ISSN 1392 - 1207. MECHANIKA. 2007. Nr.2(64)

Nanopositioning – methods and means

V. Lendraitis*, V. Mizarienė, G. Seniūnas*****
**Kaunas University of Technology, Studentų 65, 51369 Kaunas, Lithuania, E-mail: vitas_l@hotmail.com*
***Kaunas University of Technology, Studentų 65, 51369 Kaunas, Lithuania, E-mail: vimiz@ktu.lt*
****Kaunas University of Technology, Studentų 65, 51369 Kaunas, Lithuania, E-mail: gediminas.seniunas@ktu.lt*

1. Introduction

Nanopositioning is one of the key technologies which determines the development of other technologies. One of them is nanotechnology, which growth is influenced by the development of modern instrumental basis. The growing requirements in microelectronics, optics, and biology set new requirements for instrumental equipment in engineering as well as in metrology. New technologies such as nanoimprinting, scanning microscopy, scanning instruments for surface research, nanolithography, automatic identification systems and micromachining, request for ultrprecision positioning instruments, which would ensure the nanometric accuracy of positioning.

The task of nanopositioning and nanomeasurement machines is to allow the engineering technologies and control (including quality) systems to complete their tasks with the maximum accuracy, flexibility and speed. The problem is that these tasks in great measure have to be integrated with a nanometric positioning accuracy into the existing infrastructure of manufacture, the system working field of which would be tens or even hundreds of millimeters. One more requirement is that nanoinstruments and measuring devices such as nanosonde, nanopincers and nanoobjects should be integrated in these systems.

In the scanning probe microscope system in metrology center PTB (Physikalisch–Technische Bundesanstalt) in Germany (Fig. 1) traditional air bags with rough positioning channel together with probe power microscope and flexure positioning system are integrated, seeking to ensure the wide diapason of positioning (25x25x5 mm) and real nanometric accuracy (2 nm).

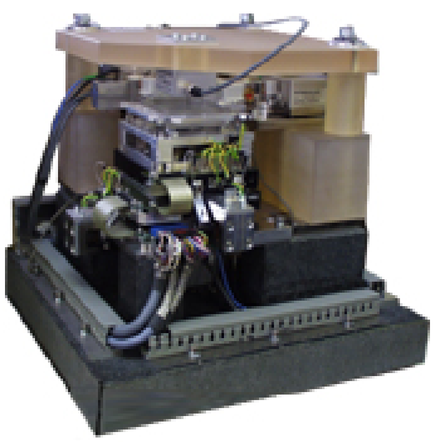


Fig. 1 Scanning probe microscope system in metrology center PTB, Germany [1, 2]

Similar way is chosen by Zyvex Corporation, which is oriented to the instrumental market of nanotechnology. The nanomanipulator by Zyvex Corp. (Fig. 2) has rough (resolution power 100 nm**)** and precision (resolution power 5 nm) positioning channels.

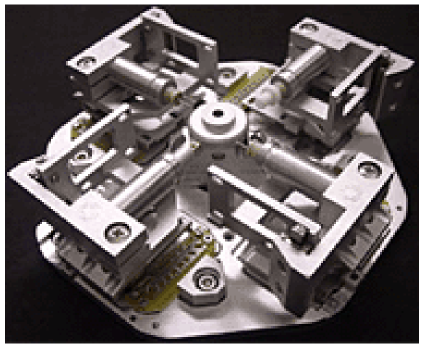


Fig. 2 Nanomanipulator with 2 channels by Zyvex Corp [3]

The maximal positioning range is 12 mm. The instrument is designed for electronic microscopy. But the statement nanopositioning usually does not mean “nano”.

During the period of great development of nanotechnology and agiotage in market, a lot of micro positioning machines and systems suddenly became nanopositioning systems by improving some features, for example, by enlarging the number of interpolation in raster displacement measurement machines. But what was suitable in microworld usually does not satisfy the purpose in nanoworld.

In this article the established positioning methods and principles are analyzed metro logically, the samples of implementing the most modern nanopositioning technologies, developed in the foreign companies and in Kaunas University of Technology (KTU), Research Center for Microsystems and Nanotechnology (RCMN) are presented.

