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MECHANISMS FOR MICRO- AND NANO-SYSTEMS

SUMMARY

In the paper designing, structures and applications of micro- and nano- systems are presented. After short introduction in fields of applications where presented systems are used authors discusses problems concerning motors and joints in MEMS. The most popular joint used in micro-system are based on flexures joints, which structure and examples are presented. Next two examples of micro-systems designed and built in Department of Robotics and Mechatronics, AGH University of Science and Technology, Krakow are presented.

Keywords: *microrobotics, flexures , piezomotors*

MECHANIZMY W MIKRO- I NANOUKŁADACH

W artykule zostały przedstawione zagadnienia związane z projektowaniem, budową oraz zastosowaniem mikro- i nanomechanizmów. Po krótkim przedstawieniu dziedzin, w których układy tego typu znajdują zastosowanie, oraz omówieniu zagadnień związanych ze stosowanymi napędami przedstawione zostały złącza stosowane w mikroukładach. Najpowszechniej stosowanym typem złącz w mikroukładach są elastyczne przeguby złączowe (tzw: flexures), których budowa oraz przykłady zostały dokładnie omówione w artykule. Przedstawiono również przykłady mikromechanizmów opracowanych w Katedrze Robotyki i Mechatroniki, AGH w Krakowie. Działanie opracowanych mechanizmów zostało najpierw sprawdzone z użyciem metod symulacyjnych a następnie badań doświadczalnych, do których wykorzystano bezstykowe metody pomiarowe. Wyniki badań przedstawiono i skomentowano w artykule.

Słowa kluczowe: *mikrorobotyka, elastyczne przeguby złączowe (flexures), piezonapędy*

1. INTRODUCTION

Within microsystems and nanosystems two type of structures can be distinguish:
1) the systems which dimensions are very small may range from several nanometers to several micrometers,
2) the systems with bigger dimensions but with high precision control of motion with accuracy on the order of micrometers and nanometers (Hubbard *et al*. 2006)

There are variety of applications of micro and nano systems, that can be found in the literature, among them the following are reported;
- hard disc read/write head positioner, which allows to increase data storage density (Toshiyoshi *et al*. 2002),
- to assembly micrometer-sized parts (Sun *et al*. 2005), positioning of parts during laser welding (Yang *et al*. 1996),
- optical communication device for optical fibers align or moving mirror positioning (Gianchandani 2008),
- micro-valve and micro-pump for medical and biotechnology applications (Dario 2000),
- electrical switches and relays (Guckel 1998),
- microelectronic devices manufacturing tools to align silicon wafers for lithography (Lee and Kim 1997).
- and many more new applications in such fields like: medicine, biotechnology, environmental technology, automotive products, appliances, etc.

Microsystems will be able to replace conventional systems when they are available at low cost. It will happened if they will be mass-produced which on other hand required huge market. To achieve lower cost of production for each individual components new manufacturing techniques have been developed. These techniques, silicon based ones, allow the production of many identical components at the same time on one wafer.

Microsystems can be design with special micro and nano techniques employing many different materials and physical phenomena (Gianchandani 2008).

Following paper discuses issues concerning of micro- and nano- systems and research results of micro-gripper designed, built and tested in Department of Robotics and Mechatronics, AGH-UST Cracow.

Micromechanical systems can be characterized by many different factors; degrees of freedom, movement range, resolution, range to resolution ratio, force, natural frequency, bandwidth, hysteresis, repeatability, accuracy and robustness.

The performance of micromechanical systems depends on choice of microactuator. The following microactuators can be chosen (below mostly used actuators are listed);
- piezoelectric actuators,
- magnetic actuators,
- electrostatic actuators,
- thermal actuators,
- electrochemical actuators.

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Piezoelectric actuators' idea is based on piezoelectric effect which relays on application of voltage to crystal lattice, which causes the material to deform in a certain direction. Piezoelectric actuators are known for their quick reaction speed and the reproducibility of the traveled distance. They are very efficient because about 50% of the applied electrical energy can be directly transformed into mechanical energy. Piezoelectric actuators can generate very high forces, which is of great importance for design of micromechanism, but available movement is relatively small, other advantage of piezomaterials are their mechanical durability, they don't react to other electric components near them, and they are not sensitive to dust. The movement to be obtained is relatively small; it is range of several nm/V. A piezoelement can expand by about 0.1–0.2% in one direction. The form and size of a ceramic component can be easily adapted to the desired task. Multilayer stack, strips, tubelet (ring) and cantilever constructions are most often used. For the typical stack construction applied voltage should be in range of 60–1000 V which respond with typical displacement 20–200 μm and force up to 30 000 N. Characteristics of strips and ring are similar, applied voltage in the range 60–1000 V gives movement range up to 50 m and forces less then 1000 N, but cantilever beam design with applied voltage in range of 60–400 V gives relatively big movement up to 1000 μm and small exerted force up to 5 N. Newest design of piezoceramics gives possibilities to make thinner ceramic layer (20–40 μm) and very thin electrodes results in reduction of required operating voltage to 100 V. Disadvantage of the piezomaterials for actuators design is depolarization effect and the coercive field strength. When limits of these values are exceeded the material will be depolarized, which is associated with loss of the specific piezo properties. The piezo materials can not work in wet environment. For most application of piezoactuator a large piezoelectric coefficient, high electrical resistance, low internal voltage and high mechanical stability are needed. For piezomaterials relation between applied voltage and movement is linear, which helps to realize dedicated controllers.

