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Investigating the kinematic performance of a positioning device with subatomic resolution

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Abstract

This paper is a follow-up to the conceptual design [1] and the prototype introduction [2] of a linear positioning device with subatomic resolution. This device is designed as a monolithic system. The linear guiding is realized by a mechanism with concentrated compliances. The position measurement is performed by tip-based scanning of the surface of a scale fixed at the moving table. Considering this setup, it becomes clear that the strongest sensitivity for kinematic deviations exists for displacements collinear to the probing axis of the tip as well as corresponding tilting motions. Deviations from an ideal straight guiding axis are mainly a result of manufacturing-related geometric deviations in the guiding mechanism. These error motions are investigated and characterised for prototype devices using an optical focus sensor in combination with a nanomeasuring machine NMM-1. To distinguish dynamic influences and static contributions to error motion, a quasi-static sequence of varying positions of the system has been performed during the measurement procedure. The determined error motions are highly reproducible due to the monolithic design from monocrystalline silicon. Consequently, the systematic error contribution of manufacturing deviations to the kinematic accuracy of the positioning device can be subsequently corrected.

Subatomic positioning, compliant mechanism, MEMS

1. Introduction

The introduced systems promise to achieve highest-precision positioning in the subatomic range along one actively actuated axis. This requires not only a high-resolution measuring principle as presented in [1]. For the best possible accuracy, the motion behaviour of the positioning table must also be extremely reproducible. Based on known behaviour a correction or compensation could be done for non-ideal motion. In the following, error influences on the reproducibility of the guiding as a key subsystem are investigated. For an exemplary system, the most relevant manufacturing-related error factors are identified and simulated using a parameterised finite element analysis (FEA) model of the guided positioning table. In this way, the motion errors can be estimated for known geometric deviations. In addition, measurements are carried out on an exemplary prototype in order to determine the order of magnitude of actually occurring error motions. Finally, experimental and simulation results are compared.

2. Methodology

The motion errors of the positioning table are first described as a model. The roll angle φ_x, pitch angle φ_y, and the shift of the table parallel to the z-axis t_z are distinguished (Fig.1). These have a direct impact on the position measurement principle since they influence the distance between the scanning probe microscope and the periodic scale on the table. In the following, the correlation between these motion errors and manufacturing-related shape deviations of the compliant joints of the guide mechanism is studied. Such shape deviations were observed in real prototypes. These are made of silicon by means of deep reactive ion etching (DRIE). An inclined sidewall is formed along the etching direction with the etch angle α_{etch}. In section 2.1, this shape deviation is reproduced in a 3D-FEA model of the mechanism and the resulting motion errors of the positioning table are investigated. The results of the model are compared to real prototype systems. These are characterized by an experimental set-up on a nanomeasuring machine (NMM-1) in combination with a focus sensor (section 2.2).

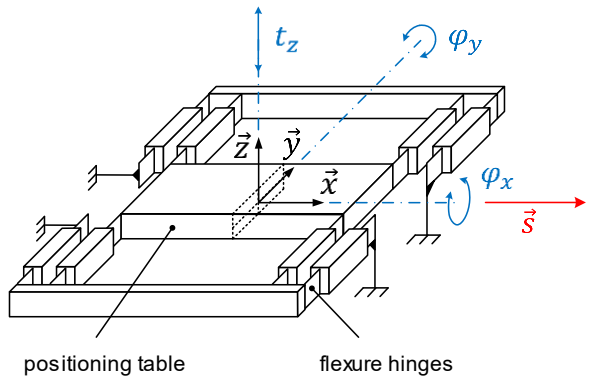


Figure 1. error motions of the positioning table

2.1. Modelling of manufacturing error influences

Due to the DRIE manufacturing process various deviations of an ideal rectangular etching profile may occur [3] Firstly, the etching profile of manufactured systems is studied.

Therefore identically structured pilot wafers were investigated using a scanning electron microscope (SEM). Referring to Fig. 2 the profile is considered to be approximated straight-edged with a slightly inclined sidewall. The observed etch angle α_{etch} is determined by means of a geometric measurement tool of the SEM. The angle showed to be below 1° for all the examined systems. Minor curvature or etching scallops are neglected. Accordingly, the shape deviation of the cross-section of the compliant joints is described as a trapezoid as shown in Fig. 3.