2. Resolution power in nanopositioning systems

Resolution power for different users may have very different meaning. With the beginning of nanotechnology era, many manufacturers of micro positioning instruments found the easiest way to solve the problem: they offer the traditional positioning instruments of open control circuit stepped “nut-bolt” mechanisms as nanopositioning instruments, the problem still exists and the old rule – resolution power is displacement decoder thread divided between interpolation coefficients is just the illusion.

Nanopositioning system is much more than just displacement sensor, interpolation circuit or medium step of motor. In nanoworld the leading role belongs to powers which are not important in macro or micro world. Such powers are friction, deformation, hysteresis, and to obtain the repetitive movement in nanometric movement distances becomes a big problem, which is impossible to solve in real world. The old knowledge which was sufficient for the development of micropositioning systems is not enough. This becomes obvious according to the data that the leaders of nanopositioning systems are new companies which started their work about a decade ago. While analyzing the tendencies in nanopositioning system market an obvious tendency in five year period is seen – the number of new small companies, which offer nanopositioning and nanometrology instruments with new methods and principles, is rapidly growing.

But the dominating tendency is still the same – it is the usage of piezo technique. Along with traditional piezoactuators, displacement piezomotors in nanopositioning are used. The possibilities of traditional piezoactuators are limited because of their physical nature, working principle – the deformation of material because of reverse piezoeffect, and limited positioning distance (up to 100 μm using piezostack actuators and up to 500 μm using mechanical transmission). Stepping motors allow to reach the resolution power of several nanometers and have practically unlimited range of positioning. But the instability of displacement piezomotor work because of the working principle itself – instability of pair friction, was the main obstacle for the successful commerce. In turn electromagnetic and piezomotors feature a "death zone" while reversing, which exceeds the resolution power of the motor several times. The problem of guides with bearings is the deflection errors in positioning in the XYZ axis. The deflection errors are thousand times larger as possible nanometric resolution power of activator, what is acceptable in microworld but it is absolutely unacceptable in nanopositioning systems.

So, real positioning, where the repetitiveness of positioning is in the nanometer level, may be ensured just in systems without friction pairs. Nanopositioning systems have to feature a high directness of transmission characteristics, as well as mechanical, wide control circuit frequency zone, and the possibility to control the movement in nanometric range. Therefore the sub-nanometric resolution power is necessary. This may be ensured only by electromechanical systems without friction pairs.

When the traditional methods and means used in micro positioning systems cannot satisfy the requirements which are essential in nanopositioning systems, new achievements are used. The achievements include: solid activator, flexure mechanical systems, and low inertia collateral kinematics of many axes, active control of trajectory, and wide range and adaptable system control. These allow solving positioning, metrological and other problems which appear in practical nanotechnology.

3. Guide in nanopositioning systems

The main rule of nanopositioning says that there must be no friction pairs in nanopositioning systems. That means that all devices which have roll or slip bearings cannot be the constituent of nanopositioning system. But air slip bearings and flexure guide may be used in nanopositioning. Flexure guides have no friction pairs, their work is based on elastic deformation of solid body.

Air bag type bearings are ideal guide when large positioning distances are necessary, but they are massive, inert and expensive. Lately with the help of powdery metallurgy materials air bag type systems of complicated construction and form, small size may be developed but they are acceptable just in special instruments because of air supply systems. Besides, air bags cannot be applied where vacuum is needed.

In turn, flexure guide cannot ensure a large distance of positioning. It is unlikely that positioning distances ≥100 mm and precision of nano metric positioning is a technological necessity but a number of laboratories try to solve this problem.

Correctly projected flexure guides are rigid mechanical constructions, which ensure high mutual axes slope, have no friction pairs and can be designed as systems with many degrees of movement. Their production is technological and exploitation is simple. These characteristics, according to the analysis of nanopositioning instrument market, make the nanopositioning and scanning systems the best choice in the field of nanopositioning instruments. Nanopositioning flexure guide types, developed in foreign companies and KTU, RCMN are presented in Fig. 3, 4.

