

# DESIGN PRINCIPLES FOR HIGHEST PRECISION APPLICATIONS

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## Introduction

Ultra precise multi-axis positioning and measuring machines have been identified as an enabling tool in the current developments in nanotechnology and further beyond. Therefore machines with an increasingly large spatial travel are being demanded while reaching accuracy in the nanometer range. High flexibility for various applications in metrology, micro-mechanics and nanotechnology is feasible. Known machines show that requirements of highest precision applications cannot be reached only through the use of closed loop control [1, 2, 3]. With a systematic machine design it is possible to better handle environmental influences and machine behavior.

## State of the Art

Machines with best accuracy and precision are required for measurement tasks in various precision applications. Therefore universal coordinate measuring machines (CMM) are used, conducting a relative motion between an object and a special tool like probe head, AFM-tip, optical sensor or another. CMM can be divided into three categories, depending on the working range, as to be seen next (Figure 1).









	Large Range		Small Range	
Name	Leitz PMM-C	Zeiss UPMC 850	Veritekt-B SPM	Veeco Explorer SPM
Structure				
Moving range	1.2 x 1.0 x 0.7 m <sup>3</sup>	1.15 x 0.8 x 0.6 m <sup>3</sup>	70 x 15 x 15 μm <sup>3</sup>	100 x 100 x 10 μm <sup>3</sup>
Developer	Leitz Messtechnik Germany [Leitz 2004]	Carl Zeiss IMT Germany [Zeiss 2004]	TU Ilmenau / PTB Germany [Jäger 1999]	Veeco Instruments USA [Veeco 2004]
	Medium Range			
Name	NMM 1	Molecular Measuring Machine	Ultra Precision CMM	Ultra Precision CMM
Structure				
Moving range	25 x 25 x 5 mm <sup>3</sup>	50 x 50 mm <sup>2</sup>	100 x 100 x 40 mm <sup>3</sup>	300 x 300 x 300 mm <sup>3</sup>
Developer	TU Ilmenau Germany [Hausotte 2002]	NIST USA [Kramar 2001]	TU Eindhoven Netherlands [Ruij 2002]	BUPE Korea [KAIST 2003]

Figure 1 – State of the Art machines

To reach best as possible accuracy all different error sources have to be considered for machine control and correction of the measurement result. One example is the CMM Sirio from Leitz Messtechnik which is

equipped with 28 temperature sensors to estimate machine deformations [4].

## Methods

To design machines for highest precision applications successfully a systematic approach is necessary. One possible approach is a four stage process (Figure 2) consisting of task specification, analysis and determination of the technological process, synthesis of functional structures including the design of solution principles and at last the design of the overall system. For the development of a nanopositioning device with a moving range of 200 x 200 x 15 mm<sup>3</sup> [5] this four stage process has been used.

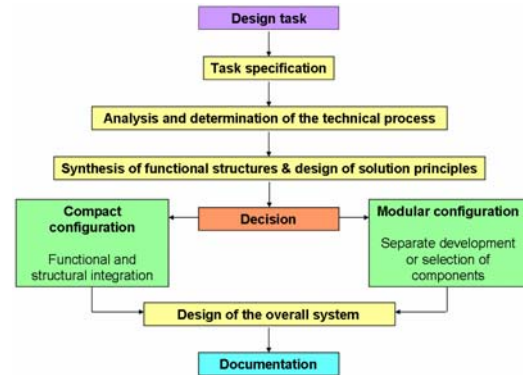


Figure 2 – Four stage design process

It starts with the specification of the task that has to be fulfilled. The next step is the analysis of the required technological processes and the given boundary conditions. Therefore all operations which have to be carried out have to be described. It leads to a generalized model that describes the overall function of the machine as well as the interactions with the expected environment.

In the next step a general functional structure can be established which serves as a base for the whole design. All necessary functions are in it included and described. Figure 3 shows a functional structure for a positioning and measuring system. It is used as a maximum functional structure this means it can be reduced if functions are not needed. For example tool movements are reduced to avoid error sources.

