Synthesis of tense piezo structures for local micro- & nano- manipulations

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Abstract.

In the present work a methodology is developed for synthesis of closed structures for micro- and nano-applications, utilizing the advantages of structured piezo-ceramics, tense piezo-actuators and closed robot kinematics structures. The synthesis of closed kinematic structure with piezo- ceramic actuators is investigated for three case studies:
A) Synthesis for parallel structures in which the basic links are connected in between, only by means of driving chains of the piezo- ceramic actuators.
B) Synthesis for parallel structures in which the basic links are connected in between in a serial chain. The driving chains of the piezo- ceramic actuators are attached parallel to the links of the basic serial chain.
C) Synthesis for parallel structures in which the basic links are connected in between in a parallel chain. The driving chains of the piezo- ceramic actuators are attached parallel to the links of these chain.
A synthesis of kinematics schemes with definite degrees of mobility based on the synthesised structures is developed in the paper. The class of the kinematic couples of the links and the immovable link are selected. Examples and graphic interpretation of the solutions are presented in the paper.

1 Introduction.

The effective piezoelectric materials together with powerful electronic driving systems pushed the attractiveness of piezoelectric actuators in the past years significantly [1-5]. Compared to competing actuators they offer substantial advantages e.g. large force, high frequency and a small size [6-9]. 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. To adapt actuator characteristics to the requirements of applications, motion amplification systems (MAS) is utilized [10-11].
Piezoelectric actuators connect in closed kinematic structures are suitable for high-precision tasks in 3D space [12-19]. The high accuracy of such mechanical systems comes from the very high structural stiffness. Generally, there are 3 types of joints between the links: kinematic, elastic and rigid. The stiffness of the mechanical construction increases in the same order. To achieve tension in closed piezo-ceramic structures it is possible to use deformation in elastic joints or antagonistic interaction of redundant actuators.
The goal of this work is to develop methodology for synthesis of closed structures for micro- and nano-applications, utilizing the advantages of tense piezo-actuators, structured piezo-ceramics and closed robot kinematics structures.

2. Synthesis of closed structures for micro- & nano-manipulation tasks based on piezo-structured ceramics.

In order to be tensed, pizo-ceramic structures must be composeed with parallel or closed topology. To achieve tension in clozed pizo-ceramic structures it is possible to use deformation in elastic joints or antagonistic interaction of the redundant actuators.
In the paper synthesis of basic closed structures for micro- & nano-manipulation tasks is presented. According to the Mechanism and machine theory the basic closed kinematic structures include links with 3, 4 and so on kinematic couples., which we describe with $\mathbf{n_j}$ ($j \geq 3$). The following relation [18] among the number of basic links in the closed kinematic structure is used:

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

Here

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

is the difference between the number of the all kinematic couples **p** and the number of all links **n** in the closed kinematic chain

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

The variants of the basic links of the close kinematic structures are derived using (1), which are presented in Table 1. In the table there are limitations on the difference (2) $\mathbf{i} \leq \mathbf{4}$, and on the number of the basic links in the closed structure

$$\mathbf{n}^0 = \sum_{j=3}^{i+3} \mathbf{n}_j \leq 3 . \qquad (4)$$

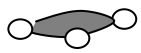
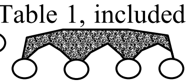
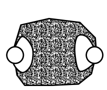
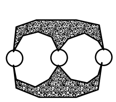
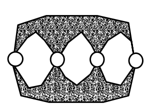
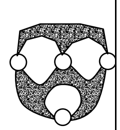
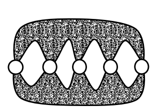
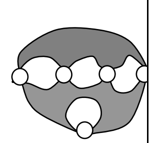
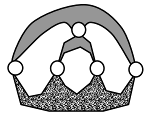
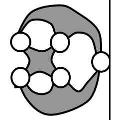
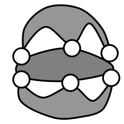
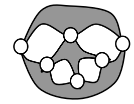
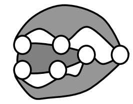
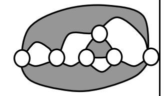
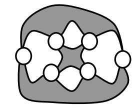
The variants of the basic links shown in Table 1 allow close structures synthesis by means of link coupling directly among them, or by means of sequential kinematics chains including one or more links from type $\mathbf{n}_2$. In Table 2 are shown the possible close structures received from Table 1, included only basic links. In Table 2 the links $\mathbf{n}_3$, $\mathbf{n}_4$ ... and so on are presented by the symbols  , showing the number of their couples .

