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Electromagnetic Parallel Microrobot for Micro- and Nano-Handling

S. Büttgenbach and M. Feldmann

Institute for Microtechnology, Technical University of Braunschweig, 38106 Braunschweig, Germany (Tel: +49-531-391-3324, e-mail: s.buettgenbach@tu-bs.de)

Abstract: In this paper we report on a novel parallel micro robot driven by Lorentz force actuators. The micro robot consists of three linear micro actuators positioned in plane forming a planar parallel kinematic structure. Each actuator is connected by polymer flexural hinges to a triangular frame in the center of the structure serving as the end effector. Advantages of such micro actuators are the facts that their displacement increases with increasing current and that they exhibit good linear characteristics according to the Lorentz force law. Therefore they allow high precision displacements. Due to the freely suspended structure, friction can be disregarded, and first movements occur already at a current of 10 µA, which results in very low thermal effects. For application to micro-and nano-handling the precise measurement of the displacement of each actuator is very important. Therefore, special capacitive micro sensors are integrated into the system, which consist of comb-like structures constituting differential capacitors. Currently, these micro sensors allow controlling the end effector in a closed loop control with high precision of 1.3 nm within a workspace of 400 µm x 400 µm.

1. INTRODUCTION

As a result of the rapid development of micro- and nanotechnologies, various applications demand the capabilities to position and handle devices over a motion range of some hundred micrometers with a resolution of a few nanometers. Consequently, nanopositioning stages and microrobots are of growing interest in MEMS technology. Furthermore, the reduction of size, weight and power consumption is an ongoing trend, which requires the availability of smart micromechanical actuators. Therefore, worldwide research is focusing on the development of new actuator concepts and materials with their particular advantages and disadvantages [Gad-el-Hak, Hahn, Feldmann a, Wang]. Many microrobots and MEMS stages use silicon technologies and electrostatic or piezoelectric actuation [Madou]. Concerning the actuation principle, piezoelectric devices can be used for nanopositioning, however, inherent non linear effects such as hysteresis and creeping need to be compensated for [Ku, Ru]. Also electrostatic actuation can be used for nanopositioning, but applying this actuation principle results in a lower resolution compared to piezoelectric actuators. Moreover, the maximum displacement is limited to some 10 micrometers, high voltages are necessary, and the displacement does not depend linearly on the actuation voltage [Xinyu]. The most important problem for nanopositioning with both principles is the open loop control where disturbances, for example thermal effects, cannot be balanced. In this paper we describe the development of a smart parallel microrobot based on an electrodynamic actuation principle with integrated position sensors. Application of the electrodynamic principle realized by Lorentz force actuators leads to high displacements up to 400 µm with a resolution of 1.3 nm. In contrast to silicon based devices these microrobots are made of metallic and polymer materials using UV depth lithography and electroplating. Thus, complex 3D microstructures with high aspect ratios of up to 60 can be realized. In addition, these outstanding technologies allow the flexible realization of complicated designs with high resolution and a layer thickness up to several 100 µm.

2. CONCEPT

The concept of the parallel microrobot is similar to the macroscopic delta robot [Raatz] and has three degrees of freedom (DOF). X-, y-motion and rotation of the end effector is possible (see Fig. 1).

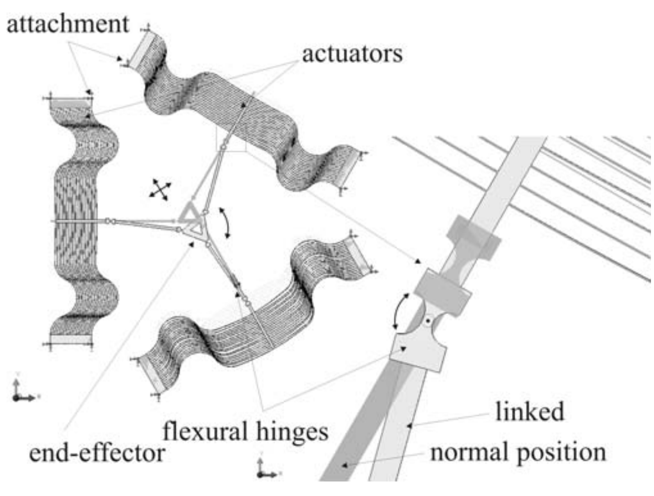

Fig. 1. Concept of the parallel microrobot with 3-DOF consisting of three Lorentz force actuators