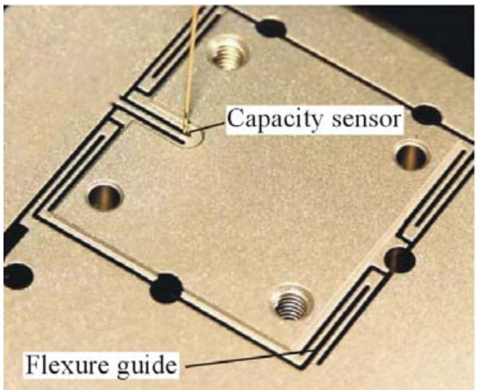


Fig. 3 Single axes nanopositioning table with active control of trajectory [4]

4. Nanopositioning system motors

As well as in guide case, nanopositioning system motor (actuator) must have no friction pairs. "Bolt – Nut" movement transmission pair, bearings, and even ultrasonic piezo motors cannot stretch the submicron precision. While designing positioning system it is necessary to realize if preference is given to nanopositioning accuracy or submicron precision is enough.

Motors without friction pairs are straight-line engines, electromagnetic voice coil and piezo actuators [5].

The first two types fit to large shift/displacement, but they posses such shortcomings as strong magnetic fields that appear in the environment of positioning instrument, a large quantity of heat, large movement inertia and low rigidity.

The positioning range of piezo electrical actuators (called PZT actuators) is restricted (about 100 μm), but they feature high rigidity, high resonance frequency (up to 60 kHz) and achieve the acceleration up to 10000 g. So PZT actuators can realize sub millisecond steps and to achieve high speed of scanning.

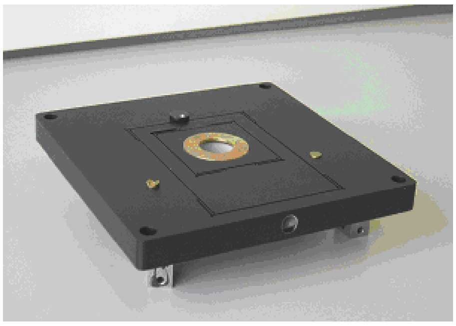


Fig. 4 XYZ nanopositioning table (scanning field 20×20×5 μm) for biological scanning atomic force microscope (KTU, RCMN)

Nowadays biological probe microscopy makes the first steps trying to design probe microscopes of television standard. Therefore XY scanners with resonance frequency meter up to 20 – 25 kHz are required. The model of XY scanner designed in KTU, RCMN and used for the work with invertor optical microscope Nikon 2000 is shown in Fig. 5. The resonance frequency meter is 19.6 kHz, scanning diapason – 6 μm.

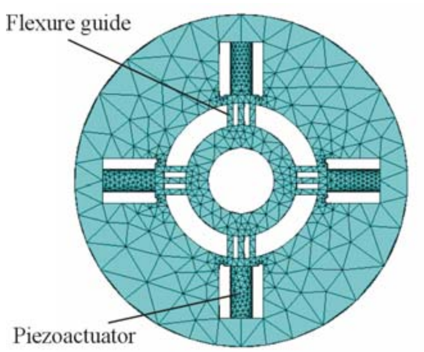


Fig. 5 The model of XY scanner for Near-field scanning optical microscope (ANSYS graphics interface)

It is possible to achieve large shifts/displacements with nanometric resolution power using PZT actuators of rigid material. This is the solution of Burleigh Inc. company. The piezo actuators designed by this firm can reach the positioning distance over 200 mm, resolution power up to 0.1 nm and speed up to 1.5 mm/sec [6]. But these actuators are designed for work with guide systems, which usually guarantee just the submicron or micron positioning accuracy despite the nanometric resolution power of motor. The relation between positioning distance and obtainable resolution power is shown in Fig. 6.

There is one more kind of piezomotors in nano positioning systems – ultrasonic piezomotors. The originator of the theory and practical application of ultrasonic piezomotors and one of the leaders in this field was Lithuania [7-10]. Practical application of ultrasonic piezomotors in Japan and the USA was studied in 1990, when the information from secret laboratories of Soviet Union reached the West.