Table 1.

$\mathbf{n}^0$	i =1	i =2	i =3	i =4
1	n_4=1			
2	n_3 =2	n_4 =2 n_3=1,n_5=1	n_4=1,n_6=1 n_5=2	n_5=1, n_7=1 n_6=2
3		n_3=2, n_4=1	n_3=2, n_6=1 n_3=1,n_4=1,n_5=1 n_4=3	n_3=1,n_5=1,n_6=1 n_3=1,n_4=1,n_7=1 n_4=2,n_6=1 n_4 =1,n_5=2

Table 2.

$\mathbf{n}^0$	i =1	i =2		i =3				
1	4 							
2	3 – 3 	4 – 4 	3 -5 	5 – 5 	4 - 6 			
3		3 – 3 – 4 	3 – 4 – 3 	3 – 6 – 3 	3 – 4 – 5 	3 – 5 – 4 	4 – 3 – 5 	4 – 4 – 4 

The variants of the basic links shown in Table 1 allow close structures synthesis of link coupling by means of sequential driving kinematics chains based on piezo ceramics. Piezo- ceramic structures can be assumed according to the Mechanism and Machine Theory as a combination of rigid links and polarised ceramic elements. The polarised ceramic elements can be estimated as actuators for linear motion, which can be modelled by the kinematic chain shown bellow:

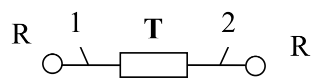


Fig.1.

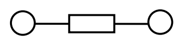
It includes two links 1 and 2 and a couple T of linear motion, which can perform locomotive functions and two rotational couples R by which the actuator is attached to the driven links. The rotational couples can be created by elastic areas in the ceramics or by additional elastic joints.

3. Three case studies of closed kinematic structure synthesis for micro- and nano- manipulation tasks.

The closed kinematic structure synthesis for micro- and nano- manipulation tasks can be investigated for three case studies:

A) Synthesis for parallel structures in which the links $\mathbf{n_j}$, ($\mathbf{j \geq 3}$) (Table 1) are connected in between, only by means of sequential kinematics chains like as driving chains clearly seen in Figure 1. The driving kinematics chains, presented in Fig. 1 are sequential chains including two links from type $\mathbf{n_2}$ and three couples.

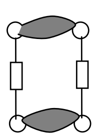
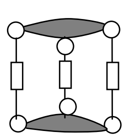
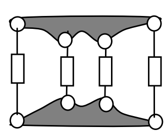
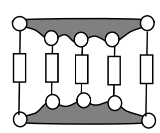
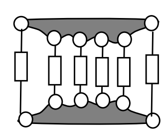
The possible kinematics structures for case $\mathbf{i \leq 4}$ and $\mathbf{n^0 = 2}$ defined as a result of the synthesis are shown graphically in Table 3 .

In this case the driving chains (Fig. 1) are defined by the symbol  . The number of these chains $\mathbf{m}$ depends on the number of the basic links (4) and on the difference (2).

$$\mathbf{m = i + n^0} \qquad (5)$$

The simplest closed structure $\mathbf{n_2 = 2}$ is shown too in Table 3.

Table 3.