Magnetic actuators operate by driving an electric current (about 400 mA) through a coiled conductor. Two types of actuator can be distinguish; magnetostrictive and electromagnetic. Magnetostriction effect, which is basis for magnteostrictive actuator operation means a dimension change of a ferromagnetic material by applying a magnetic field to it. Relative length change of 0.15–0.2% is typical for newest materials and similar to piezoelectric materials. These materials have very small hysteresis loop and they are resistive to rough environmental conditions. The Curie temperature effect is high about 380°C, but for typical piezomaterials it is about 140°C (newest piezoceramic material reached Curie temperature about 560°C). The bottle neck of this type of actuator is very small movement range, similar to piezoactuators. Magnetostrictive actuators are controlled by current, as opposed to piezoelectric actuators which are controlled by voltage. The voltage can be kept relatively low in this case which reduce cost of necessary driving circuits. Magnetostrictive actuators can be used for application when high forces, quick dynamic responses and short controlling distance with very high positioning accuracy. Typical example of design of megnetostrictive actuator is Elastic Wave Motor (EWM). In this motor electric energy is transformed into continuous linear movement. Electromagnetic actuators are typical electric motors and relays. The affectivity of electromagnetic actuators are determined by material properties and the volume of the used magnet. For this reason, the miniaturization is limited by the size of the magnet to be integrated. Inside this type of actuators two classes can be distinguished; rotational motors or linear motors. The resolution of such motors is in range 100 nm, but minimal diameter of commercially available rotational motor is about 3 mm.

Electrostatic actuators are capacitors with either air or vacuum as the dielectric. A difference of potential on both plates of capacitor induces force which is nonlinear function of the plate separation distance. Factors such as projected area between two plates and the geometry of the field fringe lines influences force – displacement relation. Electrostatic actuators generate relatively big forces normal to the plate surfaces but in very limited movement range. Comb drives are the most popular design of electrostatic actuator. In this actuator design the force is almost independent on displacements. Typical applied voltage are between 20 and 60 V which gives movement in range up to 100 μm with resolution of maximum 2 nm. This kind of system offers a very high precision level, and a simpler electronic control. In a comb drive actuator, there is no pull-in effect, unless a design error make electrodes reach each others. The displacement is linear, contrary to straight actuation. But the design is limited by the needs to place electrodes beams opposite to each other. Designer must also take care of the end stop to avoid contact between mobile and fixed part, and to keep forces quite symmetric so that the direction of the displacement is kept as planned.

One special type of an electrostatic actuator is micro-resonator which is used to replace electronic resonators, in electronic filter systems, to select a particular frequency chosen amongst several ones. Microresonators uses mechanical vibrating parts to filter signals so that only one frequency, the eigen frequency of the structure, is kept. The application is for electronic signal treatment, so, there must be a way to convert electrical signal into mechanical stimulation, and then back again mechanical vibration into electrical signal.

Thermal actuators moves due to their temperature change and expand dimension, temperature change is forced by current flow through thin parts of actuators. Thermal actuators moves only in one direction from their balanced position. Displacement from this position relies on strain, then to make bigger movement range higher temperature is required. Commonly an electrical parameters of this type of actuators require inputs of 13 V and 36 mA and operating temperature is about 600°C. Typical range of movement (for commercially available actuators) are 2 m till 550 μm and bandwidth from 6 to 1000 Hz. They are mainly used as microvalves, and actuators for different types of applications.

Electrochemical actuators operate using water electrolysis phenomena, The reaction converts water to hydrogen and oxygen gases and vice versa. The gas pressure deflects membrane and does mechanical work. After electric current is switched off the reverse reaction starts slowly until the deflected membrane returns to balanced position. Electrochemical actuators move only in one direction from the balanced position. The input voltage is relatively small, about 1.6 V and very low current 5 μA. The range of displacement is from 2 till 1000 m and they have very small bandwidth 0.01 Hz. Applications of such actuators are limited to cases with relatively slow move.

Summarizing above overview of micro-actuators they (piezo, electrostatic and magnetic type) can be used if high resolution of positioning, small range of movement (between 0.5 μm and 2000 m) and relatively high forces are required. In many typical applications to small range of movement is one of the main obstacle to employ microactuator design. In these cases the high amplification of displacement is desired. One possibility is use of a special mechanical structure based on flexure hinges design idea, which can enlarge range of movement up to several millimeters.

