MICRO/NANO-MANIPULATORS WITH STRUCTURED PIEZO CERAMIC ACTUATORS

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Abstract: This paper presents an investigation and development of mechatronic handling devices (MHD) based on a structured piezo ceramic with (3, 1)-piezoelectric effect for manipulation and processing of micro/nano operations. Following the synthesis of kinematic structure for micro- and nano-manipulation tasks based on structured piezo ceramics and closed kinematic structures, a specific multilayer design of piezo actuated MHD for micro-and nano-operations was developed. The MHD was mathematically modelled and a FE–model was created and simulated with the program system ANSYS. Comparison study of the MHD prototypes was performed using obtained experimental results. An experimental set up was created that aimed to verify the mathematical and simulation models measuring system behaviour like force, displacement and stiffness.

1 INTRODUCTION

Micro and nano manipulators are used in different fields; e.g. in micro assembly, medicine, genetics, cellular biology technology, chemistry, investigation of thin films, atomic force microscopes (AFM) and scanning tunnelling microscopes (STM).

There are known micromanipulators with piezo actuators (Kortschack, 2005; Albut, 2003; Klocke, 1998). PZT actuators offer substantial advantages for biological cell manipulation such as large force, high frequency and a small size of displacement (Patentschrift Hoerbiger Fluidtechnik, 1993; Lubitz, 2000). Other application fields involve typical manipulations such as cell penetration, cell sorting and moving or treating microorganisms. Critical issues in this case are speed of cell penetration, optimal stroke for penetration or operation, orientation of the end-effector, working space, and size of the device itself.

The increasing requirements of high precision equipment in the fields above perform a broad spectrum of handling and manipulation tasks which is a prerequisite for searching for new concepts of investigation of piezo-actuated mechatronic handling devices.

Utilizing the technological capacity for rapid prototyping of mechatronic systems based on the piezo-structured ceramics, and the improvement of such systems is a prerequisite for the development of technology for manufacturing of mechatronic handling devices (MHD) that are able to perform a certain user-requested micro- or nano-operation. The past general use of piezo-actuators in a direction of motion (3, 3 or 3, 1) is to be extended for realization of piezo-structures for the operation tasks (Kasper, 2006; Kasper, 2004; Chakarov, 2006).

By structuring ceramics as well as stacking and combining them with further elements, more piezo-actuators axis motions are subjected for development. To produce movement parameters by combining various possibilities of structuring with appropriate servo-mechanism, which is currently realisable with very complex and large systems, is a promising design approach (Bar-Itzhack, 2000; Kostadinov, 2006; Kostadinov, 2005) for which the following four parameters are significant for determination of the reference task function of any mechatronic handling device:

The first parameter is the stroke. The desired goal is an adjustment of the stroke of approximately 100 µm in all 3 directions X, Y and Z.

The second parameter is the force. It is well-known that stack actuators produce forces within the kN range, and bending transducers deliver forces up to 1 N. Neither stack actuators, nor bending

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transducers are here optimally suitable. The possibilities of structuring piezo ceramics with consideration of the generation of the stroke can be helpful in this case. Therefore, it is possible to optimize stroke and force in one design.

The third parameter is the size. The actuator for the generation of movement must be integrated into the MHD. The building area is limited. Thus, both piezo plates and piezo disks can be used as raw material. The characteristics of piezo materials are to be selected in such a way that reaches desired parameters for stroke and force.

The fourth parameter is the load speed. The structure of the piezo ceramic must be designed in such a way that the desired dynamics of the movement can be achieved. The intended speeds lie within the range of approximately 200µm/ms. Thereby, an optimization is necessary in this case too. Emphasis is the joint action of piezo ceramic and servo-mechanism system. The servo-mechanism system has to be adapted to the desired parameters for stroke and force.

2 CLOSED KINEMATIC STRUCTURES BASED ON PIEZO CERAMICS

Piezo-structured ceramics, MHD using piezo stack actuators and single ceramic actuators could be assumed by the mechanism and machine theory as a mechanism with closed kinematic structures. The polarized 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 as shown in Figure1 (Kasper, 2004, Chakarov, 2006).