$\mathbf{n^0}$	**i =0**	**i =1**	**i =2**	**i=3**	**i =4**
2	**2 – 2**	**3 – 3**	**4 – 4**	**5 – 5**	**6 – 6**
					

B) Serial - parallel structures synthesis including the basic links $\mathbf{n_j}$, ($\mathbf{j \geq 3}$) in Table 1 connected in between in a serial chain that can be included and binary links $\mathbf{n_2}$. The total number $\mathbf{n_B^0}$ of the links of basic serial chain includes links $\mathbf{n_j}$, ($\mathbf{j \geq 3}$) shown in Table 1 and binary links $\mathbf{n_2}$. The driving chains, presented in Fig. 1 connect the free couples of the links $\mathbf{n_B^0}$ of the basic serial chain in between them. A restriction is imposed for structures synthesis only including number $\mathbf{m}$ of the driving chains higher than the number of the couples connecting the links of the serial chain. The reason for this restriction derivation is the fact that all the couples of the basic serial chain are driven by means of parallel driving chains.

The kinematics structures defined as a result of synthesis for $\mathbf{n^0 = 1,2}$ according Table 1 are shown graphically in Table 4. In the Table 4 are shown the possible kinematics structures for case $\mathbf{i \leq 2}$ and the number of the links of basic serial chain $\mathbf{n_B^0 = 2,3.}$

The number of the driving chains in this case is defined by the difference (2)

$$\mathbf{m = i + 1} \qquad (6)$$

Here, the same graphical symbols are used for the link and the driving chain definition, as in Table 3. The difference in the arrangement of the links in Table2 is also assessed.The simplest closed structure $\mathbf{n_2=2}$ is shown too in Table4.

C) Parallel structures synthesis including the basic links $\mathbf{n_j}$, (**j≥3**) in Table 1 connected in between in a parallel chain that can be included and binary links $\mathbf{n_2}$. The total number $\mathbf{n_B^0}$ of the links of basic parallel chain includes links $\mathbf{n_j}$, (**j≥3**) shown in Table 1 and binary links $\mathbf{n_2}$.

Table 4.

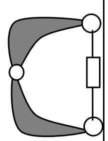
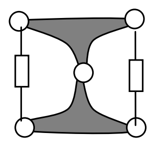
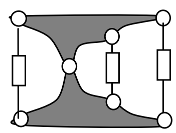
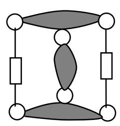
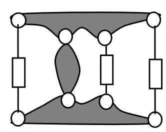
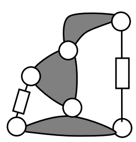
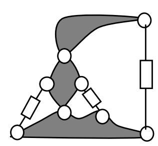
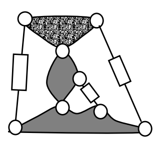
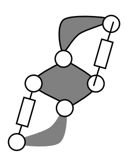
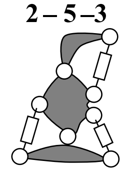
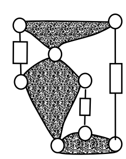
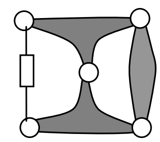
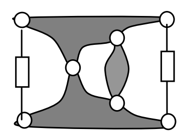
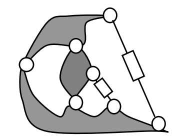
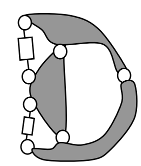
$\mathbf{n_B^0}$	**i =0**	**i =1**	**i =2**	
2	**2 – 2** 	**3 – 3** 	**4 – 4** 	
3		**3 – 2 – 3** 	**4 – 2 – 4** 	
		2 – 3 – 3 	**2 – 4 – 4** 	**3 – 3 – 4** 
		2 – 4 – 2 	**2 – 5 –3** 	**3 – 4 – 3** 

Table 5.

