A THREE-LAYER AND TWO-STAGE PLATFORM FOR POSITIONING WITH NANOMETER RESOLUTION AND SUBMICROMETER ACCURACY

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Abstract:

As a result of the progress in the multidisciplinary nanotechnology field the demand for precision positioning systems has sensibly increased in the last years. In this line, a novel two-dimensional moving nano-platform (NanoPla) is being designed. The set requirements of the initial prototype are not only high positioning accuracy and resolution but also long working range (50x50 mm), increasing the number of potential applications.

The presented paper demonstrates an illustrative part of the complete state-of-art realized, justifying and concluding with an optimal positioning system. Different long range stages have been considered and classified depending on their structure, motion system and relative motion between sample and probe. The final result is the definition of a three-layer and two-stage architecture to characterize surface topography of larger areas with an integrated Atomic Force Microscopy (AFM) system. In order to meet the requirements (nanometer resolution and submicrometer accuracy) several different precision engineering principles and finite elements method software have been used.

Keywords: Nanopositioning metrology, 2D Platform, Atomic Force Microscopy, Prototype Design

1. INTRODUCTION

The term nanotechnology involves a multidisciplinary field working on the control and manipulation issues at a length scale between 1 and 100 nanometers. The progress in this scientific discipline, accelerated in recent years, has only been possible with the instrumentation development. For this reason, the demand for precision positioning systems has sensibly increased. Since nanometer tolerances must be dimensionally quantified, the metrological challenge is focused on miniaturization, to provide micro- and nano-devices for the purposes of measuring, manipulating and machining at this scale.

Commercial available positioning systems achieve nanometer resolution but their measuring range is usually limited to a few millimeters. This aspect becomes troublesome in applications that require measuring of larger planar areas (solar cells, silicon wafers, etc.) without cutting specific samples. To overcome it, some international researchers have developed different nanostages, characterized by a larger travel positioning range [1-8].

In this way, a novel two-dimensional moving nano-platform (NanoPla) with nanometer resolution and sub-micrometer accuracy is being designed. The work range is initially set in 50x50 mm, with the goal of getting up to 300x300 mm in the future. Its applications have been oriented to topography surface characterization of larger areas in a planar part, as silicon waffles, with an integrated Atomic Force Microscopy (AFM) system. The interest of using AFMs for dimensional nanometrology applications has been increased in the last decade [9]. These systems are the most suitable solution for topographic profile mapping, due to their high vertical as well as lateral resolution.

In this work some references are presented to conclude with the optimal positioning system. The proposed prototype takes advantage of the strong points of different analyzed options, including novel design solutions for some of the problems found, all based on principles of precision engineering. The final design, verified by finite elements method software, is based on a three-layer and two-stage applied architecture and allows the AFM head displacement along the wide travel range.

2. NANOPOSITIONING STAGES DESIGN

2.1 System features and design principles for precision

To summarize the systems and components necessary in positioning precision stages, four subdivisions can be differentiated: drive system, guide system, control system and isolation system. Directly related to all precision engineering principles (classified and shown in Figure 1) these systems are next briefly described.

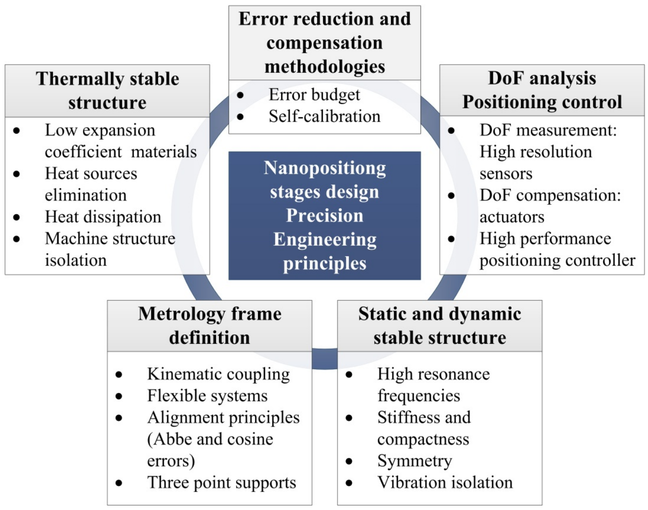

Fig. 1: Precision engineering design principles: summary.