The following chapters are presented an example of gripper for micromanipulations designed in Department of Robotics and Mechatronics, its design, simulations and test results.

2. FLEXURE HINGE BASED MECHANICAL AMPLIFIER AND ATTENUATOR DESIGN

Mechanical elements of movement transmission for micro and nano systems should fit some special requirements among them backlash free kinematic chain design play crucial role for fine positioning mechanism. One possibility of this type of mechanism design is use flexure hinges idea, which is shown schematically in the Figure 1a.

The flexure is a type of compliant mechanism which has at least one component that is sensibly deformable compared to other links. The first paper which presented terminology and different design of flexure hinge has been published at 1965 (Paros and Weisbord 1965). Nowadays, because of new requirements of nano mechanism, with fine positioning possibility, more and more application for this type of mechanism can be distinguished (Golda and Culpper 2004; Huh *et al*. 2006; Fatikow and Rembold 1997; Smith 1991; Labontin 2003) but in all MEMS structures in which movable components are included the flexure hinges are employed.

The characteristic feature of flexure hinges is sensitive axis, along which the relative rotation between the adjacent rigid parts is taking place, and stiff as much as possible about all other axes and motions.

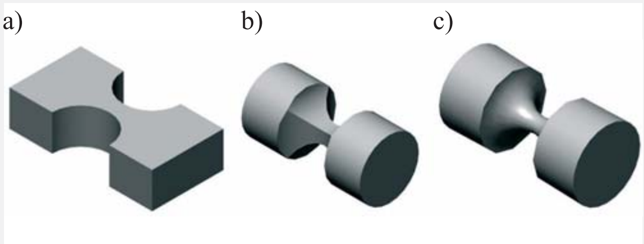

Fig. 1. Flexure hinges a) single axis, b) two axis, c) multi axis

The advantages of using flexure hinges design are; friction free and wear free motion, they are simple and inexpensive to manufacture and assembly, complete mechanism can be produced from single monolith, high movement amplification ratio can be easily implemented using mechanical leverage, the rotation and translation can be transmitted, no lubrication is required. There will be a linear relationship between applied force and displacements for small distortions. This linear relationship is independent of manufacturing tolerance, however the direction of motion will be less well defined as these tolerance are relaxed. This type of mechanism has some drawbacks among them problems with accurate prediction of force displacement characteristics on design stage. Even high manufacturing tolerances can produce relatively big uncertainty between predicted and actual performance. The problems can occur at significant stresses level when some hysteresis in the stress-strain for some materials exists. Due to this hysteresis and fatigue wear of materials at higher level of stress flexures are restricted in the distance of translation for a given size and stiffness. The flexures can not be use for large loads, accidental overload can be catastrophic or significantly reduce fatigue life. Flexure hinges can be classified in to three main classes; single axis, two axis, and multi axis design. The typical design of flexure hinges are shown in the Figure 1.

In a case of piezomotor used as a drive for flexure hinges mechanism and requirements to provide of relatively large motion distance with high resolution, it is necessary to apply some form of lever mechanism to amplify the drive action (Snyder 1993). The example of lever based mechanism used for amplification of piezo actuator displacement is shown in the Figure 2.

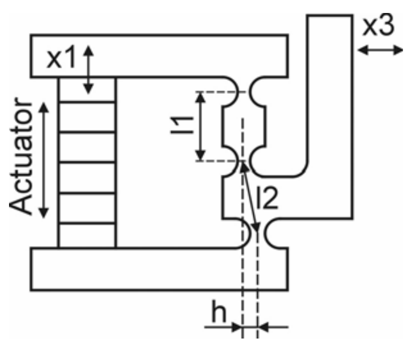

Fig. 2. Scheme of lever system with flexure hinges and pivot
See explanation in the text

The point 1 represents input, the point 2 represents pivot finally point 3 represent output. To find relation between input and output (displacement) the displacement diagram method can be employed. The method is described carefully in (Furukawa and Mizuno 1990). For particular mechanism presented in Figure 2, the relation between input and output is given by the formula:

$$x_3 = x_1 \frac{l_1}{h} \sqrt{1 - \left(\frac{h}{l_1} \right)^2} .$$

For small angles of lever rotation or h very small, the lever ratio can take very large values. As it can be noticed the relation between input and output is nonlinear (*h* depends on input displacement). It makes lever mechanism more difficult to control.

Assuming that all pivots are infinitely rigid, all lever mechanism can reversed to operate as either a displacement magnifying or attenuation mechanism. Some times a long range drive mechanism with high resolution should be used. A relatively simply way to increase resolution of long range drive mechanism is to use a reduction mechanism based on soft spring – hard spring idea. The less nonlinearity will not be detected in this concept and extremely large attenuation ratios are possibly. An example of this type of mechanism is shown in the Figure 3.