$\mathbf{n_B^0}$	**i =1**	**i =2**
3	**3 – 3** 	**4 – 4** 
		3 – 3 – 4 
		3 – 4 – 3 

The driving chains, presented in Fig. 1 connect the free couples of the links $\mathbf{n_B^0}$ of the basic parallel chain in between them. The number of the driving chains in this case is defined by the difference (2) $\mathbf{m = i}$ **.**

The kinematic structures defined as a result of synthesis for $\mathbf{n^0=2,3}$ and **i =1, 2** according Table 1 are shown graphically in Table 5. In the Table 5 are shown the possible kinematics structures for case **i =1, 2** and the number of the links of basic parallel chain $\mathbf{n_B^0 = 3.}$

4. Synthesis of kinematics schemes for micro- & nano-manipulation tasks based on the synthesised structures.

A synthesis of kinematics schemes with definite degrees of mobility **h** based on the synthesised structures can be developed. To create the kinematics schemes with definite degrees of mobility, the class **j** of the kinematics couples $\mathbf{p_j}$ of the links and the immovable link are selected. The synthesis is performed separately for case A),B) and C) about structures of Table.3, Table 4 and Table 5.

A) For parallel structures of Table 3 the number of the degrees of mobility usually is equal to the number of the actuators **h** = **m**. If the number of the actuators **m** is larger than that of the degrees of mobility **m≥h** we have actuation redundancy. This can be used for achieving the tensity, improving the dynamic parameters and removing the windages in the device. The redundancy is presented through difference

$$\mathbf{m - h = r} \qquad (7)$$

To create the kinematics schemes with definite degrees of mobility, the class **j** of the kinematic couples $\mathbf{p_j}$ of the links have to be selected. The number and the class of the kinematics couples are defined of the actuators. Each actuator according to Fig.1 possess one linear motor joint and two revolution joints. The linear couples apply 5 restrictions of the movements, or the couple possess one degree of freedom. Their number $\mathbf{p_5^l}$ is equal to the number of the actuators

$$\mathbf{p_5^l = m}. \qquad (8)$$

The revolution couples of the parallel structures of Table 2 can apply different number of restriction **j = 1…5,** defining the degrees of freedom of the device.
To determine the degrees of freedom can be used the well known equation

$$\mathbf{h = 6n - \sum_{j=1}^{5} jP_j} \qquad (9)$$

where **n** is the number of all mobile links and $\mathbf{P_j}$ is the number of all kinematics couples of class **j.**
As any actuator has two movable links and one of the basic links $\mathbf{n^0}$ is immovable, the number of all mobile links is

$$\mathbf{n = n^0 - 1 + 2m}\ . \qquad (10)$$

As the number of all kinematics couples of class **j=5** includes the number of linear couples $\mathbf{p_5^l}$ and the number of revolution couples $\mathbf{p_5^r}$ of class **5** according (8) follow

$$\mathbf{P_5 = p_5^l + p_5^r = m + p_5^r} \qquad (11)$$

According (10) and (11) equation(9) assume the form

$$\mathbf{h = 6(n^0 - 1) + 7m - \sum_{j=1}^{5} jp_j^{\,r}} \qquad (12)$$

As any actuator according Fig 1 have two revolution joints, the total number of revolution joints is defined of the number of actuators **m**

$$\mathbf{\sum_{j=1}^{5} p_j^{\,r} = 2m} \qquad (13)$$

For any structural scheme of Table 3 defined of parameters $\mathbf{n^0}$ and **i** **(i=m+$\mathbf{n^0}$),** above two equations (12),(13) allow to determine one or more variants of allocation of the different class couples and synthesis of kinematics schemes with desired degrees of freedom **h = m - r**.
If we use elastic revolution couples (geometric closed), the class of couples is limited **j = 3, 4. 5**. The possible revolution couples $\mathbf{p_j^r}$ according equations (12) ,(13) for structures of Table 3 ($\mathbf{n^0}$**=2**) with **h=1,2,3** and **i=0,…,4** are shown in Table 6.

