MECHATRONIC HANDLING DEVICE BASED ON THE PIEZO CERAMIC STRUCTURES FOR MICRO AND NANO APPLICATIONS

R.Kasper[1], M. Abed Al-Wahab[1], W. Heinemann[1], K. Kostadinov[2] , D.Chakarov[2]
[1]Institute of Mobile Systems , University of Magdeburg
[2]Institute of Mechanics, Bulgarian Academy of Sciences

Abstract:
This paper presents actually work from development of mechatronic handling devices able to accomplish certain micro- and/or nano operation tasks. Piezo ceramic structures with (3,1)-piezoelectric effect integrated into the mechatronic system will be used an actuation element. The subject of this paper is structures with more than 1 degrees of freedom appropriate for different micro- and nano-applications.The kinematic design of the actuator involves specifying the kinematic structure and required raw geometric data like actuator force and motion. Here the synthesized kinematic structures using the structured piezo ceramics are tense integrity closed structures. A fine tuning of geometric and material parameters is performed in an iterative process based on a lot of partial tasks to be achieved, with respect to: modeling, FE-simulation, design, control and experimental investigation of mechatronic handling device for micro- and nano-operations.

Introduction.

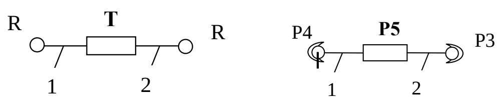
Micro and nano manipulators are mostly used in biological and microelectronics research, cellular technology, chemistry and investigation of thin films, in atomic force microscopes (AFM) and scanning tunneling microscopes (STM).
There are known micromanipulators with piezoactuators [1-5]. For biological cell manipulation fast stepping PZT flexure stage with one d.o.f is developed for cell injection [2-5]. The effective piezoelectric materials together with powerful electronic driving systems have pushed the attractiveness of piezoelectric actuators in the past years significantly. Compared to competing actuators they offer substantial advantages e.g. large force, high frequency and a small size [6,7,8,9]. Nevertheless many practical applications need larger motion, only realizable using amplification elements but resulting in bigger size and a more difficult integration and fitting of the actuator. In order to adapt actuator characteristics to the requirements of applications, motion amplification systems (MAS) must be utilized [10-11].
Piezo actuated micromanipulators with structure, as Stewart platforms are also developed [3]. Robots with Stewart platform structure have a lot of advantages [4,12]. Their small workspace in the case of cell manipulations is not a disadvantage, since it is enough for the case.

Mechanisms with closed kinematic chains [13,14,15,16,17,18] are suitable for high-precision tasks in 3D space. The high accuracy of such mechanical systems comes from the very high structural stiffness. Mechatronic systems and devices with closed kinematical structure can be used for any applications where comparatively large workspaces (till a few cubic cm) must be combined with very high resolution (a few nm). Comparing with existing systems, their main advantages are stiffness (till 100N/μm, compactness (high immunity against vibration) and simplicity (costs are very competitive). In near term, this technology can allow to commercialize "low cost" tele-micromanipulators for optical microscopes (0.1μm resolution) and inspection systems. Potential applications for these mechatronic handling devices are, for example in the electronics industry, for mask aligner and wafers- printed boards- or IC-inspection (the micro-robots would hold micro-electrodes to check electronics signals). Other applications could be used also for the alignment of optical miniature components.
The goal of this work is to develop methodology for synthesis of mechatronic handling devices (MHD) for micro- and nano-applications, comprising means for structure modeling, simulation, design and experimentation utilizing the advantages of piezo-actuators, structured

piezo-ceramics and the closed robot kinematic structures.

Synthesis of kinematic structure for micro- & nano-manipulation tasks based on piezo ceramics and closed kinematic structures.

