INTRODUCTION
The requirements of nanopositioning machines are to provide nanometer accuracy in a macroscopic spatial working volume. It should have traveling ranges of several decimeters in all directions, including the direction of gravity. That means to move macroscopic parts (e.g. measuring mirrors) and permanently actively support heavy weights in static and high dynamic modes. In order to prevent disturbances on the implemented measuring systems the dissipation loss of the actuators must be minimized. A methodical approach to the solution of this task must emanate from the design principles of precision engineering known from micrometer range. For reaching nanometer accuracy these principles must be applied, validated and refined. Therefore a nanopositioning stage with a long stroke in the vertical direction has been developed and tested to find out some basic experiences about nanometer positioning.

BASIC COARSE/ FINE CONFIGURATION
The basic idea to decrease dissipation loss coming from the active parts into the measuring system is to use actuators like self-locking spindle drives and piezotranslators that are able to oppose static loads like gravity in a nearly passive mode. Neither kind of actuator is able to fulfill the entire positioning task (both long stroke and nanometer accuracy). The same problem exists while selecting passive functional elements like guidings and bearings for the nanopositioning system. Thus the design principle of functional separation is used to combine the advantageous characteristics of dissimilar components e.g. to create fine/coarse driven structures. One possible variant of a basic technical principle working in one direction is shown in Figure 1. Different combinations of the number of actuators and passive DOF of the mechanism are possible. The shown technical principle describes a structure of actuators each with a associated guiding. Thus a precision actuator with a precision guiding e.g. elastic guiding and a coarse drive with a long travel guiding of reduced accuracy create cooperating substructures with dissimilar properties. As result the kinematic DOF of the structure is higher than the functional DOF of the object. Basically the static and dynamic positioning error of the coarse subsystem must be smaller than the traveling ability of the fine drive part.

KINEMATICS WITH HIGHER DOF
To create structures with higher maneuverability of the object the necessary number of the coarse/fine drive systems shown in Figure 1 could be combined kinematically in a series or a parallel (e.g. as hexapod) overall structure. Alternatively a fine drive substructure with the necessary DOF consisting of precision actuators and guidings can be set on top of a coarse drive substructure. This second variant has the following advantages. The fine drive components with little stroke allow the design of a lightweight optimized substructure for adjusting the positioning error in a dynamic mode. Thus the dynamic disturbance caused by the inertia while fine positioning can be minimized. Coarse drive components are more heavyweight but belong to the coarse substructure, whose primary task it is to provide a stable support for the fine drive sub-system and move it quasi-statically over relatively long ranges. Thereby a lightweight optimization is irrelevant. This is advantageous for designing a structure with high stiffness to minimize deviations. Additionally the concentrated inertia decreases the nominal frequency whereby the deviating effect of mechanical disturbances, e.g. coming from the fine drive substructure, is minimized.

FIGURE 1. basic principle of a linear coarse/fine drive system (CD..coarse drive (e.g. spindle drive), FD..fine drive (e.g. piezo translator))
EXPERIMENTAL SETUP

The experimental setup is designed as a simplified version of a nanopositioning machine that includes all necessary functional elements and allows a determined examination of the functional influence of the mechanical components in the nanometer range. The coarse/fine configuration is implemented. The fine drive subsystem is included as a discrete functional module, that can operate as a stand-alone device with 6 DOF, to allow the examination of transmission characteristics, which describes how the actuator stroke affects the object over macroscopic passive elements. A macroscopic measuring mirror for laser-interferometry is used as the object. Figure 2 shows the kinematic structure. The end effector

FIGURE 2. kinematic principle of the experimental setup

of the coarse drive subsystem is the fine drive’s base frame. This is connected to 3 vertical working spindle drives and horizontal actuators (not shown). The guidings are air bearings in horizontal direction and ball bearings that are included in the spindle drives. The maximal stroke is ±20\text{mm} and the accuracy ca. ±1\text{µm} in each direction. The fine drive subsystem is located between the coarse drive and the object whereby it is possible to adjust the actual positioning error. Figure 3 shows the realized setup and Figure 4 a typical measuring plot while moving in the vertical direction. The measuring results appear very positive because no filter and climatisation were applied while testing the setup.