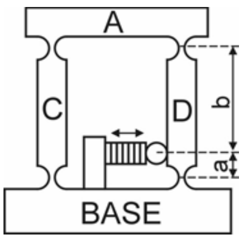

Fig. 3. Based on four-bar linkage movement amplifier for micro-structure application

For this design attenuation between actuator displacement and upper platform is simply to calculate from the formula

$$n = \frac{b+a}{a}.$$

This is most simple mechanism which can be design for attenuation purpose, but some more complex will have less distortion due to compliance in sensitive direction (Smith and Chetwynd 1991).

3. PIEZOSYSTEM UNIVERSAL POWER SUPPLY DESIGN

Piezosystems required quite high voltage for control, this is one of the most important drawback of their applications. The second requirement which has influence on power supply design is bandwidth. To achieve high speed of actuator, the bandwidth should be in interval between DC and 300 kHz. The scheme of designed electronic amplifier is shown in Figure 4. The input signal, which is maximum 20 Vpp, is preamplified in low voltage stage. There is gain controller built into this stage. The heart of the PPA2000 is high voltage amplifier. Power supply for this stage can be up to 200 Vpp. Maximum output current for this stage is 80 mA, so for most of piezoelectric actuators current amplifier is required. Last stage of PPA2000 amplifier is high current, MOSFET based amplifier. This stage can drive low load impedance with short time current up to 120 A. Amplifier can amplify input voltage from DC up to 300 kHz. Unique solution for the PPA2000 amplifier is special internal circuit, designed for driving low impedance, capacitance load up to microfarads in very wide frequency range.

To control of the piezosystem with application of designed amplifier, the voltage input signal in the range between 0 and 20 Vpp is required. The signal has to be applied for each channel independently. The amplifier is used for control of microgripper and microrobot.

4. MICRO-GRIPPER DESIGN CASE STUDY

During research in Department of Robotics and Mechatronics, concerning micro-manipulation, a micro gripper, based on flexure hinge, piezo actuator and high voltage amplifier, has been designed, manufactured and tested. The material used for gripper structure is stainless steel, because of its low cost, chemically neutral properties and satisfying resistant to fatigue.

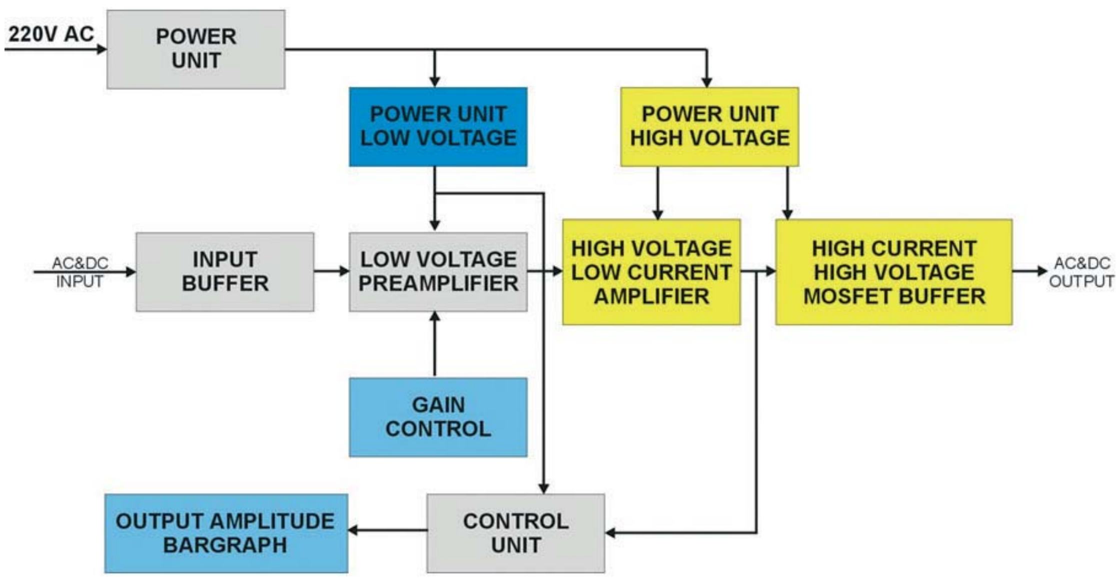

Fig. 4. Scheme of high voltage amplifier for control of piezosystem

To avoid some problems with system reliability high quality of manufacturing is required, the problem is focused on flexure hinges manufacturing with should be made with accuracy better than 0.01 mm. Presented gripper design is manufactured using electro discharge processing technology. The shape of flexure hinges is proposed circular solution with diameter 0.8 mm and thickness 0.2 mm which fits requirements of low driving force and longer displacement range. The design of microgripper is shown in Figure 5. To confirm strength and functional features the FE model has been formulated and simulated. The results are presented in the Figure 6.