The basic setup consists of three linear microactuators positioned in plane with their translation axes arranged in parallel and towards the center of the kinematic structure. Each actuator is connected by flexure hinges and couplers to a triangular frame in the center of the structure, which serves as the end effector. To isolate the different actuators electrically from each other and to reach high deflection the hinges are made of polymer. The micro actuators are based on the electrodynamic principle and called Lorentz force actuators.

3. LORENTZ FORCE ACTUATOR

The basic design of the actuators consists of electroplated copper structures, which are partially deposited on a sacrificial layer in order to produce a movable conductor above a permanent polymer magnet (see Fig. 2). The movable part is suspended from springs, which are attached to the fixed conductor and have the requirement to allow for vibrations and to generate the restoring force.

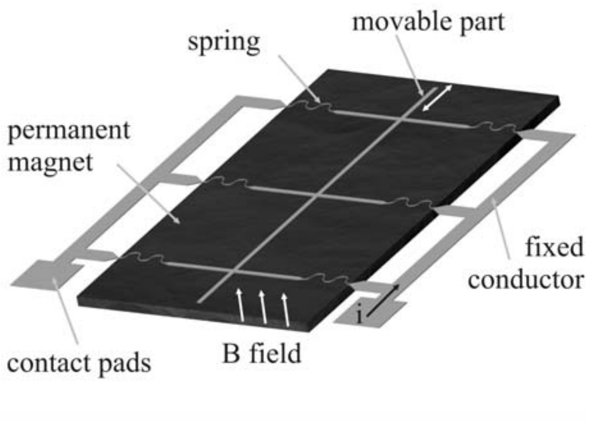

Fig. 2. Basic design of Lorentz force actuator

The fabrication process includes UV depth lithography using AZ9260, screen printing of polymer magnets, polishing of the surface and electroforming of copper conductors as well as using SU-8 for insulation and embedding. After removing the sacrificial layer by etching, the conductors are freely movable (for fabrication details see [Feldmann b]). In Figure 3 the first generation of Lorentz force actuators is shown. Different geometrical designs were realized and tested. The parameters varied span the movable conductors (number, width and thickness), the design of the springs (width, length and radius) and the permanent magnets. Furthermore different materials like electroplated copper, nickel and nickel-iron were used for the springs. The mechanical properties of different systems are measured by a micro force sensor and show a nearly linear relation between the restoring force (see Fig. 3) [Phataralaoha].

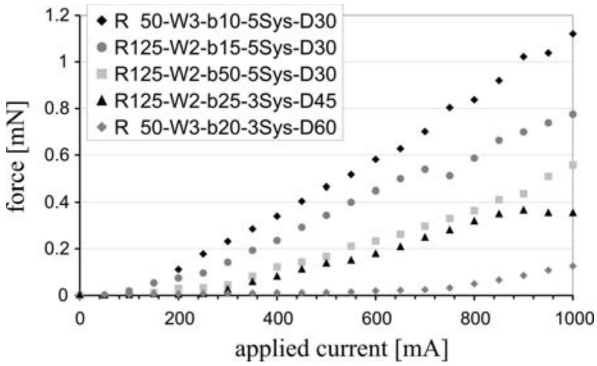

Fig. 3. Force measurement for different geometrical systems in comparison to the applied current

Based on these results a new geometrical design was simulated and produced in order to generate larger deflections and higher forces, especially for micropositioners and micromotors. The width of the springs was reduced and the length and the number of conductors increased. The required space was also minimized. The restoring force of the springs was decreased drastically in order to reach deflections up to 400 μm and higher with linear characteristic (see Fig. 4). The resistance of the conductors is less than 0.05 Ω and the reachable forces are directly proportional to the applied current. Thus, the actuators exhibit low power consumption at high bidirectional displacements which results in low thermal effects. These new powerful actuators were successfully tested (see Fig. 5).