The drive system is on charge of the motion in X and Y directions. Traditional actuators based on lead screws have the backlash drawback, because of the transmission device. To solve this problem the most common solution applied in nanopositioning stages is the use of linear motors. Their configuration with no friction parts reduces the number of drive elements (simpler design) and increases the acceleration and velocity (high dynamic characteristics and high servo bandwidth), but are also characterized by low stiffness and vibrations. Driving solutions as piezoelectric actuators and elastic hinges are only useful in a short working range. Hence, they serve as auxiliary unit improving the performance of the large travel positioning stage, i.e. in the AFM scanning task.

Linear motors require a guiding system, like linear rails, to maintain the position in the magnetic field of the magnet part. If the actuator does not have that U-configuration, to give positional feedback a control method is required. Furthermore, another system is necessary to maintain the moving part of the nanopositioning stage without friction regarding the stationary base. In order to achieve levitation, air bearings have been successfully integrated. High stiffness in vertical direction is provided by preload (magnetically, vacuum preload, etc.). Magnetic levitation (maglev) option also has no mechanical friction, but attenuates frame vibrations and can increase stiffness by servo control. In both cases, thanks to the lack of friction, accuracy is only primarily function of the metrology and control limits.

To provide positioning control and guiding, different sensor solutions are available in nanotechnology. In spite of the high cost and wavelength variations as a consequence of the air refractive index changes, interferometry solutions are the best alternative regarding long range, accuracy and traceability issues. On the contrary, linear scales, whose manufacturing imperfections are predictable and software compensated, result inexpensive and insusceptible to atmosphere variations, but their integration in a planar motion stage is unfeasible.

Capacitive and inductive sensors have sub-nanometer resolution; however operate in a short range. Two-dimensional optical encoder enables a not-guided XY planar motion. Hence, it is another solution for the feedback precision positioning control.

Finally, in AFM applications isolation of the machine and cleanliness of the sample are requisite. To avoid vibrations and stabilize temperature, an isolation system is required. Vibrations can be transmitted to the nanopositioning device through the support structure (ambient vibrations) and acoustically through the air (acoustic noise). Therefore, an active or passive vibration table can support the stage, at the same time that is protected by an acoustic enclosure and placed in a temperature controlled laboratory.

2.2 State-of-art: classification criteria

Different long range stages have been considered during the state-of-art review. Its classification depends on the following criteria: XY structure stage, motion system and relative probe-sample motion. Each contributes to the justification of the system design here presented. The main differentiation has been established in relation with the configuration of the XY motion, i.e. there are plane motion stages and stacked motion stages (see Fig. 2). Stacked stages are characterized for long kinematic chains, due to the superposition of the Y-displacement over the X-motion. This means a large-size and unbalanced structure (lack of stability) and accumulated geometric errors (Abbe error).

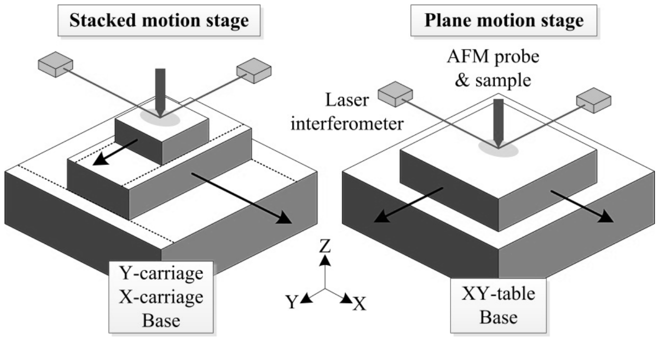

Fig. 2: Stacked and plane motion: structural differences.

Commercial AFM integrated stages only achieve a range about hundreds of nanometers, so they can be connected to a coarse motion positioning platform. In this case, two different motions regarding the sample or the probe are carried out: coarse approach and fine displacements. On the other hand, if the driving motion is applied over the whole range, surface imaging is possible along several millimeters. To avoid the required stitching large range AFMs are the other option.

Third considered classification criterion makes reference to the relative motion between probe (AFM tip) and the sample. Different scanning type can be achieved with the motion of the probe (scanning probe), the displacement of the sample (scanning sample) or by combination of both modes: separated XY and Z motions or combined tip and sample scanning systems. Noteworthy advantages for the first alternative include the not limitation of the sample size, weight or even shape. Second scanning mode fulfills Abbe principle, eliminating first order straightness and rotation errors influence on the measurement result.

3. PLANE MOTION STAGES

Drawbacks of the stacked motion establish the plane schematic like the best XY motion configuration. Therefore, this type of stages has been firstly analyzed.