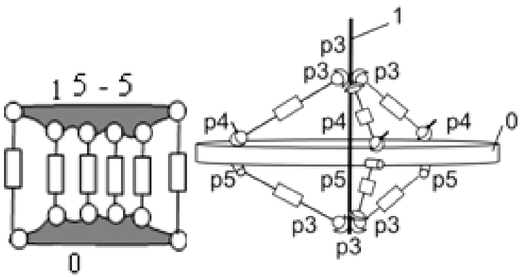

Figure 1: Kinematic scheme of MHD.

MHD for micro- and nano-manipulation tasks shown in figure 1 is characterized with 3 degrees of freedom (DOF) and 6 piezo actuators. The double sided system is built from a base plate with three piezo actuators on each side which are arranged at an angle of 120° using spherical joints.

3 MATHEMATICAL MODELLING OF A MHD FOR MICRO AND NANO APPLICATION

Following the synthesis of the kinematic structure, the design of a double sided MHD based on structured piezo actuators with integrated displacement amplifier was mathematically modelled and calculated.

Starting from the kinematic scheme given in Figure 1 a mechanical model of the MHD shown in Figure 2 was built taking into account relevant constraints resulting from construction and manufacturing. On each side of a fixed circular base plate, 3 piezo-actuators are connected with a ball joint in a vertical distance h from points $R_{1\div3}$ located in XY-plane at a distance R from the origin.

Vectors

$$\vec{r}_k = R.\begin{bmatrix}\sin(2\pi/3.(k-1))\\ \cos(2\pi/3(k-1))\\ 0\end{bmatrix} \quad \text{for } k=1\div3 \qquad (1)$$

from origin to point $R_{1\div3}$ are symmetrically distributed at angles .

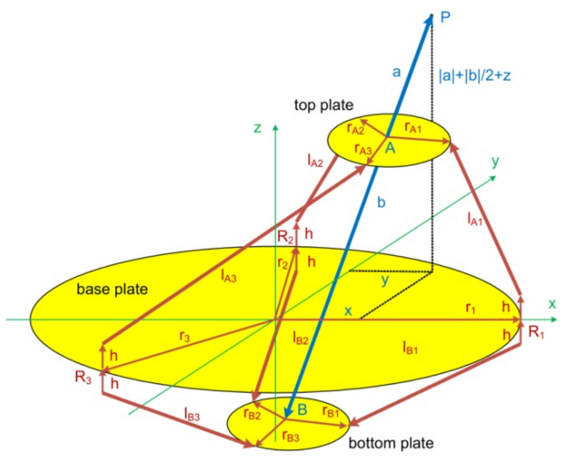

Figure 2: Mechanical Model of the MHD.

The pointer of the MHD is fixed at point B of bottom plate and led through point A of top plate to the TCP defined by point P. Vectors $r_{A1\div A3}$ at top plate and $r_{B1\div B3}$ at bottom plate are constructed similar to vectors $r_{1\div3}$ at base plate with r the radius of top and bottom plate.The pointer can be split into two vectors $\vec{b} = \overrightarrow{AB}$ and $\vec{a} = \overrightarrow{AP}$ with fixed length $a = |\vec{a}|$ and $b = |\vec{b}|$. Using Cardan angles *φ, ψ and θ* the orientation of the pointer, top and bottom plate is defined by the rotation matrix $T(\varphi, \psi, \theta) = T_X(\varphi).T_Y(\psi).T_Z(\theta)$ built by elementary rotations $T_X(\varphi)$, $T_Y(\psi)$ and $T_Z(\theta)$ of X, Y and Z-axis (Chakarov, 2006). Coordinates of the TCP are given by

$$\vec{P} = \begin{bmatrix} x \\ y \\ a + b/2 + z \end{bmatrix} \tag{2}$$

where x and y are absolute coordinates and z defines the difference to the zero position, when there are no rotations and bottom and top plate have a distance of b/2 to the base plate. Vectors defining the position and orientation of the piezo-actuators are given by

$$\vec{l}_{Ak} = \vec{P} - \vec{a} + \vec{r}_{Ak} - \vec{h} - \vec{r}_k \quad \text{for } k=1 \div 3$$