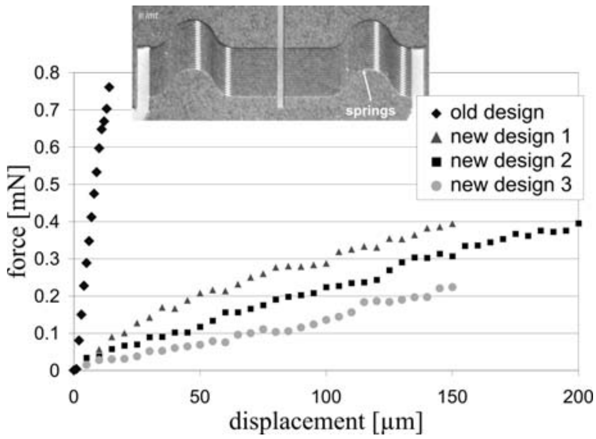

Fig. 4. Comparison of the new and the old spring design

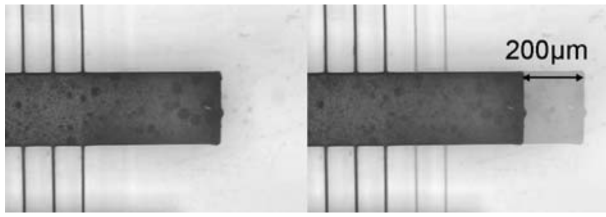

Fig. 5. Deflection of the new microactuator

4. FLEXURAL HINGES

For the optimization of the microrobot structures different flexural hinges were considered. These flexural hinges are free from backlash so that the relative motion between the couplers can be avoided. This is very important for reproducible nanopositioning with low hysteresis. The bend of the hinges is elastically and allows translation and rotation of the end effector. The hinges should be designed to give low stiffness and the required compliances in the direction of bending and high stiffness in the directions of restricted motion. The reduction of stress concentrations due to geometry or clamping effects is also important. To avoid fracture of the hinges different simulations were performed (see Fig. 6). The aim of the optimization of the design of the flexural hinges deals with the minimization of the residual stress as well as the reachable bending (see Fig. 7). The maximum bending of the hinges was calculated in consideration of geometric parameters like different workspace, coupler length and size of the microrobot and amount to 2 degrees. However the geometric optimization of the hinges allows bending up to 6 degrees. In this way, the size of the microrobot can be reduced and the workspace can be enlarged in further developments.