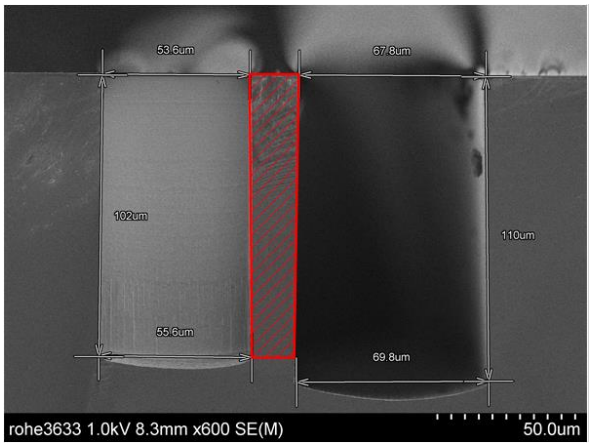


Figure 2. *SEM image of etching profile (hatched area - solid)*

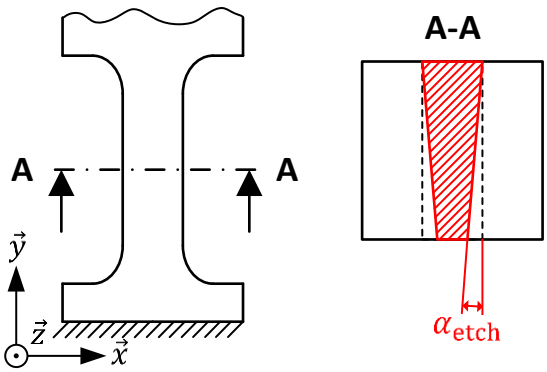


Figure 3. trapezoidal deformation of cross-section of flexure hinges

The model of the guiding mechanism presented in [2] is transferred into a parameterised 3D-FEA model. Here the variable etch angle α_{etch} is entered as a parameter for all 16 joints. Since the distribution of geometric deviations within the area of a single chip appeared to be homogenous, the same value for α_{etch} is assumed for each of the joints. Because the design is based on concentrated compliance, the couplings between the joints are assumed to be unaffected by deformation. Consequently, inclined sidewalls are not applied for the couplings.

For each simulation study, a stepwise displacement of the positioning table from the zero position (joints not deflected) to the end position of the positioning range is defined as a boundary condition. The shift and rotation of the local coordinate system of the table, with its origin in the geometric centre of the table, is analysed and evaluated. Thus, the 6 degrees of freedom of the table can be examined as a function of the travelled table position s and the etch angle.

2.2. Experimental measurement of motion behaviour

The motion parameters of the positioning table φ_{x}, φ_{y}, as well as t_{z} have to be recorded with a resolution in the sub-microradians and picometre range. Specific values obtained from the FEA can be found in Fig. 5. Due to the chip design, only the areas above and below the positioning table are available as free approaching spaces for measuring devices. The surface area of the positioning table is approx. 3000 × 800 µm². Consequently, conventional high-precision sensors for angular measurements, like autocollimators, can not be employed to characterize the system. Various measuring devices were tested in practice. For the measurements described in the following, a setup of a focus sensor in combination with a NMM-1 [4] is employed due to availability. Furthermore, this setup enables the opportunity to conduct automated long-term measurement series to be carried out with the prominent accuracy of the NMM-1. The x- and y-motion is controlled by the NMM-1 stage to realize the scanning pattern (Fig. 4).