for the upper ones and

$$\vec{l}_{Bk} = \vec{P} - \vec{a} + \vec{b} + \vec{r}_{Bk} + \vec{h} - \vec{r}_k \quad \text{for } k=1 \div 3$$

for the lower ones. As a result of the construction, actuators are joined to the base plate in a vertical distance h, leading to $\vec{h} = h.e_Z$, with $\vec{e}_Z$ the unit vector in Z-direction. Modelling a piezo-actuator as a massless elastic bar, its force at the end points can be written as:

$$\vec{F} = c.(|l| - l_0 + \Delta l).\vec{l} \,/ |l|. \tag{3}$$

For each actuator $\vec{l}$ has to be replaced by its individual vector $\overrightarrow{l_{A1\div 3}}$ or $\overrightarrow{l_{B1\div 3}}$ respectively. From geometry, the forceless length of all actuators is

$$l_0 = \sqrt{((b/2 - h)^2 + (R - r)^2)} \tag{4}$$

The spring constant *c* of each actuator can be approximated by $c = A.E/l_0$ with the actuator's elasticity module *E* and sectional area *A*. The elongation $\Delta l = (A.d_{31}/l_0).U$ is driven by the control voltage *U*, with piezoelectric constant d_{31}, which is negative for the 3,1 effect utilized in this application. In the control system, voltages U_1, U_2 and U_3 of the upper actuators can be driven individually, whereas only one voltage U_Z is used to control the 3 lower actuators. To calculate the 3 actual position coordinates *x, y* and *z* as well as the 3 orientation angles *φ, ψ and θ* the principle of equilibrium of forces

$$\overrightarrow{\Delta F} = \sum_{k=1}^{3} (\overrightarrow{F_{Ak}} + \overrightarrow{F_{Bk}} + \overrightarrow{F_{TCP}}) = 0 \tag{5}$$

and torques

$$\overrightarrow{\Delta M} = \sum_{k=1}^{3} ((\vec{b} + \overrightarrow{r_{Bk}}) \times \overrightarrow{F_{Bk}} + \vec{a} \times \overrightarrow{F_{TCP}}) = 0 \tag{6}$$

are used. Here $\overrightarrow{F_{TCP}}$ is external force acting at the TCP. These 6 equations can be solved e.g. numerically by minimizing the square of the residuals

$$\left\|\overrightarrow{\Delta F}\right\|^2 + \left\|\overrightarrow{\Delta M}\right\|^2 \to Min \tag{7}$$

using LSSOLVE method from Maple's optimization package. To achieve residuals of 10^{-12} and below, less than a second of computation time is needed starting from pointer's zero position as initial values. Thus, computational speed is high enough to use this model to adapt geometric and material data of the MHD to fulfil the design goals. The resulting parameters are given in Table 1:

Table 1: MHD geometric and material parameters.

Parameters free to improve design goals				
A	*a*	*B*	*E*	
37.5mm²	49.5mm	10.5mm	80kN/mm²	
Parameters fixed by construction				
R	*h*	*R*	d_{31}	
40mm	4mm	7.5mm	18e-8	

4 FEM-SIMULATIONS OF A MHD FOR MICRO- AND NANO-MANIPULATION TASKS BASED ON STRUCTURED PIEZO CERAMICS AND CLOSED KINEMATIC STRUCTURE

FE-model of MHD for micro- and nano-manipulators based on the kinematic scheme with 3 DoF shown in Figure 2 was created and simulated. The FE-model is presented in Figure 3. The system is pre-strained within itself. That gives the possibility for 3D motion on the end effector and makes the joints free from backslash. Applying the same control voltage to 3 actuators in the bottom; a movement with 90° to the basic surface (Z-axis) can be reached. If a different control voltage on the other three actuators is applied, it is possible to get movements on X, Y and Z directions. The arrangements of the actuators are seen in Figure 4.

The results given in Figure 5 are calculated in FE simulation for PZT with a thickness of 1.5 mm. FE-models built up using ANSYS allow the coupled treatment of mechanical and piezo-electrical effects. Attention has been paid on nonlinear effects in geometry of the motion amplification system and its connection elements to the piezo-ceramic base plate. At the first step, the actuator (A1) was charged and discharged at a voltage of 800 V.