Piezo-structured ceramics and MHD using piezo stack actuators and single ceramic actuators can be assumed according to the Mechanism and Machine Theory as a mechanism with closed kinematic structures. The polarised ceramic elements, piezo stack actuators and single ceramic actuators can be estimated as actuators for linear motion, which can be modelled by the kinematic chain shown in Fig.1.



a) b)

***Fig.1**. Kinematics chain of ceramic actuators.*

It includes two links 1 and 2 and a couple **T** of linear motion, which can perform locomotive functions and two rotational couples **R** by which the actuator is attached to the driven links.
The generated closed kinematic structures include links with 2, 3, 4,… and so on kinematic couples, which we describe with number $\mathbf{n_2}$, $\mathbf{n_3}$, $\mathbf{n_4}$.... , etc. There exists the following relation among the basic links in the closed kinematic structure [16],[17]:

$$\mathbf{2i = \sum_{j=3}^{i+3}(j-2)n_j} \qquad (1)$$

Here $\mathbf{n_j}$ is the number of the links, which forms **j (j≥3)** kinematics couples with the other links,

$$\mathbf{i = p - n} \qquad (2)$$

is the difference between the number of all kinematics couples **p** and the number of all links in the closed kinematics structure

$$\mathbf{n} = \sum_{j=2}^{i+3} \mathbf{n_j} \qquad (3)$$

The variants of the basic links of the close kinematics structures are derived using (1), which are presented in Table 1. In the table the difference (2) and the number of the basic links in the closed structure are limited $\mathbf{i \le 3}$, $\mathbf{n^0 = \sum_{j=3}^{i+3} n_j \le 3}$.

***Table1**. Variants of the basic links of the closed kinematics structures.*

$\mathbf{n^0}$	i =1	i =2	i =3
1	$\mathbf{n_4=1}$		
2	$\mathbf{n_3=2}$	$\mathbf{n_4=2}$	$\mathbf{n_4=1, n_6=1}$
		$\mathbf{n_3=1, n_5=1}$	$\mathbf{n_5=2}$
3		$\mathbf{n_3=2, n_4=1}$	$\mathbf{n_3=2, n_6=1}$
			$\mathbf{n_4=3}$
			$\mathbf{n_3=1, n_4=1, n_5=1}$

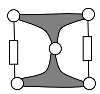
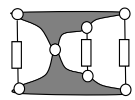
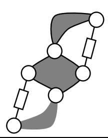
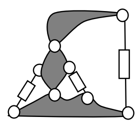
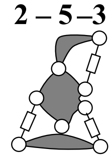
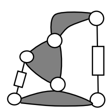
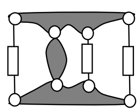
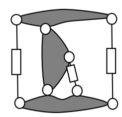
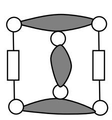
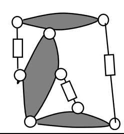
The variants shown in Table 1 allow close structures synthesis by means of link coupling directly among them, or by means of open kinematic chains including one or more links from type $\mathbf{n_2}$. The driving kinematics chains, presented in Fig. 1 are similar open chains including two links from type $\mathbf{n_2}$ and three couples.
MHD for micro- and nano- manipulation tasks have closed kinematics structure includes the basic links connected in between in a serial skeleton chain. The total number $\mathbf{n^0}$ of the links of basic serial chain includes links $\mathbf{n_j}$, **(j≥3)** shown in Table 1 and binary links $\mathbf{n_2}$. The driving chains, presented in Fig. 1 connect the free couples of the links $\mathbf{n_j}$, **j=2,3,4…** of the basic serial chain in between them. The number of the driving chains **m** in this case is defined by the difference (2).

$$\mathbf{m = i + 1} \qquad (4)$$

These structures can be called serial-parallel and can be implemented either in structural ceramics or in MHD using piezo stack actuators and single ceramic actuators.
The kinematics structures defined as a result of synthesis are shown graphically in Table 2. In this case links with 2, 3, 4,… and so on kinematics couples are presented by the symbols, showing the number of their couples, while the driving chains are shown according to (Fig. 1). The difference in the arrangement of the links in Table 1 is also assessed.
It is necessary to be selected the immovable link and the type of the kinematics couples of the links in order the synthesised kinematics structures in Table 2 to be used for MHD creation for micro- and nano- operation tasks. The connections among the links can be either rotational or linear in the

serial-parallel structures in Table 2, and they can be combined in the spatial (3D) case.