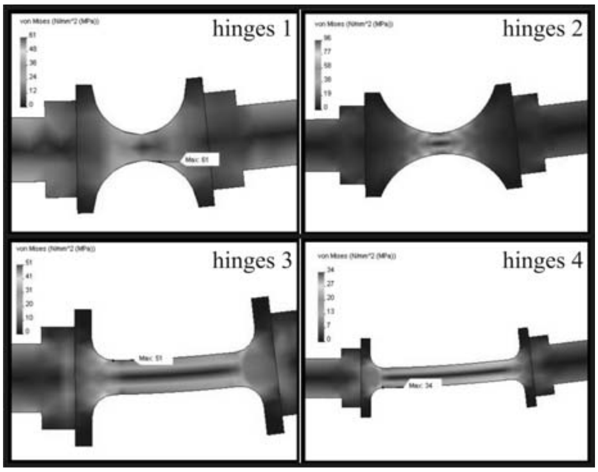

Fig. 6. Simulation results of the residual stress for different flexural hinges

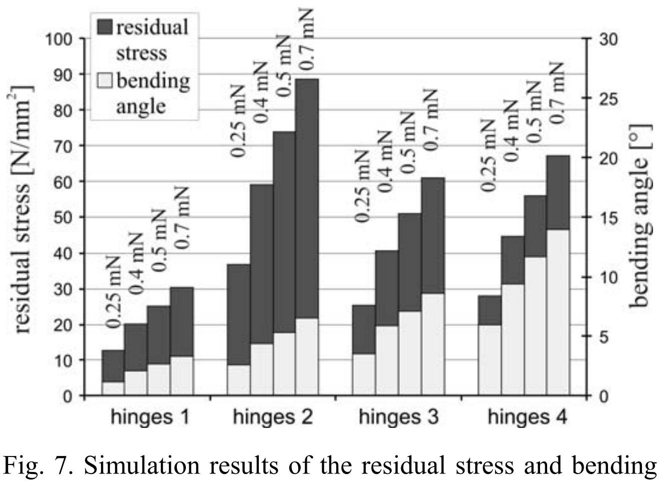

Fig. 7. Simulation results of the residual stress and bending angles for different flexural hinges

5. MICROROBOTS

The hinges and the microactuators were combined in a first generation of microrobots, which confirmed the concept successfully. In order to use these microrobots for micro- and nano-assembling measurement of the displacement of the microactuators is very important in order to verify the position of the end effector. Therefore, in a second design micromirrors were integrated into the robot arranged at the end of each actuator structure (see Fig. 8). Using these mirrors the deflection of the structures can be detected by commercial optical measurement systems from Keyence. The smallest resolution of these devices is about 10 nm. Therefore, a test stand was designed and developed where the optical measurement systems can be adjusted to the microrobot and to the micro mirrors, respectively. The microrobot was fixed and contacted by a holder unit (see Fig. 9). The power supplies for the actuators and the data acquisition of the optical measurement systems can be controlled by an automated scheduler. Different tests were performed, which give information about the interdependency of the actuators and characterize the structure of the microrobot. Also the displacement of the actuators in dependence on the applied current can be measured and shows the expected linear relation according to the Lorentz force law (see Fig. 10).

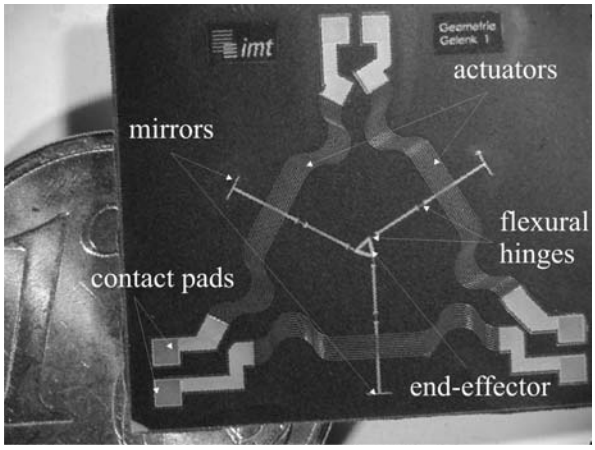

Fig. 8. Microrobot with mirrors

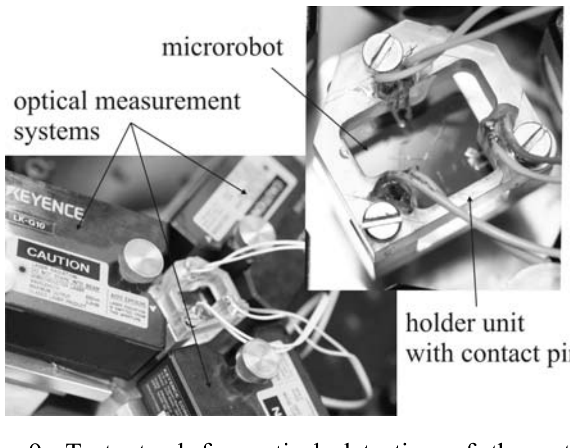

Fig. 9. Test stand for optical detection of the actuator displacement

Furthermore, the microrobots were tested with regard to their durability. It turned out that the robot can be moved over 80 hours and 800 cycles with high reproducibility, low hysteresis, without destruction and no measurable thermal effects. However the required space for the whole setup is not appropriate for a micro robot. Therefore, a concept for the integration of micro position sensors into the micro robots instead of the optical measurement systems was developed and realized.