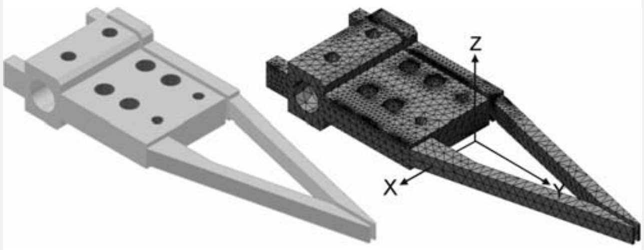

Fig. 5. Microgripper and its FE model

a) b)

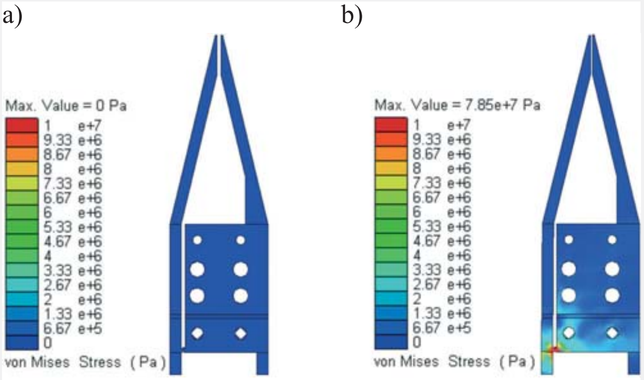

Fig. 6. Results of stress simulation for: a) open; b) closed microgripper

The maximum strength (for maximal deflection) in area of the flexure hinge is about 10 MPa, which is less then stress limit for infinite number of load cycles on Woehler plot for applied material. To confirm calculation results an experiment using active thermography has been done. The stand for stress distribution testing is shown in Figure 7. As an exciter a piezo actuator was used, designed as a stack SCMA-P9 (Noliac). The piezo stack has dimensions 10 × 10 × 20 mm and is manufactured from PZT type S1 and permits for expansion of 29 μm +/–15%. During the experiment signal generated by high voltage amplifier has been used for excitation of piezo actuator and to synchronize thermograhy camera. Lock – in method combine with thermo camera imaging has been applied for direct stress measurements. The results are shown in the Figure 8 and confirms stress level and distribution around flexure hinge.

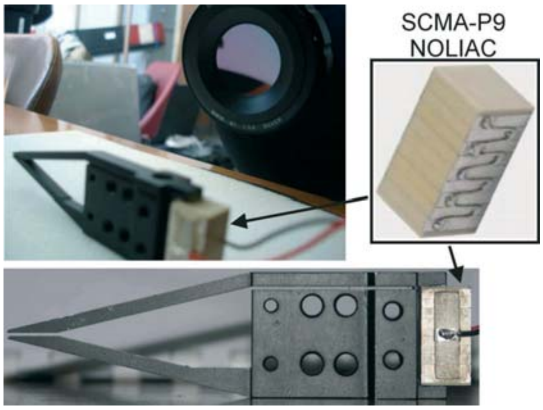

Fig. 7. Scheme of experimental stand with piezostack used as actuator

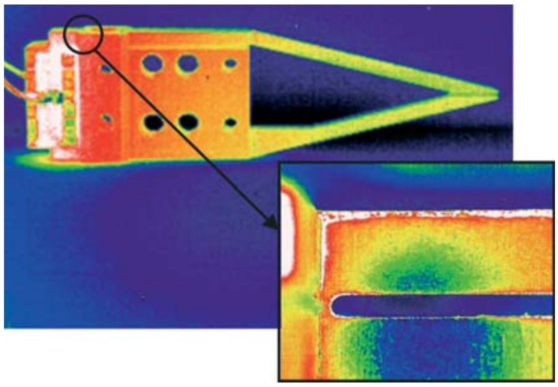

Fig. 8. Results of active thermography based stress measurements

The next step of experiment has been test of the performance of designed actuator. To assess dynamic properties of gripper the input signal applied to system under the test has a form of rectangular wave presented in Figure 9a. Measured and recorded response in a form of time plot of displacement and velocity are presented in the Figure 9b and c. As it can be easily notice from the results, dynamic properties of the structure should be taken into account during control of gripper position, to avoid vibration of its parts.

Another example is designed at the Department of Robotics and Mechatronics of the AGH University of Science and Technology an ultra-precision micromechanical device with high motion resolution, Figure 10a. The system is designed as modules and consists of the following elements: stack piezoelectric actuator with integrated strain gauge, monolithic motion amplifier, parallel mechanism (ensuring parallel motion), base with fixing elements, and transparent plexiglass shield. The device has been designed in a way to enable its extension by fixing various functional elements (Fig. 10b). The system operates by amplifying the range of movement of the piezoelectric actuator, while at the same time, maintaining high motion resolution and relatively high final force. The joints are built of titanium, which ensures no backlash, no friction and enables high precision of movement, with resolution below fractions of nanometer.