Table 2. *Closed kinematics structures for MHD.*

n^0	i =1	i =2	
2	3 – 3 	4 – 4 	
3	2– 4 – 2 	2– 4 – 4 	2 – 5 –3 
	2– 3– 3 	4– 2 – 4 	3– 3 – 4 
	3– 2– 3 		3– 4 – 3 

The number of the degrees of mobility **h** of the generated mechanism is defined by the number of the couples $\mathbf{p_j}$ from a different restriction number **j** $(\mathbf{1 \le j \le 5})$ according to the known relation

$$\mathbf{h=bn-(b-1)p_5-(b-2)p_4-(b-3)p_3-(b-4)p_2-(b-5)\,p_1} \quad (5)$$

Above, $\mathbf{n} = \sum_{j=2}^{i+3} \mathbf{n_j} - \mathbf{1}$ is the number of all movable links implemented in the mechanism and **b** is the total number of the restrictions, (**b = 6** and **3** in spatial (3D) and in plane (2D) case respectively).
The kinematics chains of the actuators presented in Fig. 1 b possess according to (5) zero degrees of mobility. Thus, they do not change the number of the degrees of mobility of the mechanism. The number of the degrees of mobility of the basic chain determine the number of degrees of freedom of the mechanism. To move the device without redundancy, the number of the degrees of mobility of the basic chain have to be equal to the number the actuators (4) **h = m**.
Thus for example, on the basis of the structure **4 – 4** in Table 2 it can be build up MHD for micro- and nano- manipulation tasks possessing three degrees of mobility **h=3** and three piezo actuators **m = 3** as shown in Fig. 2.

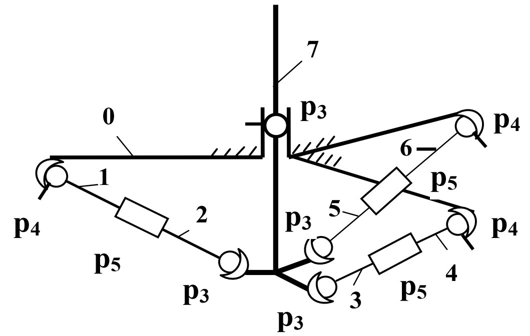


Fig. 2. *Kinematics scheme of MHD with h=m=3.*

The basic chain of mechanism includes two links 0 and 7 from type **4** with 4 kinematics couples. They are connected by means of one couple from class $\mathbf{p_3}$**,** allow one linear and two rotational movements. Link 0 is chosen as immovable one. The mechanism includes three piezo actuators in a spatial (3D) allocation (Fig. 1.b). The entire number of the links and the couples from a different class is as follows: $\mathbf{n = 7, p_5 = 3, p_4 = 3, p_3 = 4}$ for which according to (5) **h = 3.**

Computer simulations of a MHD for micro- & nano-manipulation tasks based on piezo ceramics and closed kinematic structure.

A model of MHD for micro- & nano-manipulation tasks based on the kinematics scheme in Fig.2 was created and simulated with the program system ANSYS.