DYNAMICS OF FINE DRIVE

The fine drive subsystem must permanently adjust the existing positioning error resulting from mechanical deviations. That ability is given and limited by the transmission behavior of the sub-system which depends on several soft- and hardware solutions of the system e.g. controller, DAQ, delay of actuators etc. An analysis was required to quantify the contribution of mechanical design parameters to the overall transfer function. The design of the fine drive substructure (Figure 2) was optimized according to the design principles of precision engineering for reaching high possible dynamics. The basic kinematic structure has a sufficiently passive DOF to avoid over-determination and deforming constraints, which is reached by a necessary number of links. The links are designed as elastic or multi-part rolling elements to minimize stick-slip-effects, clear mounting tolerances, reach small construction height and high stiffness in the working directions of the actuators. A very small number of passive transmission components avoid sources of error resulting from elasticity. The actuators are located as near as possible to the object to get lightweight moving parts and to create stiff connections. Especially in direction of gravity the length of the force flow is minimized and minimal bending stress is generated. The lateral dimension around the center of gravity is demanded in order to create available space for the laser beam of the measuring system to touch the measuring mirror in the vertical direction. The mechanical components are designed in very el-
mentary shapes to allow a specific and most accurate analysis of its influence on the mechanic characteristics of the overall system. Quasi-static positioning is satisfactorily possible, but the nominal frequency of the passive fine drive substructure of ca. 250 Hz is hard limiting the ability of adjusting dynamic deviations in the nanometer range, although the design is according to the precision engineering principles. The reason for that is the insufficient stiffness of the structure caused by the bending transmission elements and multipart links under Hertzian stress which are represented in the model in Figure 5. Compression/ tension loads appear to be irrelevant. To evaluate a design element and its parameters, their specific contribution to the overall elasticity must be quantified. Thus theoretical modeling of the mechanical parameters is applied. This eliminates the influence of non mechanical parameters that are necessary to operate the realized experimental setup on the analysis.

For the multi-part links the stiffness can be analytically calculated using a simple model like Figure 6 and common empirical equations to describe the approach of surfaces under loads in the case of Hertzian stress. The resulting elasticity depends on the geometry, curvature, material and preload. In the considered design the stiffness of point contact is about 20 kN/mm and of line contact (e.g. ball against chamfering) about 300 kN/mm which are relatively very high single values. For expanded and complex transmission elements FE-method for the calculation of a stiffness is advantageous. The only relevant element of the experimental setup is the mirror mounting whose stiffness has been calculated to about 16 kN/mm (Figure 7). The damping ratio of the entire system was measured with about $10^{-2}$.

**Figure 7.** Identifying stiffness with FEM

**INTERPRETATION OF THE PARAMETERS**

A important result is the knowledge that links and bending transmission elements have a stiffness of the same magnitude. That means that neither kind of design element is insignificant in a dynamic analysis. The mistake is probably using a FEM or MBS for an examination while considering the system either as a homogenic elastic structure or as a combination of solid parts with connections of specific behavior.

To model the entire system the single elasticities must be connected. The number of elasticities of bending transmission elements is minimized because of the usage of the design principle of shortening the force flow. In contrast the design principle of avoiding over-determinations produces a multitude of links in series which decreases the overall stiffness. This design principle appears adaptive to reach high accuracy in precision engineering of μm-ranges. In the nm-range the demands on stability to disturbing forces are higher by a factor of 1000. To get demonstrative information about the possible performance of the designed mechanical structure the model can be simulated in a time domain neglecting all disturbances of peripheral devices existing in a real structure. Thus the designer learns about the behavior of the passive mechanical structure. Figure 8 shows how the model follows testing scenarios according to a scanning task of a surface with different scanning velocities. The limitation of the ability to follow the vertical steps by the mechanical part of the system is identifiable.

**POTENTIAL DESIGN IMPROVEMENT**

Because the coherence of single geometrical parameters and elasticity is known and the mechanical ability can be simulated, the theoretical effect of varying the design can be calculated. The
FIGURE 8. Scanning surface with $v_x = 3.5\mu m/s$ and $v_z = 350\mu m/s$

The goal is to maximize the dynamic ability by increasing the nominal frequency. The first variation assumes that the material is changed from steel to $Al_2O_3$. The results of further variations are shown in Figure 9. Figure 9:above shows that it is easier for design to increase the stiffness of a bending transmission element than that of a link (by increasing diameters of included balls), even for different aspired stiffness ratios. In Figure 9:below the expected nominal frequency at different parameter values is plotted. The diminishing dependency shows a practical limitation of the dynamic ability at a suboptimal level for nanopositioning tasks as long as just parameters are varied. The functional insufficiency seems to be caused by the structural design solution. That means that the design principles of precision engineering of the $\mu m$-range or the demands on dynamics are not reasonable for the nanopositioning range.

SUMMARY
A design for nanopositioning tasks basing on coarse/ fine drive configuration was developed and successfully tested as a prototype sample in an experimental setup. The principle is optimized for low dissipation losses and high dynamics and accuracy in $nm$-precision around the working point. The realization of the structure is according to the design principles of precision engineering. The mechanical setup was analyzed to quantify the influence of mechanical design elements and their parameters on the nanopositioning ability. In particular, the elasticities were examined. The results show that the passive mechanical structure and its components do not appear to be irrelevant in reaching necessary dynamics in order to fulfill the nanopositioning task. The design principles of precision engineering must be evaluated differently to apply them in the nanopositioning range. The elasticity of links as well as bending transmission elements must be considered in mechanical simulations.

REFERENCES
