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Conceptional design of a positioning device with subatomic resolution and reproducibility

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Abstract
In order to satisfy upcoming demands to probe or manipulate objects at subatomic level within a wide addressable range of up to 1 × 1 mm², a novel class of devices needs to be developed from bottom up. In various scientific and technical research fields there is an interest in reproducable subatomic level measurement methods. Potential applications could be in cell biology, nanoscale surface or quantum object research, to name just a few examples. Among others, a positioning stage with subatomic resolution will be an essential functional unit. As a first proof-of-concept, a positioning stage for a linear motion was chosen. Drive, transmission, guidance and position sensing functions are designed in form of a monolithic structure based on MEMS technology. Actuation and measurement strategies were evaluated comprising for instance comb structures to actuate and measure linear motion. Compliant mechanisms are deployed for linear guiding and as a transmission element to achieve highly reproducible motion.

subatomic positioning, compliant mechanism, MEMS

1. Introduction

Regarding the rapid progress and the growing relevance of nanotechnologies in technical, scientific and medical fields, nanopositioning and nanomeasuring machines assist in making smallest objects, surfaces and processes observable. The limit of subatomic resolution combined with a large positioning volume up to the mm-range has not yet been exceeded within multidimensional positioning technology. In comparison nanopositioning and measuring machines like the NMM-1 or NPMM-200 developed at TU Ilmenau, provide a spatial resolution of 0.1 nm [1]. In this paper, a novel setup is introduced, which is intended to enable surface measurements at relatively flat objects with a reproducibility below 100 pm and a planar resolution down to the low femtometer range. A planar range of motion of up to 1 × 1 mm² is targeted. A first approach is here presented, which is based on MEMS structures manufactured from monocrystalline silicon.

2. Principle for positioning with subatomic resolution

The elaborated setup is inspired by the Abbe comparator principle and is accordingly based on the assumption that minimal measuring errors for a planar measuring task occur if a planar scale is aligned with the virtual probing plane of a test specimen (see figure 1). The resolution of interferometer based length measuring systems is heavily dependent on the wavelength of the laser light. A further reduction of the wavelength or a higher sampling rate encounters physical-technical limits. Typical wavelengths here are in the range of several hundred nanometers and resolutions down to the low pm range are achieved under optimal conditions [2].
In the approach presented here, the optical reference signal is to be substituted by a mechanical scale in order to aim for positioning resolutions in the low femtometer range. The scale is defined by the atomic lattice of a substrate attached to the stage. A multi-tip scanning probe system determines a position change of the scale in six DOF metrologically traceable to the atomic lattice constant. Tip-based measuring systems such as atomic force microscopes (AFM) or scanning tunneling microscopes (STM) are intended to scan the atomic lattice scale as they achieve highest lateral resolution at negligibly loads.
The scale and the specimen are placed on a rigid positioning table. For subatomic resolving motion of the table an actuator works in closed-loop control with the position measuring system. Each component of the metrological loop is subject to disturbing influences such as temperature fluctuations. Consequently, the whole setup must be operated in a appropriate climate and vibration controlled environment to minimize external disturbances. However, assuming a longitudinal table size up to a few millimeter and a temperature stability within the operation space of ±0.01 K, thermal expansion is still in the same order of magnitude as the targeted reproducibility. Hence, structures need to be designed to be insensitive even to minute temperature changes. Self compensating methods need to be deployed.

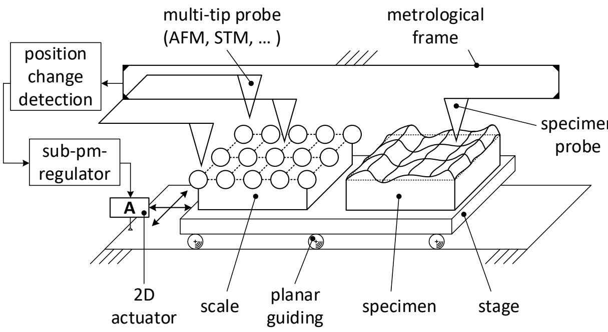

Figure 1. sketch of principle setup

3. First approach for a positioning stage

For the proof of concept, a reduced set of requirements is considered:

- 1 DOF-motion mode
- limited positioning range of ±2 µm
- absolute resolution of less than 100 pm
- reproducibility in the low pm-range.

This enables a back and forward counting of single atoms of the atomic lattice as a first approach of subatomic resolved positioning.