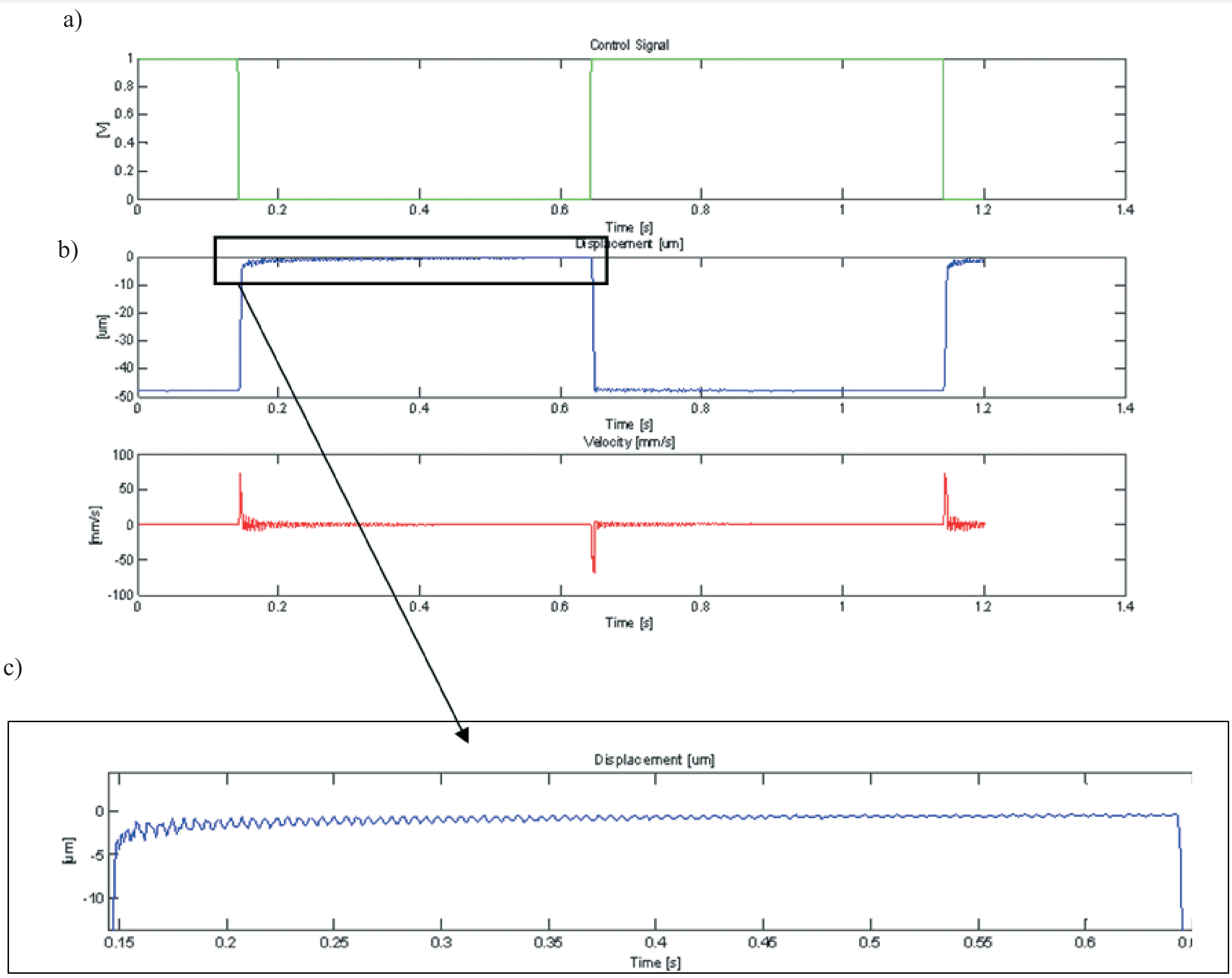

Fig. 9. Experimental results (a–c)

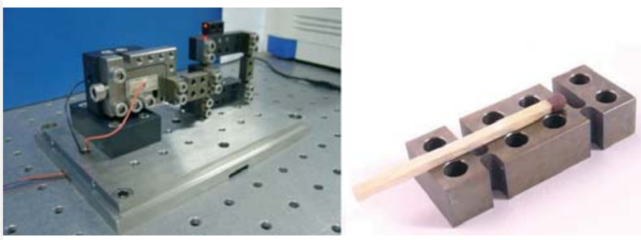

Fig. 10. Structure of linkage mechanism with flexure hinges

The principle of operation of the construction is based on amplification of translational movement of piezoelectric element through monolithic amplifier with specific shape. The amplifier converts the translational movement of the piezoelectric actuator into rotational movement of working element, ensuring amplification of the range of movement. Next, rotational movement is converted back into translational movement through lever mechanism. Total amplification of the range of movement reaches 30 times. Hence, using piezoelectric actuator with 30 micrometers stroke travel range reaches 0.9 mm.