The commerce of such motors was started by Nanomotion Company, Israel, just in 1992. But the commerce of such type motors is intensive nowadays, especially when German company Physik Instrumente (PI) takes part in the process. The motors of such type for this company are designed by ex-Ukrainian scientists [4].

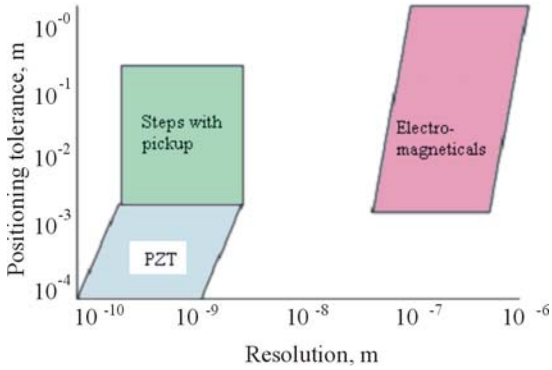


Fig. 6 Relation between positioning distance and obtainable resolution power using different motors

But these motors face the problems of friction pairs and their resolution power is just up to 50 nm. Their advantage is high big positioning speed – up to 250 mm/sec, and fixation of position when control voltage is switched off.

A new and substantial contribution of PI in nanopositioning field is nanopositioning motors of NEXLINE class, which ensure pico metric resolution power and practically unlimited positioning distance. They are analogous to the motors of Burleigh Inc. and Inchworm in their working principle, but their repulsive force is bigger and the degree of mechanical stability is higher. The proposed actuators have positioning distance up to 20 mm, resolution power 10 nm, step leveling time 10 msec, work frequency up to 3 kHz [11].

It is necessary to mention the direct current (DC) leveling actuators which give the resolution power of 50 nm when the distance of positioning is 50 mm, but the hysteresis of reversal movement is about one micron, and reiteration is 0.1 μm. In order to increase the accuracy, they are integrated with the PZT actuator. Such system is produced by client's request and its characteristics are not standardized [12].

One more motor type which is still at the development stage is magnetostrictional motors. The working and appliance principles are analogous to piezoactuators and are known well. The main problems which disturb practical and commercial application of these motors are a high price of the main manufacturing material with giant magnetostrictional effect - Terfenol-D, electromagnetic method of manipulation and a large quantity of heat. It is possible that in several years the price will decrease about 80 % [13], but it is hardly believed that in the nearest future magnetostrictional motors will be a rival for piezomotors of nanopositioning systems.

5. Nanometric displacement measurement methods and means

Indirect displacement measurement means are usually used in micropositioning. They are cheap but they do not fulfill the requirements that are set for the nanopositioning systems. Indirect measurement means are motorized rotational decoders, piezoresistive sensors that are fitted on actuators or consoles. But their action is connected with the friction mechanisms that appear in the movement or deformation transmission pairs. Direct measurement means, which use noncontact methods and measure the displacement in the most important place, are more preferable for nanopositioning systems. Such means are capacity sensors, laser interferometers, and noncontact optical displacement decoders. In the research laboratories sensors (ex. probe read methods) are created according new methods but they are still not widely used.

6. Measurement resolution and linearity

Displacement decoders are one of the optimal means for measuring a large displacement. Most of them use optical grating with the step of 20, 10 or 2 μm.

In order to achieve the nanopositioning characteristics with the accuracy of 10 or 5 nm as it is shown in promotional prospects [4, 5], measurement signal interpolation is needed.

Though in millimeter displacement range the linearity of most displacement decoders is quite high, it reaches up to 20% in optical grating range. The reasons of additional errors may be: misalignment between guide and measurement sensor axes, nonlinearity of guides, or variable loads of connecting measurement cables to positioning system. These can be the reasons of additional measurement displacement errors that reach several tens or more nanometers. For real nanopositioning a stable positioning system, which would ensure the reiteration of movement in nanometer accuracy, is required.