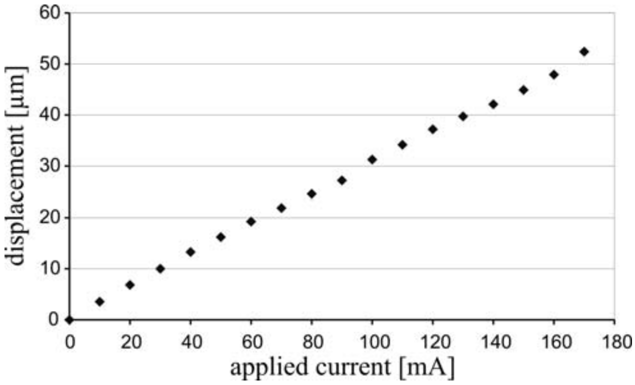

Fig. 10. Optical measurement of the displacements depending on the applied current

6. INTEGRATED POSITION SENSORS

Due to the concept of the Lorentz force actuators, which requires producing movable conductors, the selected sensor principle is based on a differential comb-shaped capacitor, in which a movable electrode is arranged in the center of a fixed upper and a fixed lower electrode (see Fig. 11). The center electrode is connected to the actuator and insulated by a polymer connecting element. Different capacitors were realized and first integrated into a test design, which featured integrated micro mirrors in order to be able to compare the resolution of the position sensors and the optical measurement systems. Figure 12 shows a closed-up view of the electrode configuration.

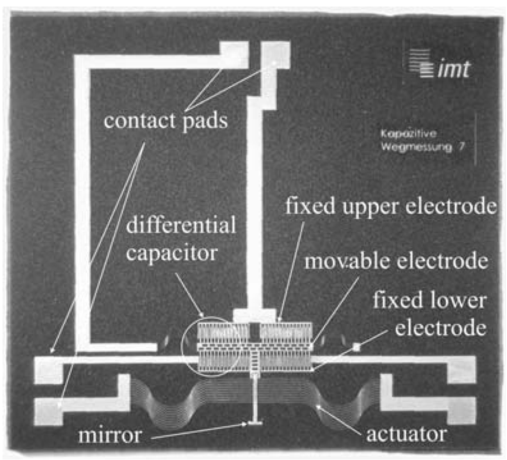

Fig. 11. Test design to compare the performance of the capacitive position sensor to the optical measurement system

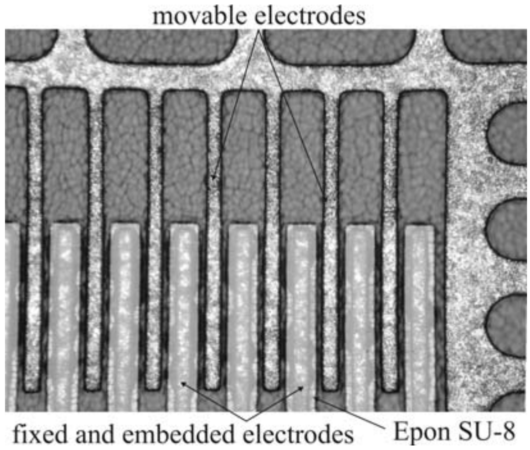

Fig. 12. Close-up view of the comb-shaped capacitor showing the movable and the fixed, embedded electrode

The fixed electrodes were embedded into a polymer to avoid a short circuit in case of dumping of the electrodes. This could possibly result from high forces at the end effectors. The maximum deflection of the movable electrodes was adapted to the maximum work space of the microrobot. To detect the change of the capacitance a capacitance-to-digital converter from analog devices was used. First measurements show that the optical measurement system and the capacitive sensor exhibit a good linear relation over the maximum bidirectional displacement of ±200 µm. Also for small displacements the capacitive sensor is as good as the optical device (see Fig. 13).