Table 6.

h	i=0, m=2	i=1, m=3	i=2, m=4	i=3, m=5	i=4, m=6
1	p_4=1, p_5=3	p_4=4, p_5=2 p_3=1, p_4=2, p_5=3 p_3=2, p_5=4	p_4=7, p_5=1 p_3=1, p_4=5, p_5=2 p_3=2, p_4=3, p_5=3 p_3=3, p_4=1, p_5=4	p_4=10 p_3=1, p_4=8, p_5=1 p_3=2, p_4=6, p_5=2 p_3=3, p_4=4, p_5=3 p_3=4, p_4=2, p_5=4 p_3=5, , p_5=5	p_3=1, p_4=11 p_3=2, p_4=9, p_5=1 p_3=3, p_4=7, p_5=2 p_3=4, p_4=5, p_5=3 p_3=5, p_4=3, p_5=4 p_3=6, p_4=1, p_5=5
2	p_3=1, p_5=3	p_4=5, p_5=1 p_3=1, p_4=3, p_5=2 p_3=2, p_4=1, p_5=3	p_4=8 p_3=1, p_4=6, p_5=1 p_3=2, p_4=4, p_5=2 p_3=3, p_4=2, p_5=3 p_3=4, p_5=4	p_3=1, p_4=9, p_3=2, p_4=7, p_5=1 p_3=3, p_4=5, p_5=2 p_3=4, p_4=3, p_5=3 p_3=5, p_4=1, p_5=4	p_3=2, p_4=10 p_3=3, p_4=8, p_5=1 p_3=4, p_4=6, p_5=2 p_3=5, p_4=4, p_5=3 p_3=6, p_4=2, p_5=4

					$p_3=7$, , $p_5=5$
3	X	$p_4=6$ $p_3=1, p_4=4, p_5=1$ $p_3=2, p_4=2, p_5=2$	$p_3=1, p_4=7$ $p_3=2, p_4=5, p_5=1$ $p_3=3, p_4=3, p_5=2$ $p_3=4, p_4=1, p_5=3$	$p_3=2, p_4=8$, $p_3=3, p_4=6, p_5=1$ $p_3=4, p_4=4, p_5=2$ $p_3=5, p_4=2, p_5=3$ $p_3=6$, , $p_5=4$	$p_3=3, p_4=9$ $p_3=4, p_4=7, p_5=1$ $p_3=5, p_4=5, p_5=2$ $p_3=6, p_4=3, p_5=3$ $p_3=7, p_4=1, p_5=4$

B) Serial - parallel structures of Table 4 allow the basic serial chain to determine the degrees of mobility of the device **h**. The couples of this chain can be elastic and can carry necessary restrictions. The actuators are treated as identical structural groups with a zero degrees of mobility (Fig.2). The class of the rotation couples of the actuators are chosen in such a way according (9), do not to change the degrees of mobility of the basic chain. The class of the rotation couples for the spatial (3D) case are shown in Fig. 2.

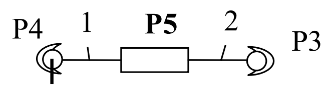


Fig.2. Class of the actuator couples for the spatial (3D) case.

The number of the actuators usually is equal to the number of the degrees of mobility **m=h**. If the number of the actuators **m** is larger than that of the degrees of mobility **m≥h** we have actuation redundancy presented through difference (7). This can be used for achieving the tensity, improving the dynamic parameters and removing the windages in the device.
The class of the couples of the basic serial chain is determined according equation (9) presented as

$$\mathbf{h = 6(n_B^0 - 1) - \sum_{j=1}^{5} j p^0{}_j} \qquad (14)$$

where $\mathbf{n^0{}_B}$ and $\mathbf{p^0{}_j}$ are the number of the links and the joints of the basic serial chain.
The couples number of the basic serial chain is determined according the number of his movable links after equality

$$\mathbf{n_B^0 - 1 = \sum_{j=1}^{5} p_j^0} \qquad (15)$$

For each structure of Table 4 with desired degrees of freedom **h**, above two equations (14), (15) allow to determine the class of basic chain couples and their number.
If the class of revolution couples is limited **j = 3, 4. 5,** the possible couples $\mathbf{p_j}$ of the basic serial chain with **h=1,2,3,4,5** degrees of mobility and $\mathbf{n_B}^0$=2,3 are shown in Table 7.

Table 7.