Laser interferometer is a standard means in nanometrology but because of operation principle its characteristics is nonlinear. Heterodyne interferometers ensure the sub-nanometric resolution, but their characteristics is not linear, too. This nonlinearity appears because of beam polarization ellipse, beam perpendicular error and other optical errors, which enlarge nonlinearity. Commercial interferometers have measurement errors of 2–5 nm, but it is not enough for nanometric positioning devices. Very specific knowledge of interferometry and specific devices are necessary in order to achieve the less range of errors. Therefore the feedback corrections or calibration devices are used (Fig. 7).

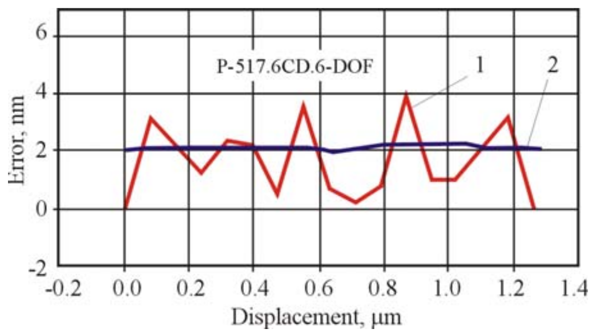


Fig. 7 Movement linearity of positioning device with feed-back control system (Physik Instrumente): *1* - movement feed-back control was done with heterodyne interferometer; *2* - movement feed-back control was done with capacity sensor

Summing up the results of displacement measurement sensors suitability for nanopositioning, it is possible to state that the highest precision is ensured by double - plate capacity sensors with absolute displacement.

These sensors ensure measurement precision up to 0.1 nm; they are simple and cheap. Capacity sensors with their measurement range fit well to the console guides; therefore such integrated nanopositioning systems are in great demand. Capacity sensors of raster type have high nonlinearity, so they may be applied considering their requirements.

In order to solve the precision problems of large positioning range (up to 100 mm or more) and nanometric positioning range, the two-level positioning systems are applied – rough (micropositioning) and integrated accurate (nanopositioning) system [2, 14].

In order to reduce positioning errors, which appear because of friction pairs, the materials with low friction coefficient or thin cover, for example, diamond cover or wolfram – carbide are used. But it is just an experiment that is not applied in industry because of expensiveness and inefficiency [15].

Nanometric precision positioning is achieved in practice [5], but it is not a trivial problem, as practical design and maintenance of such systems requires deep specific knowledge, that is different from the knowledge required for micropositioning system realization.

7. Nanopositioning system precision and speed

In modern systems the speed of processes becomes an important technological and economical parameter. Information recording systems require performing positioning in milliseconds or even faster, because nanometric precision is one of the main parameters in information recording capacity. Every positioning step, which is performed faster in split milliseconds than a competitor does it, means a large sum of money, especially in mass production. Therefore it is necessary to evaluate the requirements of high-speed while developing the nanopositioning system. This means that the positioning motor's capability to develop a high acceleration is one of the nanopositioning system parameters. As mentioned above, the highest acceleration is achieved by piezo actuators (PZT motors). They can reach 10.000 g and ensure the reaction to step control signal in 0.1 msec. Usually it is faster than inertia of mechanical system allows. But along with the increasing management speed, the possibility of transitive processes and vibration generation in nanopositioning systems is growing, too. So for positioning system it is much more important the speed of reaching stability, than the speed of system's movement from one position to another. It is an established belief that systems structural vibrations can be dampen by applying anti-vibration means and thus slowing down the system work, especially these transitive processes that are beyond the management system work. But the newest works in management system algorithm creation field in a large measure solve this problem. New means, which allows damping structural resonances of nanopositioning systems, is a management technology, made in Massachuset Technology Institute and commercialized by Convolve Inc. (New York, NY; htpp://www.convolve.com). The essence of management is: vibration signals are measured during work and the measurement results are input into control circuit thus damping oscillation in the system with positioning circuit itself. The example of this technology application to nanopositioning system is shown in Fig. 8, 9.