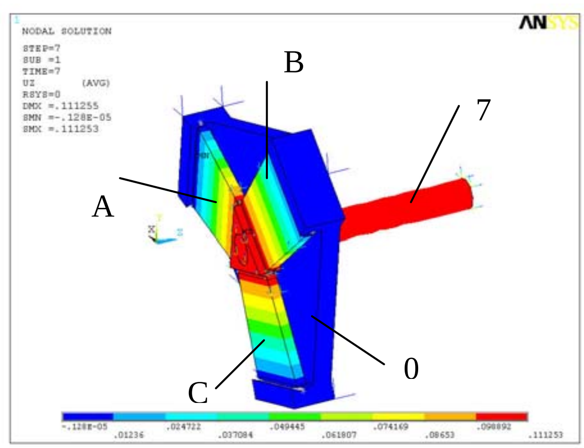


Fig.3. ANSYS model of MHD with 3 piezo actuators A, B and C

The model presented in Fig.3, has a steel plate immovable base 0 which connected by spherical joins with the actuating lever 7.
Three piezo actuators A, B and C are arranged in the angle of 120° using spherical joints according Fig 2. The system is pre-strained through wave spring. That gives the possibility for 3D motion on the end effector and make the joints free from backlash. By applying the same control voltage at the 3 actuators; a movement with 90° to the basic surface (Z-axes) can be reached. If different control voltage on the actuators be applied, it is possible to become X , Y and Z directions movement. The results given in Fig.4 are calculated in FE simulation for PZT with a thickness of 1 mm .

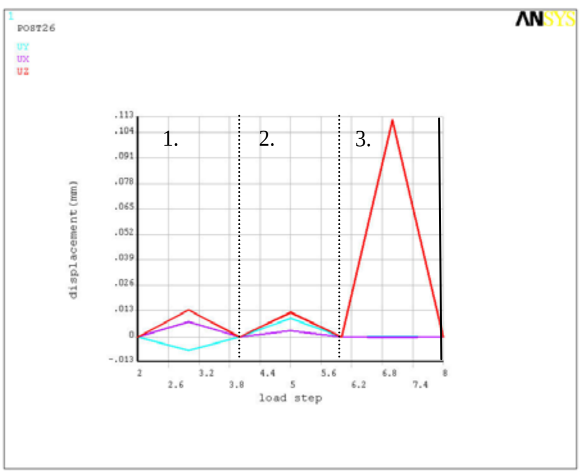


Fig.4. FE simulation results.

The experiments are carried out on tree stages.
At first stage actuator B has been charged and discharged at voltage of 250 [V] and we become a displacement on X, Y and Z directions respectively -8, 8, and 13[µm]. On other hand the second zone only actuator C has been actuated as B, where X =4, Y = 10 and Z = 13 [µm]. By zone 3, the three actuators are been charged and discharged at voltage of 900 [V], as expected we get a displacement just in Z direction around 111 [µm] and a force of 100 [N] is generated.
Cooperating all 3 actuators with different linear extension, it is possible to permit an exact positioning of the end effector in the work space . In this case a high demands on the control unit is needed. For the system a 3 channels are necessary.

In the prototype model 1 mm thick piezo platen with (3,1) effect was used, i.e., here a control with at least 1000 V is necessary.
The necessary supply voltage is given by the actuators thickness. To reduced it, the actuator can be produced from several layers.
A prototype model was designed, built and measured (Fig.5). The experimental results were compared with the simulated data.

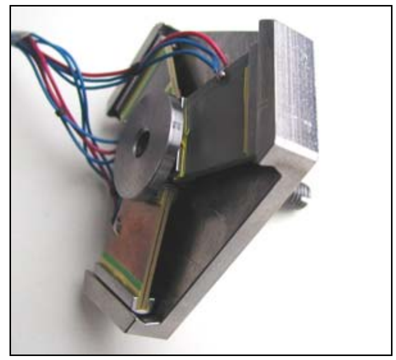


Fig.5. Prototype model of MHD.

It has been proven that the prototypes show very similar data in the experimental tests.

Conclusions.

In the paper an approach is presented for synthesis of closed structures appropriate for mechatronic handling devices (MHD) based on the structured piezo-ceramics or for MHD using piezo stack actuators and single ceramic actuators for micro- and nano-applications. The technical admissible variants of structures are synthesised and tabular systematized. A FE-model is developed for mechatronic handling devices for micro- and nano-applications based on these structures . The MHD prototype presents a new dimension of force and motion achieved. The development of this type manipulator is just at the beginning. The results achieved with this prototype will promise significant improvement in the future. This can be achieved by optimizing the structure and the geometry applying the method based on mechanical structured piezo ceramics [15].