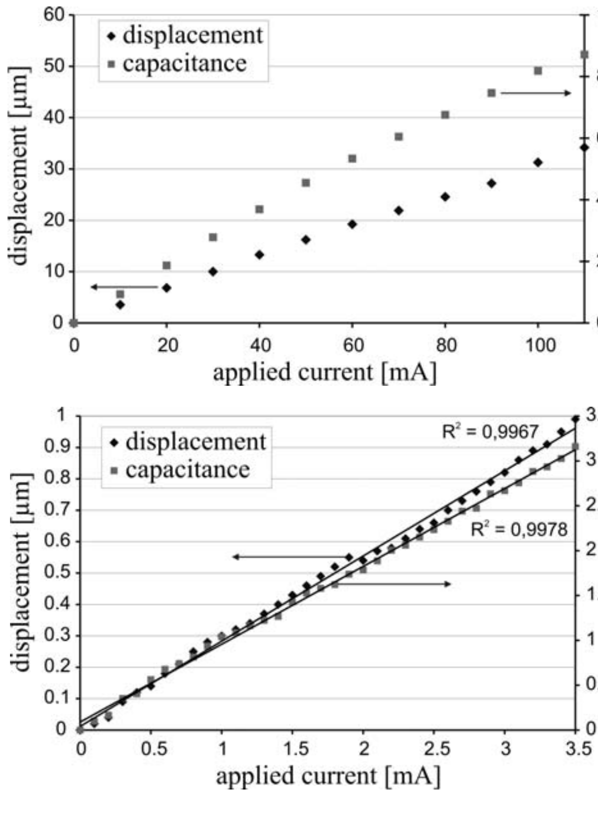

Fig. 13. Comparison between optical and capacitive measurement systems (for capacitor geometry with the biggest electrode gap)

In addition the capacitance-to-digital converter has a resolution down to 4 aF, which results in a measurable step size of 1.3 nm. This is a much higher resolution than achievable by the optical system. The position sensors were also integrated into the microrobot and successfully fabricated (see Fig. 14). For testing this smart microrobot a new holder unit and the implementation of three capacitance-to-digital converters are currently under way.

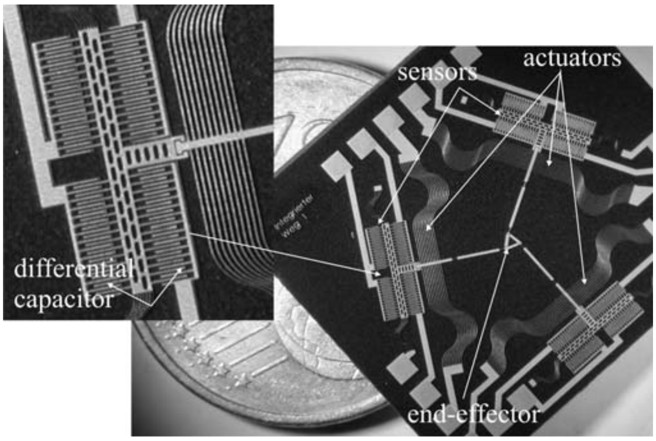

Fig. 14. Photograph of the smart parallel microrobot with differential capacitive sensor