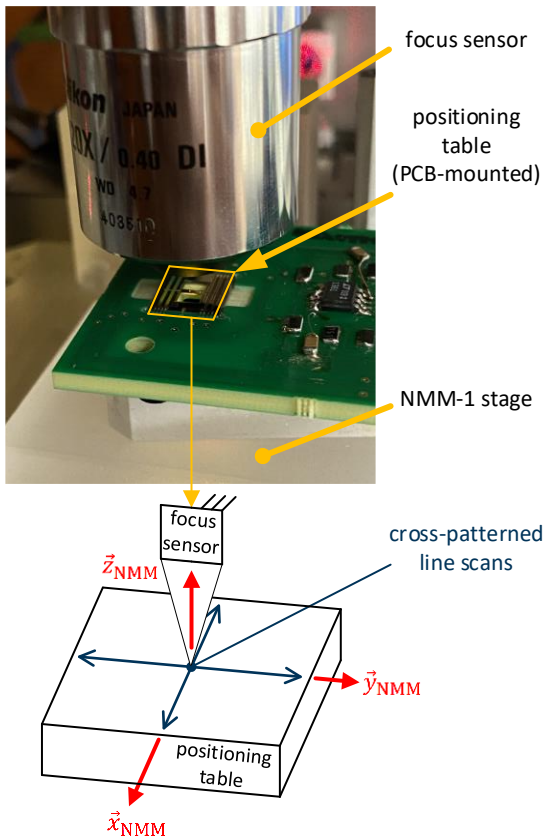


Figure 4. measurement setup with focus sensor in the NMM-1

Starting from the centre position of the table, line scans are performed in a cross pattern along the x-direction as well as in the y-direction. The length of the line scan in x_{NMM}-direction is 750 µm and in y_{NMM}-direction 2500 µm. The line scans are evaluated by line fits, in order to estimate the angles φ_{x} and φ_{y} (Fig. 1). The translational motion along the z-axis t_{z} is evaluated at the centre of both scans. The angular resolution is calculated by the vertical resolution of the focus sensor and the scan length along each axis (Table 1).

Between each measurement, the positioning table is moved in 10 V steps applied to the electrostatic direct drive (see [1] for detail). A full measurement interval ranges from 0 V to 100 V. Each interval is conducted in both

directions (forwards and backwards) to capture any effects that could lead to different behaviour between elongation and return travel of the table. Multiple cycles are carried out for each measurement series. In order to reduce the influence of drift on the measurement result, the data are compared over the time frame of single voltage intervals but not over all cycles. Deviations at a static position in the z-direction afterwards are interpreted as remaining noise and residual drift.

Table 1. resolution of motion errors

measured parameter	resolution
roll angle φ_x	1.32 µrad
pitch angle φ_y	0.40 µrad
shift t_z	1.00 nm

3. Estimation of manufacturing-related motion errors

According to the determined shape deviations of the cross-section of the flexible joints, values from 0.25° up to 1.00° with a step width of 0.25° are assumed for the etch angle α_{etch}. Simulation studies for table positions from 0 µm to 10 µm are carried out with a step width of 2 µm. The results for the pitch angle φ_y and the shift t_z are shown in Fig.5. There are no results shown for roll angle φ_x, since the symmetric mechanism design does not show any deflection in this direction in the FEA.

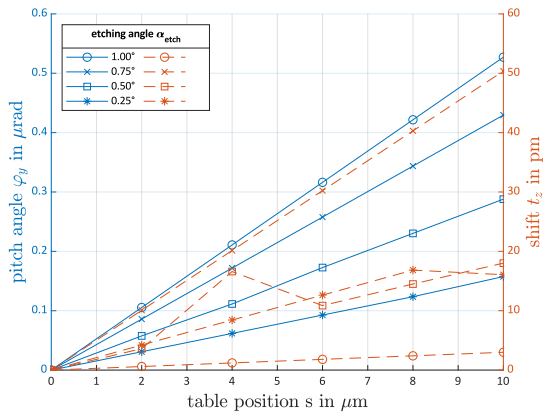


Figure 5. FEA results of error motions vs. table position.

For positive, non-zero etch angles, small but significant rotations φ_y of up to 0.51 µrad are shown. The pitch angle is linearly dependent on the etch angle. For the shift, a non-linear behaviour is revealed with changing α_{etch}. This could indicate superimposed deformation effects of the positioning table. With a max. value of 50 pm, this influence is very small. But the causes have to be clarified in further investigations.

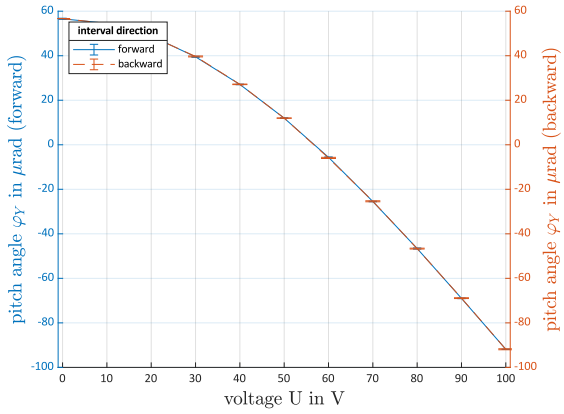
4. Measurement of motion errors on a real system

The resolution of the measurement with the available focus sensor is very close to the expected rotation values of the error motions estimated in section 3. For the shift along the z-axis the setup is not able to resolve within pm-range. Nevertheless, the experimental investigation is carried out to qualify the system with this temporary limitation. Further improvement has to be targeted in future work.