Resolution and precision of the travel range depend on the control electronics applied and the measurement system, and may reach nanometers. Total exit force of the last shifting segment reaches c.a. 10 N. Total travel range can be extended by using some additional amplifying elements. This allows achieving the range of movement exceeding 10mm. However, it should be noted that the increased range of movement leads to lower operational force and may reduce motion resolution.

The whole system has one degree of freedom (1DOF), and the travel range being translational movement. Modular construction of the device enables its extension, and building systems with three (3DOF), six (6DOF) or more degrees of freedom. It is also possible to transform the translational final movement into the rotational one, if needed.

The system is controlled by a high voltage amplifier (0–200 V), enabling suitable power supply for the piezoelectric actuator and ensuring the required movement dynamics of the whole system. Control signal can be adjusted to the requirements of the control system (typically, it is the analogue control signal 0–10 V). The scheme of applied controller and experimental stand is shown in Figure 11. The frequency of operating system may reach 1 kHz at this case.

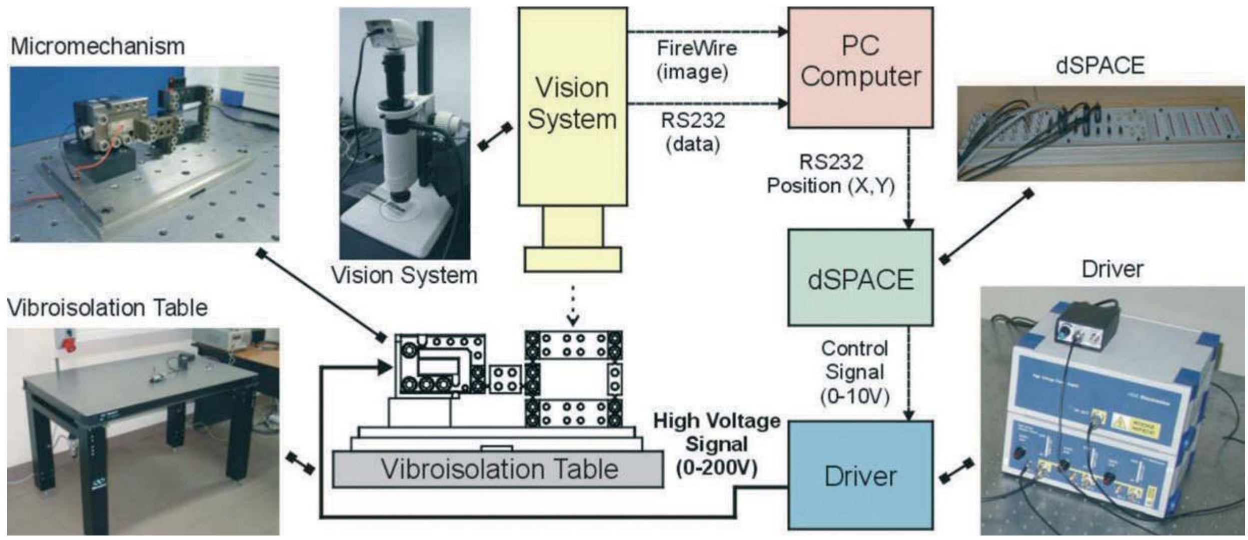

Fig. 11. Scheme of tested linkage mechanism

This system consist of optical unit (vision system), PC computer, drivers and external real-time operating control system (dSPACE). The vision system consists of measuring optics LEICA Z16 APOA with the camera LEICA DFC290 and the illuminator LEICA CLS 100X. The vision system, dependent upon the lens and image enlargement, enables resolution up to 0.2 μm/pixel, with image size 300 μm × 400 μm. The image acquisition takes place through the Fire Wire (IEE1394) interface to PC, then the image is processed through the algorithm build in C++ and the position, calculated within the camera coordinates (XY), is transmitted to the fast prototyping system dSPACE using RS232 interface.

Control algorithm of the micromechanism is based on measurement of position of the effector by the vision system, generates the corresponding control signals which are transferred driver of the piezoelectric actuator. The driver process the control signal into high voltage enabling precision movement of piezoelectric actuator.

The system is used in applications requiring high movement precision, such as fiber optics and optics technology, biotechnology, microscope observations, nano/micro positioning and assembling, as well as a sub-system in other complex micro-mechanical constructions, including microrobots.

5. CONCLUSIONS AND FINAL REMARKS

There are many new solutions in micro and nano positioning system design. As regards mechanical part of these positioning units the flexure hinges are most commonly use. As it was presented in the paper dynamic properties of the flexure hinges are important in design and control design. Methods for flexure hinges testing, that allow to assess their properties in efficient way, are based on contactless, vision measurements. Proposed fast prototyping technology, for controller design is an useful technique even for multi - degree of freedom high precision actuator. Nowadays, piezoactuator seems to be one of the most popular in use but also simplest in design and implementation.