The second and third steps were when charging and discharging the actuators (A2) and (A3) in a similar way. The fourth step was applying the same control voltage to the bottom three actuators (A456).

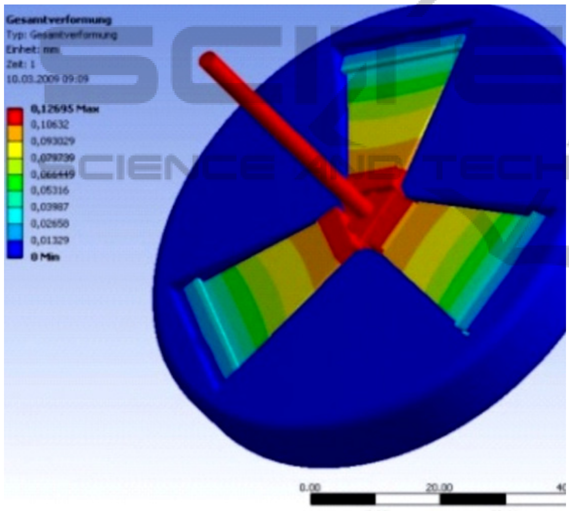

Figure 3: Double-sided MHD FE-model.

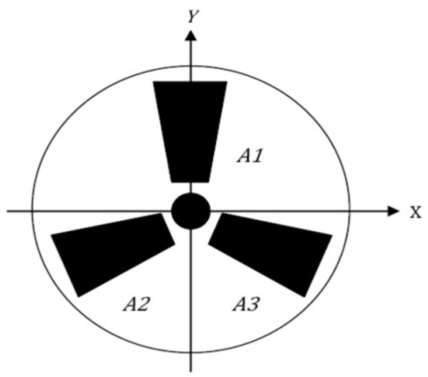

Figure 4: Arrangement of the upper Piezo-actuators A1, A2 and A3 of the Double-sided MHD.

A movement perpendicular to the basic surface (Z-axis) was then reached. The results of the FE method are given in the figure below.

As expected, we get a displacement in Z direction around 130 µm and a force of 100 N is generated.

Co-operating all 3 actuators with different linear extension, it is possible to permit an exact positioning of the end effector in the work space.

5 STUDY AND DESIGN OF THE DEVELOPED PROTOTYPES OF MHDS

To verify the mathematical and the FE- models, a prototype of MHD for micro- & nano-manipulators based on the kinematic scheme in Figure 1 was developed. The steel plate (left top Figure 6) has an immovable base which is connected by spherical joints to the actuating lever.

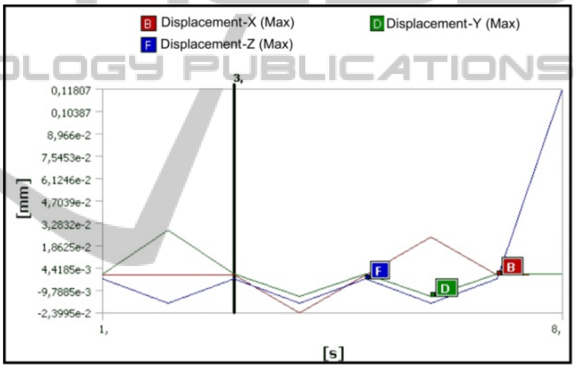

Figure 5: FE Simulation Results of the Double-sided MHD.

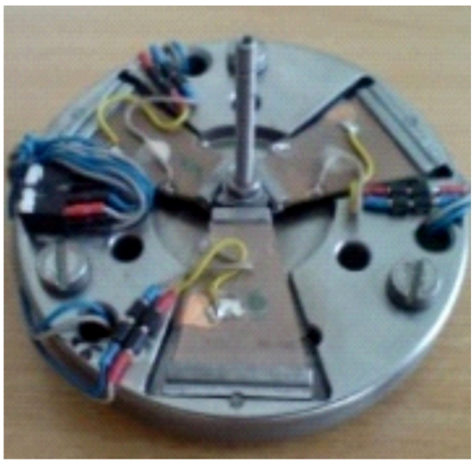

Figure 6: MHDs Prototype.

