DESIGN OF HIGH PRECISION POSITIONING AND MEASURING MACHINES USING VIRTUAL PROTOTYPING

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Abstract

Multi-coordinate positioning and measuring machines (NPM machines) of high accuracy in range of nanometres are enabling 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 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

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 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: 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 example 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 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 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 have 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
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 (Table 1). 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

<table>
<thead>
<tr>
<th>Functions of NPM machines</th>
<th>Application fields of NPM machines in</th>
<th>Electronic</th>
<th>Nanooptics</th>
<th>Nano-fabrication</th>
<th>Nano-materials</th>
<th>Bio-technology</th>
<th>Nanometrology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibrating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measuring</td>
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<td>■</td>
<td>■</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Testing</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td></td>
<td>■</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manipulating</td>
<td>■</td>
<td>■</td>
<td>■</td>
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<td>■</td>
<td></td>
</tr>
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<td>Treatment</td>
<td>■</td>
<td>■</td>
<td>■</td>
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<td></td>
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<td>■</td>
</tr>
<tr>
<td>Structuring</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td></td>
<td></td>
<td></td>
<td>■</td>
</tr>
<tr>
<td>Assembling</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td></td>
<td>■</td>
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<td></td>
</tr>
</tbody>
</table>

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

Analysing 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 construction from disturbing influences.

One fundamental concept to accomplish this objectives is the arrangement 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.
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 measuring units, the frame and the control and data processing components are the basic platform components.

![Diagram of the measuring system](image)

**Figure 2: Principle of the measuring system**

Tools and fixtures of objects are so called non platform components designed or selected for each type of machine. With respect to the different application areas of such machines a function-oriented configuration is 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.

![Diagram of the maximum function structure of the machine](image)

**Figure 3: Maximum function structure of the machine**
<table>
<thead>
<tr>
<th>Modules</th>
<th>Variants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>![Frame Variants]</td>
</tr>
<tr>
<td>Metrology frame</td>
<td>![Metrology Variants]</td>
</tr>
<tr>
<td>Mirror</td>
<td>![Mirror Variants]</td>
</tr>
<tr>
<td>Guides</td>
<td>![Guides Variants]</td>
</tr>
<tr>
<td>Gravity force compensation</td>
<td>![Gravity Variants]</td>
</tr>
<tr>
<td>Fixation elements</td>
<td>![Fixation Variants]</td>
</tr>
<tr>
<td>...</td>
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</tbody>
</table>

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).

![Variants of the overall structure](https://via.placeholder.com/150)

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 Serial 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 preferred.

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 to simulate these properties as early as possible using virtual prototypes and optimize the dominating parameters for saving time and effort in the concrete states of the design process and the bodily realization.

4.2 Simulation of Solution Principles

Based on the favored 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

<table>
<thead>
<tr>
<th>Type of information</th>
<th>Possibilities for analysis, simulation and optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualitative described elements and relations</td>
<td>characteristic of motion combination of solution elements classifications</td>
</tr>
<tr>
<td>Quantitative described elements and relations</td>
<td>variation of the element number, form and position Variation of dimensions working space, overall and connecting dimension error and tolerance analysis</td>
</tr>
<tr>
<td>Functional quantities</td>
<td>kinematics, static,...</td>
</tr>
</tbody>
</table>
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 6: Design system MASP with the motion concepts of a) a serial layout and b) a parallel layout of a NPM machine](image)

![Figure 7: Interdependences of the NPM machine components](image)
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 element 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).

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

![Figure 9: Operations of the FEA processing](image)

![Figure 10: FEA on the measuring mirror of a NPM machine](image)
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 lightweight design using alternative materials and joining technologies are necessary. One possible approach is shown in Figure 11.

![Figure 11: Extreme lightweight design of a new measuring mirror](image)

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 steps of the design process with the means of virtual prototyping](image)

6. Acknowledgement