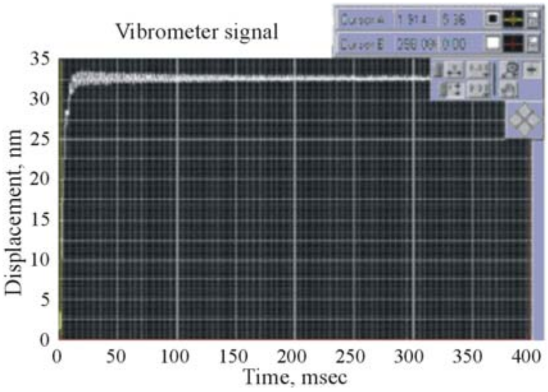


Fig. 8 Vibrations caused by piezodrive last for hundreds milliseconds

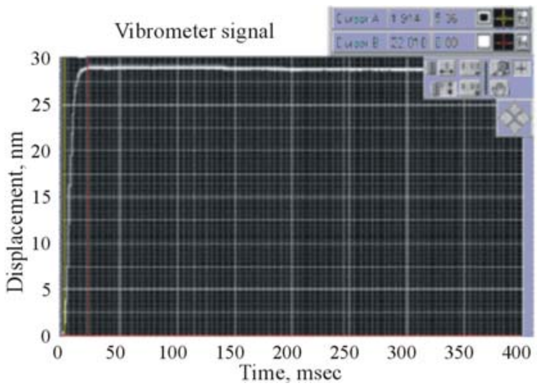


Fig. 9 The application of control technology decreases the transition process up to tens milliseconds

The application of this technology allows to minimize the transitional processes in management system and to realize the transition from position *A* to a stable position *B* during time $1/f_0$, where f_0 is the first resonance.

Piezodrive can realize step impulse in milliseconds but the vibration of the whole system, which appears because of motor stroke, excites the vibration of system parts and damping of these vibrations lasts hundreds of milliseconds.

Using modern technologies it is possible to decrease the length of transitional process up to tens of milliseconds [7].

8. Static and dynamic precision

Resolution, linearity characteristics and precision define the static quality of positioning system work. But it is difficult to evaluate correctly by static parameters quality of the system, which works in scanning or trajectory realization conditions. For evaluation of system dynamic features the term of frequency bandwidth is applied. The bandwidth characterizes the system amplitude response to action signal in the whole frequency range. But the information of static precision and bandwidth is not sufficient for characterizing the system dynamic features.

For example, the information about raster line linearity in scanning regime or the real coincidence between the raster line and the measured line on scanned surface is not included.

In order to evaluate quality of the system dynamic features, it is necessary to make measurements for various signal management forms and to find ways for dynamic error compensation. The difference between possible trajectory and real trajectory made by device is called tracking error. In modern nanopositioning systems, for example in probe raster microscopes, this is done by digital management methods, when necessary corrections are put into management signal form, in order to minimize the difference between possible and real trajectory. Usually it is an experimental work reasoned on the real system test and gradual correction of management algorithm. In traditional piezopositioning systems with proportional-integral-derivative (PID) control, tracking error is up to 10-20 % from scanning range, so the idea of a real nanopositioning becomes worthless (Fig. 10).

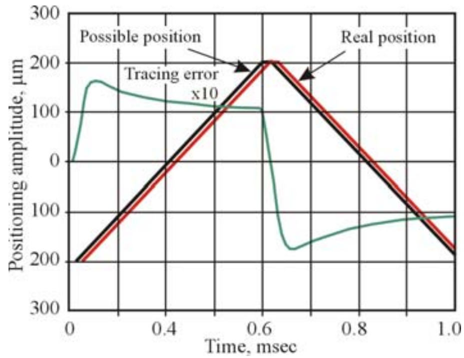


Fig. 10 PZT positioning system controlled by traditional PID

The error grows together with scanning or positioning speed. It is obvious that tracking error is the key parameter in nanopositioning systems.