Therefor the design is drafted according to the following criteria:

- contactless transmission of drive forces
  - ⇨ implementation of capacitive comb actuator
- minimized friction
  - ⇨ application of a flexure hinge guiding mechanism
- reduced absolute thermal sensitivity
  - ⇨ decreased size of metrological relevant parts
  - ⇨ self compensating methods
- highly predictable thermal behavior
  - ⇨ structure as simple and symmetrical as possible
- approaching quasi-ideal elastic material properties
  - ⇨ using monocrystalline silicon as basic material

Furthermore, MEMS structures are suitable for an initial study, as they are relatively cost-effective and well studied in terms of miniaturization and the required process technology.

3.1. Proof of concept design

Guiding is based on flexure hinge mechanism of a double parallel spring guide mirrored at the actuation axis of the endeffector (see figure 2). Silicon-on-insulator (SOI) wafers serve as the base material. The flexure hinges are designed to act as a concentrated compliance. This reduces relevant deviations of shape caused by the etching processes to a small part of the whole mechanism compared to extended leaf spring hinges. Additionally, the behaviour of the overall mechanism can be influenced in a specific manner by varying the hinge contour [3]. Due to the possibility of etching structures on both sides of the chip, the actuator, the guiding and a position sensor can be integrated as a single monolithic body. As the actuator, a capacitive comb drive is applied to generate contactless drive force while causing relatively low heat during operation. All components of the mechanism are part of the the device layer of the chip. This layer has a height of about 100 µm. Assuming an aspect ration of 1:10, the electrodes of the actuator are placed in a minimal trench distance of 10 µm. A connected high resolution power supply (Act PSU) provides a working voltage of up to 100 V with a step resolution of 5 mV. The chosen lateral operating mode of the actuator determines a theoretical linear resolution in the operating range of 3 fm to 100 pm [4].

3.2. Measurement setup

To validate the characteristics of the actuated stage, two variants of measuring systems are considered. The first variant comprises a comb structure similar to the actuator, but it serves as a capacitive linear distance sensor. A 24-bit capacitance to digital converter (C2D sens) is mounted close to the chip on the adjacent printed circuit board. A resolution of approx. 40 pm can be achieved by scaling the number of sensor combs to 600.

The second variant is implemented by attaching an optical grating as a first approach but aiming for the use of monocrystalline substrate of a known atomic lattice. Scanning of such a substrate by using an STM allows metrological traceability to the lattice constant. The lateral resolution of the STM for the first approach is assumed with less than 10 pm using a tip probe which is individually actuated by an internal piezo drive to enable work in constant height mode. A camera microscope should be implicated for the alignment of the probe and the scale.

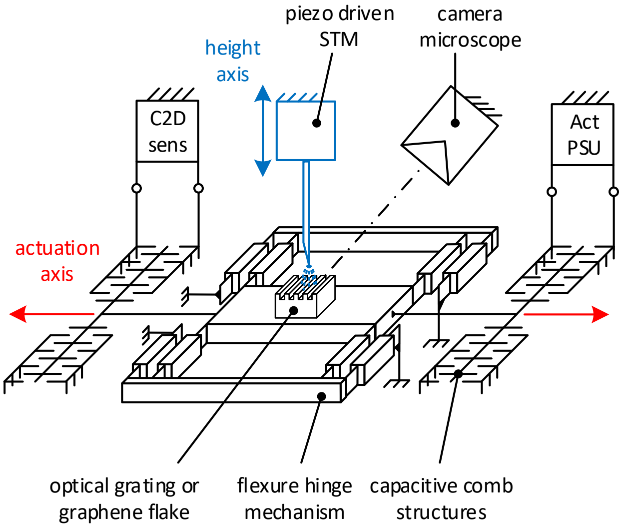

Figure 2. Scheme of the testing setup for actuator and guiding

4. Conclusion and Outlook

Due to the challenging requirements of subatomic resolved and reproducible planar positioning, an iterative approach is chosen. This enables short feedback loops and consequently a continously improving progress. As a first iteration step a MEMS-based linear guiding flexure hinge mechanism is presented using capacitive comb actuation with a resolution down to fm-range. The resolution is scalable by the number of combs. Two different but simultaneously acting position measurement systems should validate the reproducibility of the stage and the characteristics of the actuator independently from each other. A next step would be a stage moved in 2 DOF with an enlarged addressable range. A possible approach could be a two-stage design, as shown in [5]. The presented stage design in figure 2 could act as the second stage for highly resolved positioning. But it should be mentioned, that a serial kinematic arrangement potentially decreases the reproducibility. Since the thermal behaviour of silicon is considered as a disadvantage, the positioning reproducibility could be further increased by the use of thermaly unsusceptible materials as ultra-low-expansion (ULE) glasses or other materials.

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