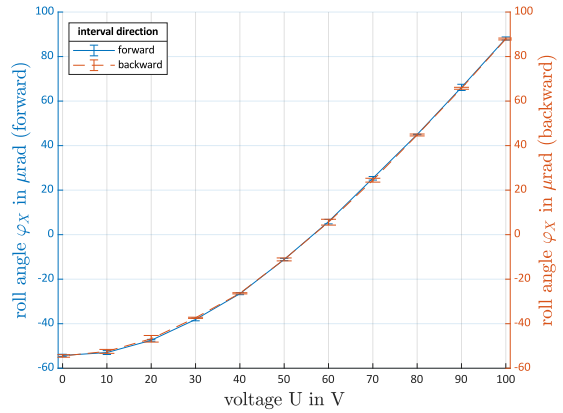
To validate the measurement procedure in general, initial measurements are made on a damaged system. For 5 full voltage intervals, that system shows a relatively strong but reproducible deflection of the positioning table in relation to the applied voltage. In Figs. 6a) and b) a rotation of up to 90 µrad for φ_x and φ_y can be seen. Fig. 6c) shows a shift t_z of up to approx. 130 nm and a slight hysteresis between forward and backward travel.

Table 2 standard deviation of measured motions

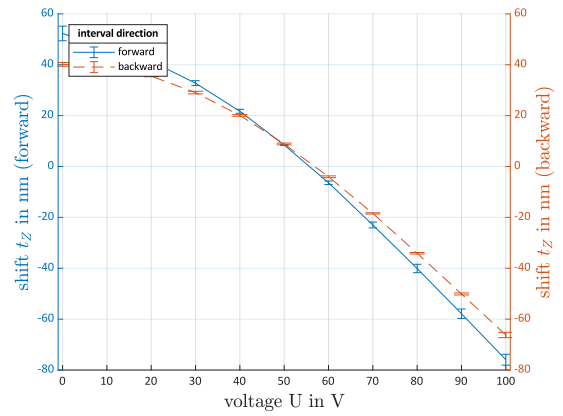
measured parameter	standard deviation
roll angle φ_x	$\pm$ 2.5 µrad
pitch angle φ_y	$\pm$ 1.3 µrad
shift t_z	$\pm$ 3.5 nm



a) pitch angle vs. actuator voltage



b) roll angle vs. actuator voltage



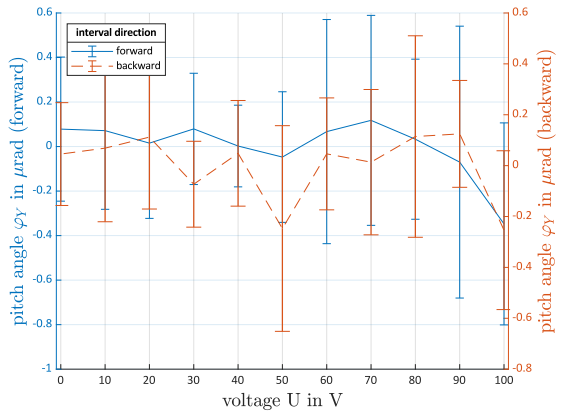
c) shift vs. actuator voltage

Figure *6.* error motions of the damaged system

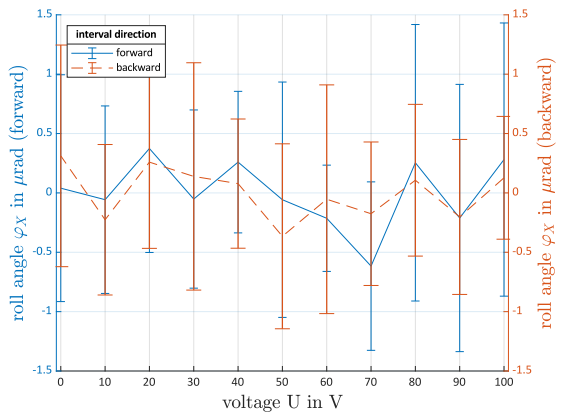
Results for the measurement of an intact system are shown in Figs. 7a)-c). Here, 9 full voltage intervals are recorded. Pitch and roll angles are within the resolution ranges

determined in Table 1 over the full voltage range. This can be clearly seen in the relatively large spreads of the error bars. A similar behaviour is shown for the shift t_z. No clear indication of hysteresis or correlation to voltage can be seen here. The measured motion errors seem to be below the resolution limit of the experimental setup. This suggests that the maximum deflection of the table is at most in the same order of magnitude as the standard deviation of the respective measured data. The maximum values are listed in Table 2.