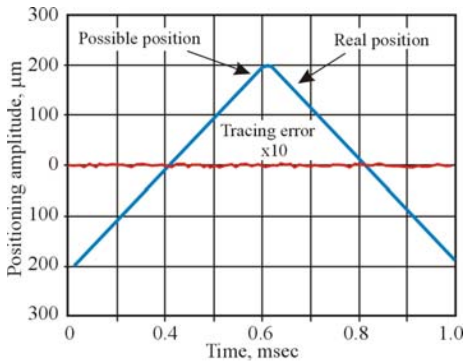


Fig. 11 PZT positioning system with adaptive digital linearization

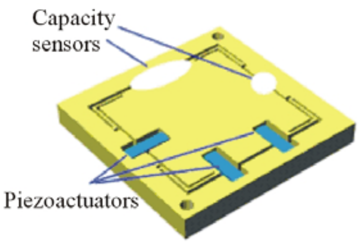
The latest achievements of calculation technique, the increase of calculation speed and power permit the real application of adaptive digital control methods and the decrease of dynamic errors from microns to nanometers, even at high frequency dynamic acceleration (Fig. 11). It is very important in scanning microscopy, nanolithography.

9. Sequential and parallel kinematics

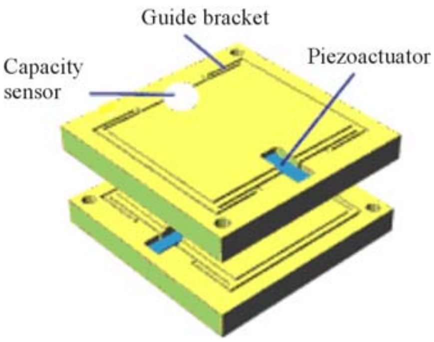
In nanopositioning fields such as scanning (raster) microscopy (laser and probe) it is necessary to scan the object in XY plane and to realize the nanometric positioning control in Z direction.

Scanning speed in such systems may reach up to 100 Hz and more. Nowadays, as it was mentioned before, TV standard scanning microscopes are commercialized (both Bristol university and KTU, RCMN are involved in the development). In order to achieve such scanning speed (25 shots per second, the structure of a shot is 128x128 or 300x300 raster points), the scanning system resonance must be in 20-30 kHz range. The desirable scanning field is 15x15 μm. Therefore a very fast technique for signal digital processing and management is needed.

From the point of mechanical systems it may be achieved using the parallel kinematics XY or XYZ axes scanning systems. They may be both closed or opened. Parallel kinematics (Fig. 12, a) allows decreasing mobile mass, the system is monolithic and inflexible, and both XY axes are identical. Integrated capacity sensors allow compensating the axis interaction and nonlinearity, making the corrections with control signal. Thus active trajectory control is realized. Meanwhile the sequential kinematics (Fig. 12, b) accumulates errors of separate axis.



a



b

Fig. 12 Scanning table: a – scanning table of parallel kinematics with guide turn compensation; b – an example of sequential kinematics scanning

For example, the calculations show that in case of sequential kinematics the error of lower platform from axe is ±10 μrad (table size is 100 mm) will bring the error of 2 μm in upper platform. Table size, its stability and even cable connection, which make friction and hysteresis assembly and influence positioning characteristics in nanometric level, will cause some problems, too. The problems become bigger if there is a need to integrate such system with inverted optical microscope.

Therefore parallel kinematics (Fig. 12, a) is one of optimal solutions when high nanopositioning quality is needed. Integrated capacity displacement sensors and axis angular sensors allow compensating of axes interaction and angle turns, ensuring high linearity of nanopositioning characteristics.

In order to ensure temperature stability the following materials for system construction are used: diuraluminium (aviation diuraluminium), stainless steel and invar. The requirements for price, quality and working environment determine the choice.

Such kinematics problem appeared while developing the Biological atomic force microscope integrated with Nikon 2000 inverted microscope, seeking to control the object optically and to position and scan it with scanning probe microscope in nanometric precision. It is problematic to find a correct solution for XYZ scanner realization, which is integrated with inverted microscope and which fulfils the specific speed (low tracking error) requirements. It was impossible to find such scanner in the market, so it was developed in KTU, RCMN (Fig. 13). But this was achieved only with parallel kinematics construction (Fig. 4).