The functional structure leads to the design of the solution principles. These principles are the base of the whole machine design. Because of this they have to be developed with care. Design principles are applied to reach an optimum design beginning in this early phase

of development. Virtual Prototyping methods are used to check that the principles will work.

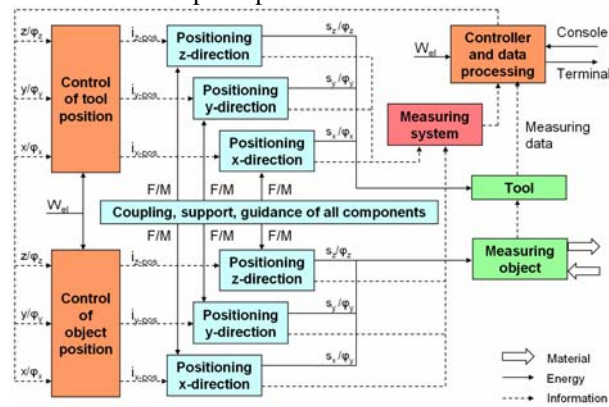


Figure 3 – Functional Structure

Tools and objects can 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 variant of machine. This function-oriented configuration is indicated because the machines are only produced in small numbers.

In the next stage the structures will be designed around the functions. The specified functional structure and the determination of the movements are the basis to realize the function-oriented configuration of the machine. A configuration matrix can be used to find possible solutions. This matrix can be easily expanded to include new potential solutions.

The last stage in the methodology concerns the design of the embodiment and ends with the detail design including all necessary documentations.

## Design Principles

High precision applications require machines with outstanding performance, which means very good dynamic behavior combined with highest precision. It is obvious and recommended that design principles should be used consequently for the whole machine design to reach these requirements [5, 6].

Unfortunately in times of high speed computers and closed loop control the importance and the benefits of design principles are underestimated. They can be used to:

- avoid random errors and reduce systematic errors,
- reduce the effects of environmental influences (e.g. temperature, vibration),
- realize a predictable system behavior,
- simplify the machine control.

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.

Because of this design principles should be applied beginning in this early stage of design. Nevertheless 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 next.

### Principle of Small Error Arrangement

Systematic and random errors should be avoided as best as possible. For example first order measuring errors can be eliminated by the arrangement of object and measuring system in one line according to the so called Abbe principle. This principle can be expanded also to three axes (Figure 4).

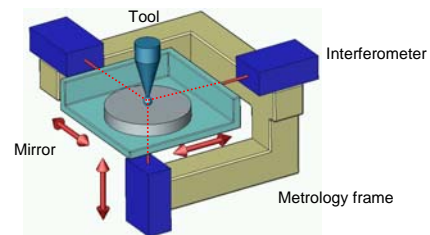


Figure 4 – Abbe principle for three axes

### Principle of Function Separation

Depending on the level of abstraction, the overall functional 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 fulfill a single defined function which reduces negative influences from interactions of several functions on the control loop. 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.

### Principle of Function Integration

On the opposite, the principle of function integration combines several functions in one component. It is applied for compact, miniaturized and lightweight design and less number of mechanical interfaces. Especially for auxiliary functions it is useful to apply this principle.

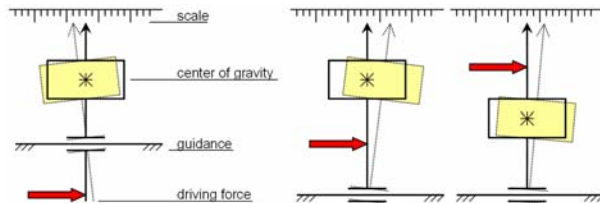
It strongly depends on the special case which of both principles should be applied.

### Principle of Force Transmission

A general principle of the precision machine design is to reach a short and direct force flow. To minimize 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. Methods of Virtual Prototyping can be used to simulate and optimize the force flow.

If a direct force flow without resulting moments is not possible additional measures should be taken. For example force should not result in a small contrary motion, as to be seen in the following picture (Figure 5).