For its importance and relevance concerning this project, Multi-Scale Alignment and Positioning System (MAPS) [2] should be cited primarily. This system incorporates different interchangeable manufacturing and measurement modules based on a 10x10 mm range ultra-precision nanopositioning stage. The fundamental MAPS contribution in NanoPla development is related to its home-made Halbach planar linear motors, manufactured at the Center for Precision Metrology, University of North Caroline at Charlotte (UNCC).

One of the initial NanoPla requirements is the use of commercial components when possible, for future industrial applicability. However, it has been proved that there is not available commercial solution to provide a two-dimensional pure plane motion over a long range. Avoiding complex configurations, hand-made linear motors were ordered to the UNCC. Characterized by creating two dual-drive forces (vertical and horizontal direction) its good behavior has been proved in several tests: great dynamics (absence of iron minimizing cogging), high thermal conductivity (aluminum as structural material) and own damping (eddy current internal generation).

Another UNCC nanopositioning stage with the same actuators is the sub-atomic measuring machine (SAMM) [3].

With a longer range (25x25 mm), its main feature is the different levitation scheme. MAPS uses a central air bearing, in comparison to the magnetic levitation (maglev) applied in SAMM system. The moving platen, magnetically suspended, is floating in oil to support its weight and to provide mechanical damping and high-frequency coupling between stationary and mobile parts. Immersion of a large part of the system under oil supposes a complicated stage structure. Air bearings are adopted as NanoPla levitation solution, locating three vacuum preloaded air bearings in a 120º arrangement.

In order to achieve nanotechnology requirements, most used positioning control solution is laser interferometry. High cost is not a problematic when large travel motion can be measured with nanometer resolution and submicrometer accuracy. Capacitive and inductive sensors are often selected to evaluate deviations in Z, θ_x and θ_y.

Planar motion forces to reject linear encoders and commercial grid encoders are a solution if exists enough area for the rest of the components and sample. Ro et al. [4] have developed a compact ultra-precision stage with a range of 20x20 mm. The size reduction goal has been achieved by locating motors and air bearings in the same area, but a grid encoder is installed in the middle of the table increasing the global size. Additionally, its 0.1 µm repeatability concludes that if higher accuracy is required, laser interferometer should be the XY sensor system.

Nanopla incorporates a fiber optic laser encoder system for X, Y and θ_z evaluation and three capacitance gauges for parasite motions.

Other important design decisions are the relative motion between probe and sample and scanning type. Representative nanopositioning stage to justify this aspects is the Molecular Measuring Machine (M^3) [5], designed to achieve sub-nanometer resolution over a 50x50 mm area.

Focus on the motion system, if the designed stage does not attain the necessary stability for the AFM scanning motion (NanoPla) or higher accuracy is required (M^3 system), a combination of coarse and fine motion should accomplish. Hence, fine motion resolution is only limited by the control electronic noise. NanoPla first prototype will integrate a 3-DoF piezostage to ensure the adequate scanning motion, displacing the sample during the fixed position of the AFM tip. Coarse travel stage will move the AFM along the entire range of 50x50 mm.

Table 1 summarizes briefly the four plane motion cited stages, NanoPla system and the following stacked stages included in next point.

Table 1: Large range nanopositioning stages classification.

	XY range (mm)	XY structure	Motion system	Relative motion
[2]	10x10	Plane	Large range	Scanning sample
[3]	25x25	Plane	Large range	Scanning sample
[4]	20x20	Plane	Large range	Scanning sample
[5]	50x50	Plane	Coarse + fine	Combined
[6]	25x25	Stacked	Large range	Combined
[7]	400x400	Stacked	Large range	Scanning sample
[8]	50x50	Stacked	Coarse + fine	Sample
NanoPla	50x50	Plane	Coarse + fine	Scanning sample AFM long range

4. STACKED MOTION STAGES

In spite of the weakness structure of stacked stages, different nanopositioning systems stand out for their good global performance. Following platforms have been selected to show the importance of the right material selection, metrology frame definition, vibration and thermal isolation.

Fan et al. [6] have developed a low-cost micro-CMM (coordinate measuring machine) for 3D nano-measurements covering a 25x25 mm area. Co-planar design decreases Abbe error, owing to X- and Y-tables are located in the same plane. Ultrasonic motors form the driving system and its position feedback is given by hologram grating scales. Concentrate on materials, it should be noted that the whole stage is made of Invar® (nickel iron alloy normally used in coupling elements to avoid thermal deformations) and the arch-shaped CMM-bridge of granite, to obtain thermal accuracy and higher stiffness. The main structure of Nanopla stage is made of aluminum due to cost issues, easy machining and good mechanical properties.