The necessary operating voltage is determined by the actuator's thickness. To reduce it, the actuator can be produced from several layers. In our case the prototype has been developed from Piezo plate (3, 1 effect) with thickness equal to 0.5 mm. Every actuator has 3 layers where a control with max.1000 V is necessary. Finally, a prototype was designed and manufactured (Figure6).

An experimental set-up based on digital microscopy and software application (Shulev, 2010) for the prototype's control was used for the experimental investigation.

The experiments were taken analogously to the simulations with the Maple and FEM models. As a scanning, a point on the top of the end-effector is chosen. The experiments were performed with a microscope and camera visualization.

The motion of the scanning point has been studied separately along each axis according to the control equation below.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0 & U_{x2} & U_{x2} & 0 \\ U_{y1} & U_{y2} & U_{y3} & 0 \\ U_{z1} & U_{z2} & U_{z3} & U_{z4} \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_Z \end{bmatrix} \quad (8)$$

Pictures of the probe were taken after each step of changing the control voltage in order to determine the displacement in the X, Y and Z direction. Since the scanning point is actuated by Piezo-elements with open-loop control system, it is of great importance to know the specific behaviour of each piezo element and the motion characteristic.

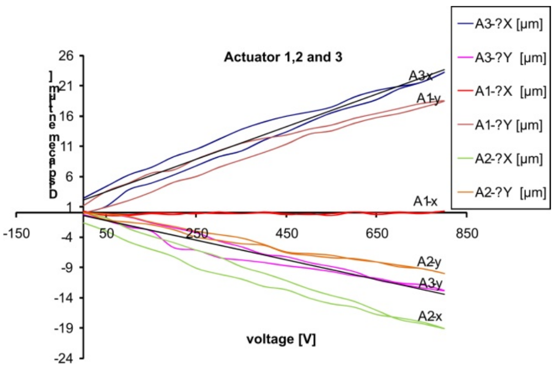

Figure 7: Experimental Results of the Double-sided MHD.

Therefore, an experimental result was obtained from each one. The FEM model was solved with the obtained piezo motions that are in the range of 0 to 9 µm. The dynamic frequency and repeatability of the developed system are under investigation as well. The results are given in Figure 7.

The experimental results were summarized and compared with the simulated and mathematically calculated data. The summarized results are given in the table 2.

Table 2: Summarized Results.

Step		[B] Displace-ment X [µm]	[D] Displace-ment Y [µm]	[F] Displace ment Z [µm]
1-A1	Maple	31	0	-18
	FEM	28	=0	-18
	Exp. Results	18	0	-
2-A2	Maple	-16	27	-18
	FEM	-13	24	-18
	Exp. Results	-10	19	-
3-A3	Maple	-16	-27	-23
	FEM	-13	-24	-18
	Exp. Results	-13	-23	-
4-(A456)	Maple	0	0	119
	FEM	0	0	118
	Exp. Results	-	-	110

The differences between measurements, calculations and FEM were due to inaccuracies in the production of the individual elements and in the measurements, as well as the deviation of the real MHD prototype from the adopted mathematical and FEM models. However, it has been proven that the prototype showed very similar data in the experimental tests.

6 CONCLUSIONS

The development of mechatronic handling devices (MHD) based on a structured piezo ceramic with (3, 1)-piezoelectric effect for manipulation and processing of micro/nano operations was investigated. Following the synthesis of kinematic structure for micro- and nano-manipulation tasks based on structured piezo ceramics and closed kinematic structures, a specific multilayer design of piezo actuated mechatronic handling devices for micro-and nano-operations was developed. The system was mathematically modelled, and a FE–

model was created and simulated with the program system ANSYS.

A comparison study of the mechatronic handling device prototypes was performed using obtained experimental results. An experimental set-up was used specially created for investigation of such micro robots.

The mathematical and simulation models were verified, as well as the system of its behaviour (force, displacement and stiffness). It has been proven that the prototype showed very similar data in the experimental tests to the theoretical data.

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