7. DISCUSSION AND FURTHER INVESTIGATIONS

The development of such microrobots is not yet completed. The results presented here describe the first characterization, but show the outstanding potential of electromagnetic parallel microrobots for micro- and nano-positioning and -handling. Due to the forceful optimization of the fabrication technologies different features will be enhanced in the future. Smaller structures of the capaticitors and especially smaller electrode caps will be realized resulting in higher sensitivity of the position sensors. This means, that in future microrobots step sizes under 1 nm will be conceivable. Another aspect is the reduction of the total size of the microrobot with identical or larger work space. Furthermore, concepts for different end effectors will be developed and integrated into the existing process chain. Thereby many different areas of application are possible, such as grippers, movable mirrors or spikes for nanomanipulation. In addition, the substrate can be structured in the area of the work space in order to allow for optical monitoring for special applications. Also the existing measurement electronics and the feedforward control setup will be extended and improved for automatic control of multivariable systems. This is necessary in case of the parallel structures, because the three actuators interacting with each other. In further analytical calculations for the kinematic structures and for the position of the end effector the migration of the instantaneous center of rotation of the hinges will be taken into to account in order to compensate for this effect and to achieve higher reproducibility. Due to the micro fabrication using UV depth lithography and electroplating with flexible design possibilities other kinematic structures for parallel robots will be realized.

8. CONCLUSIONS

In this paper we described the development of a MEMS based parallel microrobot with three degrees of freedom (DOF), i.e. in plane translation in two direction and rotation. The actuator principle is based on the Lorentz force law, which allows bidirectional displacements and is directly linear to the applied current, which is advantageous for open loop control. In addition we integrate position microsensors for each actuator into the microrobot in order to realize a closed loop control to reach high precision displacements up to ± 200 µm with a resolution of 1.3 nm, high reproducibility, and to balance external and internal disturbances. Furthermore, these microrobots exhibit low power consumption at low voltages and have a high durability, which is demonstrated by endurance tests over 80 hours.

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REFERENCES

Feldmann M., S. Büttgenbach (2007)a. Novel Variable Reluctance (VR) Micro Motors with Compensated Attraction Force: Concept, Simmulation, Fabrication and Test. In: *IEEE Transaction on Magnetics*, Vol. **43**, Issue 6, pp. 2567-2569, ISNN 0018-9464.

Feldmann M., S. Büttgenbach (2006)b. Novel Versatile Electro Magnetic Micro Actuators with Integrated Polymer Magnets: Concept, Fabrication and Test. In: *Actuator 2006*, pp. 709-712, ISBN 3-933339-08-1.

Gad-el-Hak M. (2002). MEMS Handbook. CRC Press, Boca Raton, New York.

Hahn M., M. Bedenbecker, H. H. Gaatzen (2007). Evaluation of Linear Hybrid Microstep Motor by Means of Magnetic Flux Measurement. In: *IEEE Transaction on Magnetics*, Vol. **43**, Issue 6, pp. 2588-2590, ISNN 0018-9464.

Ku S. S., U. Pinsopon, S. Cetinkunt, S. Nakajima (2000). Design, fabrication, and real-time neural network control of a three degrees of freedom nanopositioner. In: *IEEE/ASME Transactions on Mechatronics*, Vol. **5**, No. 3, pp. 273-280.

Madou, M. (2002). Fundamentals of microfabrication. *CRC Press*, Boca Raton, New York, Second Edition.

Phataralaoha A., S. Büttgenbach (2006). A Novel Design and Characterization of a Monolithic Three Axial Micro Probe for Dimensional Metrology. In: *APCOT 2006*, pp. 234.

Raatz A., J. Hesselbach, F. Trauden (2006). Modeling Compliant Parallel Robots. In: *ASME IDETC/CIE 2006*, CD No. 99190, ISBN 978-0-7918-3784-9.

Ru C. H., L. N. Sun (2005). Improving positioning accuracy of piezoelectric actuators by feedforward hysteresis compensation based on a new mathematical model. In: *Review of Scientific Instruments*, Vol. **76,** 095111.

Wang W., Z. Yao, J.C. Chen, J. Fang (2004). Composite elastic magnet films with hard magnetic feature. In: *J. Micromech. Microeng.*, Vol. **14**, pp. 1321-1327.

Xinyu L., K. Kekyoung, Y. Sun (2007). A MEMS stage for 3-axis nanopositioning. In: *J. Micromech. Microeng.*, Vol **17**, pp. 1796-1802.