R.; Meerkamm, H., “Approach to evaluate the precision of technical systems”, Proceedings of ICED ’01, Vol. 3, Glasgow, 2001, pp.C586/031.

Prof. G. Höhne, M. Lotz, Prof. R. Theska, Dr. T. Brix, T. Frank and T. Hackel
Technical University of Ilmenau, Department of Mechanical Engineering, Engineering Design Group
PO Box 100565, 98684 Ilmenau, Germany
Phone: +49 3677 69 2473, Fax: +49 3677 69 1259
E-mail: guenter.hoehne@tu-ilmenau.de and markus.lotz@tu-ilmenau.de