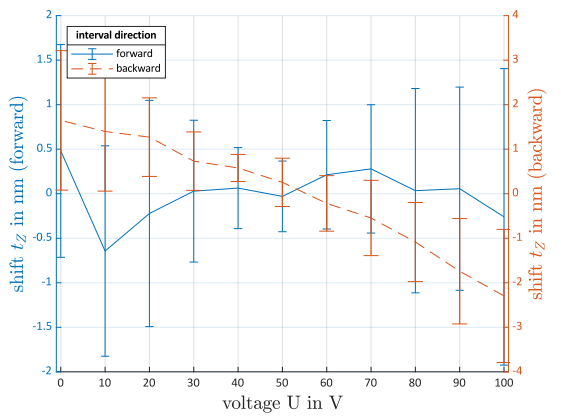
Consequently, an estimation of the actual motion deviations of the positioning table in terms of an upper limit is possible. In order to achieve higher resolutions, either a significantly higher positioning range of the positioning system must be realised, or another measuring system must be integrated, which is planned in the future.



a) pitch angle vs. actuator voltage



b) roll angle vs. actuator voltage



c) shift vs. actuator voltage

Figure 7. error motions of the intact system

5. Summary

The precision of the guiding system is mainly influenced by the displacement of the positioning table collinear to the measuring axis of the position measuring system, as well as by the two tilting movements around the two orthogonal axes. For a guiding range of 10 µm, the expected motion errors due to manufacturing-related deviations of the joint geometry were estimated by means of FEA. For a homogeneous distribution of α_{etch} of up to 1° over all compliant joints, the results are φ_y = 0.16…0.51 µrad, φ_x = 0 µrad and t_z = 3…50 pm. For the latter, a non-linear dependence was shown. For the rotation, a linear dependency has been revealed.

Using a focus sensor integrated into the NMM-1 developed at the TU Ilmenau, the behaviour of real prototypes is investigated. The performance of the measurement setup, which is limited to a single-digit nm and µrad range, is not able to resolve systematic errors predicted by the FEA model. Consequently, no definite value for the contribution to the overall accuracy can be defined. However, the range can be estimated towards the upper limit shown in Table 2. The lower limit can be estimated from the calculated values of the FEA simulation (Table 1).

6. Conclusion and future work

According to the conducted measurements, the presented silicon-based compliant mechanism is qualified to realise highly precise linear guided motions for the targeted positioning tasks with subatomic accuracy. The precision of the motion is defined by the motion errors of the guided table from an ideal guiding path and the associated contribution to the overall uncertainty of the position measurement system. The motion errors of the examined prototype guides are so small that they could not be resolved by the employed measurement system.

However, the uncertainty influence can be estimated towards an upper limit. The experimental data and the values of the model-based evaluation are not yet fully comparable at this stage of the work, but they remain in an overlapping range. The FEA results for the shift showed a non-linear relationship to the etch angle. Superimposed deflection effects of the table under stress are suspected. The exact causes will be determined in the upcoming steps. The procedure presented will be repeated on systems that reach a much larger positioning range of up to 100 µm. This should lead to a further increase of the resolution.

References

[1] Hebenstreit R et al. 2020 Conceptional design of a positioning device with subatomic resolution and reproducibility *Proceedings of the euspen 20th International Conference & Exhibition (Virtual Conference)*

[2] Hebenstreit R et al. 2022 First prototype of a positioning device with subatomic resolution *Proceedings of the euspen 22nd International Conference & Exhibition, Geneva, CH*

[3] Rangelow 2003 Critical tasks in high aspect ratio silicon dry etching for microelectromechanical systems *Journal of Vacuum Science & Technology*, **A 21**, 1550 https://doi.org/10.1116/1.1580488

[4] Jaeger et al. 2009 The Metrological Basis and Operation of Nanopositioning and Nanomeasuring Machine NMM-1 *tm-Technisches Messen*, **76(5)**, 227-234 https://doi.org/10.1524/teme.2009.0960