REFERENCES

Cugat O., Delamare J., Reyne G. 2003: *Magnetic micro-actuators and systems*. IEEE Trans. Magnet, vol. 39 (6), pp. 3607–3612.

Culpepper M.L., Chen S.C. 2004: *Modeling and design of a digitally actuated compliant mechanism for Cartesian micro/nano-manipulators*. Journal of Precision Engineering, vol. 12, pp. 240–264.

Dario P., Carrozza M.C., Benvenutto A., Menciassi A. 2000: *Micro-systems in Biomedical Applications*. J. Micromechanics and Microengineering, 10, pp. 235–244.

Fatikow S., Rembold U. 1997: *Microsystem Technology and Microrobotics*. Springer.

Furukawa E., Mizuno M. 1990: *Displacement amplification and reduction by means of linkage*. Bull. Japan Soc. Prec. Eng., 24 (4), pp. 285–290.

Gianchandani Y.B., Tabata O., Zappe H. 2008.: *Comprehensive Microsystems*. Elsevier, vol. 3, pp. 1–65.

Gianchandani Y.B., Tabata O., Zappe H. 2008: *Comprehensive Microsystems*. Elsevier, vol. 1.

Golda D., Culpepper M.L. 2004: *Small scale Micro/Nano Manipulators in precision alignment and positioning*. Proc. of American Society of Precise Engineering, Orlando, FL., pp. 297–299.

Guckel H., Fisher K., Stiers E. 1998: *Closed Loop Controlled, Large throw, Magnetic Linear Actuator with 100 μm structural height*. Proc. IEEE Micro Electro Mech. Syst., pp. 414–418.

Hale L.C. 1999: *Principles and techniques for designing precision machines*. University of California Press.

Henneke E.G. II, Reifsnider K.L., Stinchcomb W.W. 1979: *Thermography, An NDT Method for Damage Detection*. J. Metals, pp. 87–94.

Hubbard N.B., Culepepper M.L., Howell L.L. 2006: *Actuators for Micropositioners and nanopositioners*. Applied Mechanics Reviews, Nov. vol. 59, pp. 324–334.

Huh J.S., Kim K.H., Kang D.W., Gweon D.G., Kwak B.M. 2006: *Performance evaluation of precision nanopositioning devices caused by uncertainties due to tolerances using function approximation moment method*. Rev. Sci. Instrum., 77, 015103.

Lee C.W., Kim S.W. 1997: *An ultra-precision Stage for Alignment of wafers in advanced Microlithography*. Precision Engineering, vol. 21, issue 2–3, pp. 906–912.

Lobontiu N. 2003: Compliant Mechanisms design of flexure hinges, CRC Press, Boca Raton.

Nash S.K. Zhoung Z.W. 2007: *A microgripper using piezoelectric actuation for microobject manipulation*. Sensors and Actuators A: Physical, vol. 133, issue 1, pp. 218–224.

Paros J.M., Weisbord L. 1965: *How to design flexure hings, machine Design*. November, pp. 151–170.

Prusak D., Uhl T., Petko M. 2006a: *Mikrorobotyka – nowy kierunek rozwoju robotyki*. PAK 5', pp. 5–8.

Prusak D., Uhl T., Petko M. 2006b: *Parallel Microrobots – concept and prototyping*. 12th IEEE International Conference on Mehods and Models in Automation and Robotic MMAR 2006. Międzyzdroje 28–31 sierpień.

Shih C.J., Lin C.F. 2006: *A two-stage topological optimum design for monolithic compliant microgripper integrated with flexure hinges*. Journal of Physics: Conference Series 34, pp. 321–342.

Smith S.T., Chetwynd D.G. 1991: *Foundation of Ultraprecision mechanism design*. Gordon and Breach, New York.

Smith S.T. 2000: *Flexure, Elements of Elastic Mechanism*. CRC Press, Boca Raton.

Snyder J.J. 1993: *Accurate, inexpensive, thermal expansion microtranslator*. Rev. Sci. Instrum., 64 (5), pp. 1351–1354.

Sun Y., Piyabongkarn D., Sezen A., Nelson B.J., Rajamani R. 2002: *A high – aspect – Ratio two-axis electrostatic microactuator with extended travel range*. Sensor and Actuators A, A102, 1–2, pp. 49–60.

Thielicke E., Obermeier E. 2000: *Microactuators and their technologies*. Mechatronics, vol. 10, p. 431–455.

Toshiyoshi H., Mite M., Fujita H. 2002: *A MEMS piggyback actuator for hard disc drive*. J. Microelectromechanical Systems, vol. 11, issue 6, pp. 648–54.

Yang R., Jouanech M., Schweitzer R. 1996: *Design and characterization of a Low- Profile Micropositioning stage*. Precision Engineering, vol. 18, issue 1, pp. 20–29.