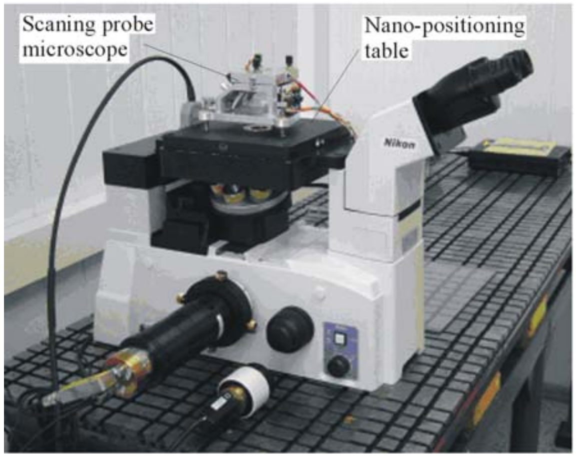


Fig. 13 Nanopositioning table of parallel kinematics XYZ integrated with inverted optical microscope Nikon 2000. Scanning field: 20×20×5 μm, resolution - sub-nanometric (KTU, RCMN)

10. Conclusions

1. To solve the problems of high positioning distance (up to 100 mm and more) and nanometric precision coordination, two level – rough (MicroPositioning) and precise-nanopositioning systems, it are applied.

2. Positioning with nanometric reiteration level is possible in the systems without surface friction pairs.

3. Evaluating the increase of positioning speed (introduction of TV standard) and precision of nanometric reiteration position, the absolute priority nowadays is given to cantilever flexure guidings, the submilisecond duration steps implementing by piezoelectric actuators.

4. For nanopositioning systems with feedback, considering the displacement, it is most expedient to use capacity sensors (precision up to 0.1 nm), or displacement decoders with optical gratings (precision up to 5 nm).

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NANOPOZICIONAVIMAS – METODAI IR PRIEMONĖS

R e z i u m ė

Straipsnyje nagrinėjamos nanopozicionavimo problemos, atlikta taikomų metodų ir pozicionavimo sistemų analizė. Pateikti naujausi nanopozicionavimo technologijų laimėjimai, jų taikymo pavyzdžiai – lygiagreti kinematika, gembinės kreipiamosios, vibracijų aktyvaus slopinimo algoritmai valdymo sistemose, pozicionavimo paklaidų šalinimas, greitaveikis pozicionavimas, t.y. reikšminiai elementai, be kurių beveik neįmanoma užtikrinti pozicionavimo sistemų nanometrinio tikslumo. Pateikti pavyzdžiai bei suformuluoti teiginiai naudingi nanopozicionavimo priemonių projektuotojams ieškant optimalių sprendimų.

V. Lendraitis, V. Mizarienė, G. Seniūnas

NANOPOSITIONING – METHODS AND MEANS

S u m m a r y

The article deals with nanopositioning problems. The analysis of applied methods and positioning systems is performed. The most advanced achievements in nanopositioning technologies are presented as well as the samples of their implementation – parallel kinematics, cantilever guides, vibration active decrement algorithms in control systems, elimination of positioning errors, high-speed positioning, i.e. significant elements, without which it is not practically possible to guarantee nanometric precision in positioning systems. The presented samples and formulated statements are useful for the designers of nanopositioning means looking for optimal solutions.

В. Лендрайтис, В. Мизарене, Г. Сянюнас

НАНОПОЗИЦИОНИРОВАНИЕ – МЕТОДЫ И СРЕДСТВА

Р е з ю м е

В статье рассматриваются проблемы нанопозиционирования, выполнен анализ использованных методов и систем позиционирования. Представлены новейшие достижения технологий нанопозиционирования, примеры их реализации – параллельная кинематика, консольные направляющие, алгоритмы для активного подавления вибраций в системах управления, устранение погрешностей позиционирования, быстродействующее позиционирование, т. е. ключевые элементы, без которых невозможно практично обеспечить в устройствах позиционирования нанометрической точности. Приведенные примеры и сформулированные положения полезны проектировщикам при поиске оптимальных решений средств нанопозиционирования.

Received October 22, 2006