Acknowledgements: The authors gratefully acknowledge the support of the project funding by the DFG “Mechatronic handling devices based on

piezo-ceramic structures for micro- and nano-applications".

References:

1. S. Fatikow, R. Munassypov: An Intelligent Micromanipulation Cell for Industrial and Biomedical Applications Based on a Piezoelectric Microrobot, Proc. of the 5th Int. Conf. on Micro Electro, Opto, Mechanical Systems and Components (MST'96), Berlin, 17-19 September 1996, pp. 826-828.
2. Burleygh Instruments Inc., http://www.burleigh.com
3. Physikinstrumente GmbH, M850 HEXAPOD 6 Axis Parallel Kinematics Robot, http://www.physikinstrumente.com/
4. Kleindiek Nanotechnik, Reutlingen, Germany, nanotechnik.com/mm2.html; http://nanotechnik.com/tilttabl.html
5. Dr. Volker Klocke, Nanotechnik, Motion from the Nanoscale World, CD-ROM Version 1.5, 1998.
6. Patentschrift Hoerbiger Fluidtechnik GmbH, AT 396392 B, 25.8.1993, Piezo-Ventil.
7. Patentschrift der Festo AG & Co., EP 1104863 A2, 06.06.2001.
8. Linden, D.: Hydraulisches Piezoservoventil NG10, O+P Ölhydraulik und Pneumatik 43 (1999) Nr. 7 S. 538-543.
9. Lubitz, K.; Schuh, C.; Steinkopff, T.; Wolff, A.: Properties and Reliability of large PZT multilayer actuators, ACTUATOR 2000, 7th International Conference on New Actuators, June 2000, Bremen, Germany, S.58-61.
10. Kasper, R.; Heinemann, W.; Wagner, A. (1998): Modelling and Control for Piezoelectric Actuators for High Speed Applications. 25.8.-28.8.1998, 4th International Conference on Motion and Vibration Control, MOVIC, Volume 1, S. 231-236, ETH Zürich, Switzerland.
11. Kasper, R.: Mechatronisches Design integrierter Piezoaktoren, 21 – 22. März 2002, ISOM 2002 „Innovative Antriebstechnik" S. 379 – 392, ISBN: 3-00-007504-6. Chemnitz.
12. T. Tanikawa and T. Arai, "Development of a Micro-Manipulation System Having a Two-Fingered Micro-Hand", IEEE Transactions on Robotics and Automation, Vol.15, No.1, pp.152~162. 1999.
13. K.-M. Lee and S. Arjunan. A three-degree-of-freedom micromotion in-parallel actuated manipulator, IEEE Transaction on "Robotics and Automation", vol. 7, pp.238-247, 1999.
14. P Gao and S.-M. Swei. A six-degree-of-freedom micro-manipulator based on piezoelectric translator. Nanotechnology, vol. 10, pp. 447-452, 1999.
15. Kasper R. M.Al-Wahab, Mechanically Structured Piezoelectric Actuators. ACTUATOR 2004, 9th International Conference on New Actuators, June 2004, Bremen, Germany, S.68-71.
16. Kasper, R, R.Goetze, N.Weist. Optimierung mechanischer Wegüberzetzungseinheiten für Aktoren in Konsum- und Produktionsgütern, WTU, UFZ, - Umweltforschungszentrum Leipzig-Halle GmbH (Az.1955A/0025).
17. Chakarov, D., P. Parushev. Synthesis of Parallel Manipulators with Linear Drive Modules. International Journal "Mechanisms and Machine Theory", Vol. 29, ISSN 0094-114X, pp. 917-932, 1994.
18. Ionescu Fl., K. Kostadinov, Piezo actuated Micro robot for Micro and Nano manipulations, ARA Journal, Volume 2000-2002, Nr.25-27, Montréal (Québec), Canada, 2002, ISBN 3-00-009654-x, pp. 98-103 .