**Figure 5 – Dynamic Force Compatible Arrangement**

In the left figure the driving force results in a small motion opposite to the force which can confuse the controller. To optimize the dynamic performance the right hand setups should be preferred.

#### *Principle 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.

#### *Principle 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.

Over constrained 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.

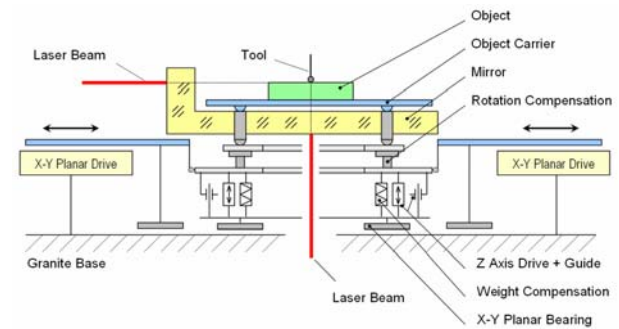
#### *Example*

One possible solution for a high precision machine is shown in Figure 6. The given design principles will be described on this example of a machine design.

The position of a three-face mirror, which carries the object is measured by three fixed laser interferometers. First order position errors are eliminated by the ar-

rangement of the interferometers. Abbe's principle will be respected in all three axes because 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 [2].

The metrological frame is separated from the machine frame (Figure 4). This isolates the metrological frame 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.



**Figure 6 – Technical Principle**

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 minimizes moments of tilt, which cause second order measurement errors.

To avoid hot spots and unwanted thermal influences the design is symmetric. The x-y planar drives are shielded by a plate to reduce convection. Therefore thermal influences to the laser beams can be reduced.

All couplings of functional elements are well constraint. This is very important to avoid deformations induced by dynamic forces or different expansion coefficients.

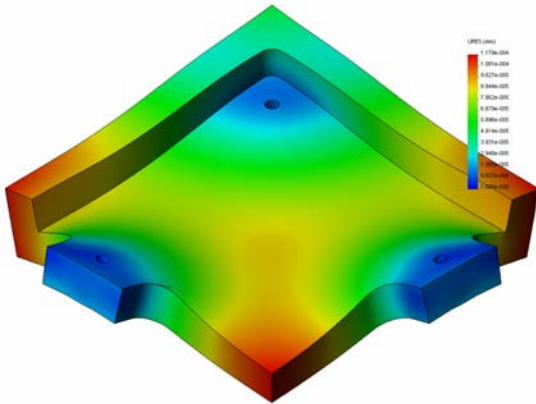
## **Virtual Prototyping**

Beginning in early phases of design the virtual prototyping method [7, 8, 9] can be used to check that the technical principles and the embodiment design consisting of parts and assemblies will work. For this purpose there are several different tools.

MASP, a tool for constraint solving, is used in our case to simulate movements, forces and tolerances of a principle solution. Following tools are that of simulation with multi-body systems (ALASKA) and that of finite element analysis (CosmosWorks and ANSYS).

One typical component for high precision machines is the measuring mirror of the interferometric measuring

system. It is necessary to measure the position of the object in three coordinates.



**Figure 7 – FEA deformation of measuring mirror**

For the given example of the measuring mirror (Figure 7) it is important to optimize the position of its supporting points. The aim is to minimize 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 points easily by only one parameter. The supporting points themselves were modeled as a contact area to comply with the real system as best as possible.

Virtual Prototyping is very useful and more and more necessary especially for important machine components which are often very complex and expensive. They can be tested without physical prototypes during the design phases. Therefore results of the simulations and knowledge of the future behavior can be integrated in the whole system design earlier.

The aim is to make important decisions on the optimum design in early phases of design. Thus it is possible to save time and money and to reach better design solutions.

## Conclusion

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.

By using virtual prototyping techniques it is possible to optimize 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 com-

ponents 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.

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## Key words

design principles, virtual prototyping, design methods