Materials are even further important in metrology frame definition. Zerodur® glass ceramic is the most used option, characterized by its very low thermal expansion coefficient. Silicon carbide (SiC) is the other precision choice according to its hardness, rigidity, low expansion and thermal conductivity.

Isara-400 commercial system [7] is worthy of consideration due to its particularly long range (400x400 mm), the fulfilled Abbe principle and its metrology frame design. XY-plane motion stands out by the mirror monolithic Zerodur table, which localizes three refractive sides for feedback laser interferometer positioning. This part integrates a SiC work piece table (sustained in three points), and rests on a granite base by three flat air bearings (weight preloaded). Vertical frame, based on a SiC beams assembly, displaces the metrology structure of the probe.

Two metrology frames are differentiate in NanoPla design: stationary frame (piezostage, sample and laser encoders) and moving frame (AFM and plane mirrors). In the initial prototype they are made of aluminum, but in a future will integrate Zerodur pieces. Both are connected by three identically spaced flexure mounts to diminish thermal gradient effects.

To conclude with the state-of-art study the last stacked motion stage should be presented. As is well known, in precision engineering is important to manage error sources. Buice et al. [8] have developed a log-rang 6 DoF (degree-of-freedom) stage to manipulate and scanning large specimens. In the cited work experimental evaluation about environmental effects and control has been carried out.

Control strategy approach is out of this study, but vibration isolation is possible resting the whole machine in an active or passive table and enclosing it in a special structure. Temperature variations of the laboratory have to be controlled to ensure temporal stability inside and outside. This configuration will be followed in NanoPla: vibration isolation table, temperature controlled air conditions and possible enclosure, function of global achieved performance.

5. PROPOSED DESIGN AND FEM ANALYSIS

To carry out the long travel range, and maintain compactness, stiffness and high resonance frequencies, a three-layer and two-stage applied architecture are defined, as shown in Fig. 3. In the moving platform are located lightweight components and devices without wires like linear motor magnets. Fixed bases incorporate bulky elements, i.e. stators and laser encoders.

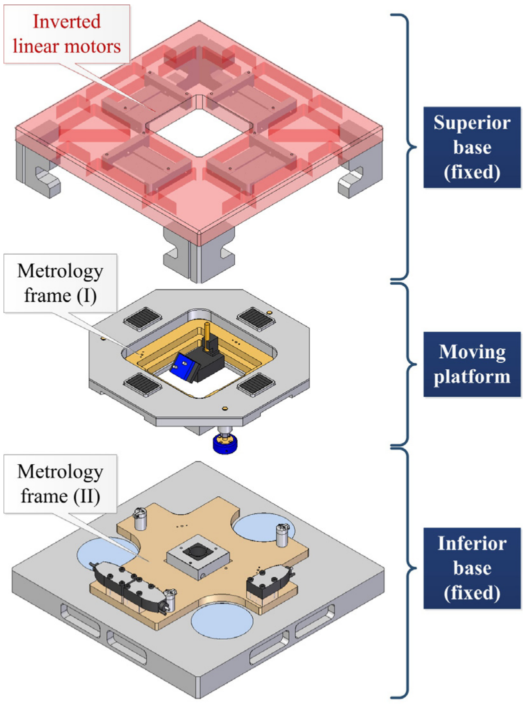

Fig. 3: Proposed design: three-layer architecture.

To verify and optimize the proposed 3D model structural static and modal analyses by finite element method (FEM) have been effected. After convergence tests (quality mesh procedure), the goal of the study was established to make lighter the moving platform, increase stiffness and ensure natural frequencies of the stage over the operation limit. The stage deformations analysis in different points of the entire range is very important, because of relative displacements between (0, 0) and (±25, ±25) mm positions should be at the order of nanometers. Air bearings behavior characterization was also FEM analyzed, to study essentially its stability with air and vacuum flows (air gap stiffness).

Finally, for the proposed design an error budget was previously calculated, based on the combination of a mathematical machine model and geometrical errors estimation the related to the platform motion [10]. Error mapping techniques based on reversal methods has been also explored for nanopositioning stage self-calibration [11].

6. CONCLUSIONS

A novel nanopositioning stage for AFM integration is on development. A new three-layer and two-stage applied architecture has been defined for compactness and improved performance. Proposed prototype is based on the state-of-art study, precision engineering principles and FEM structural static and modal analysis.

7. FUTURE RESEARCH

Future specific tasks will involve assembly, integrated control development and self-calibration procedure definition. Linear motors will be tested to determinate and compare predicted and measured force profiles. Calibrations methodologies based on reversal techniques will establish measurement positioning accuracy of the system.

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