H	1	2	3	4	5
$n_B{}^0=2$	$p_5=1$	$p_4=1$	$p_3=1$	X	X
$n_B{}^0=3$	X	$p_5=2$	$p_4=1, p_5=1$	$p_4=2$	$p_3=1, p_4=1$

Each basic couples of class **j** must be included in **(6-j)** closed cycles with the actuators of structure to get the drivability. The couples of the basic chain with definite class, can be as revolution as well as linear

C) In the parallel structures of Table 5 the actuators are treated too as identical structural groups with a zero degrees of mobility (Fig.2). The basic parallel chain determines the degrees of mobility of the device **h**. The number of the actuators is equal of the number of the degrees of mobility **m = h**, or it is larger of them **m > h.**

The class of couples $\mathbf{p_j{}^0}$ of basic parallel chain is defined by equation (9) as

$$\mathbf{h = 6(n_B^0 - 1) - \sum_{j=1}^{5} j p^0{}_j} \qquad (16)$$

where $\mathbf{n^0{}_B}$ and $\mathbf{p^0{}_j}$ are the number of the links and the joints of the basic parallel chain.
The total number of the couples of basic parallel chain is equal of the number of the its links:

$$\mathbf{n_B^0 = \sum_{j=1}^{5} p_j^0} \qquad (17)$$

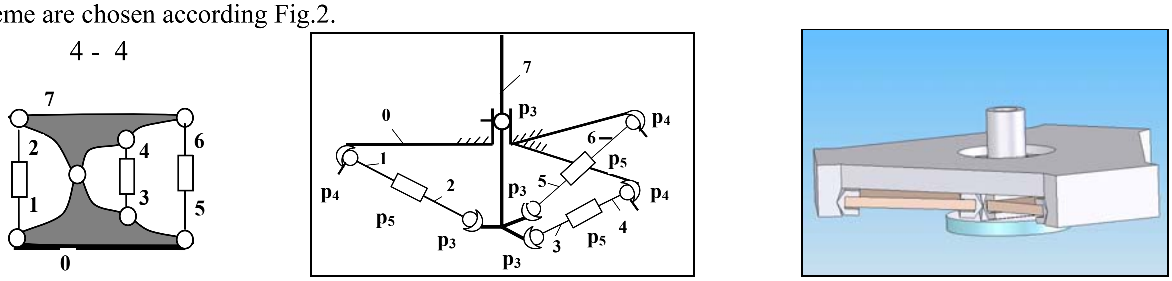
Above two equations allow for each structure of Table 5 included $\mathbf{n_B^0}$ links**,** to specify the class of the couples of the basic parallel chain with **h** degrees of mobility. If the class of elastic revolution couples is limited **j = 3, 4. 5**, the possible solutions for structures with **h=1,2,3,4,5** degrees of mobility and $\mathbf{n_B^0}$**=3,4** are shown in Table 8.

Table 8.

h	**1**	**2**	**3**	**4**	**5**
$\mathbf{n_B^0=3}$	$\mathbf{p_3=1, p_4=2}$	$\mathbf{p_3=2, p_4=1}$	$\mathbf{p_3=3}$	X	X
	$\mathbf{p_3=2, p_5=1}$				
$\mathbf{n_B^0=4}$	$\mathbf{p_3=1, p_4=1, p_5=2}$	$\mathbf{p_3=1, p_4=2, p_5=1}$	$\mathbf{p_3=2, p_4=1, p_5=1}$	X	X

5.Examples.

5.1. To be synthesized device with two links of the basic serial chain $\mathbf{n_B^0=2}$ (structure type B) and three degrees of freedom **h=3.** The number of the actuators to be equal to the number of the device degrees of freedom **m = h = 3.** According equation (6) and Table 4. structure **4 – 4** corresponds to the above parameters. The structure is symmetric and each basic link can be chosen as immovable one as is shown in Fig.3 a). After equations (14) , (15) or results in Table 7, the possible couples distribution of the basic serial chain is $\mathbf{p_3=1.}$ On the above it can be build up kinematics scheme of a device for micro- and nano- manipulation tasks as shown in Fig.4 б). Actuator chains in the scheme are chosen according Fig.2.



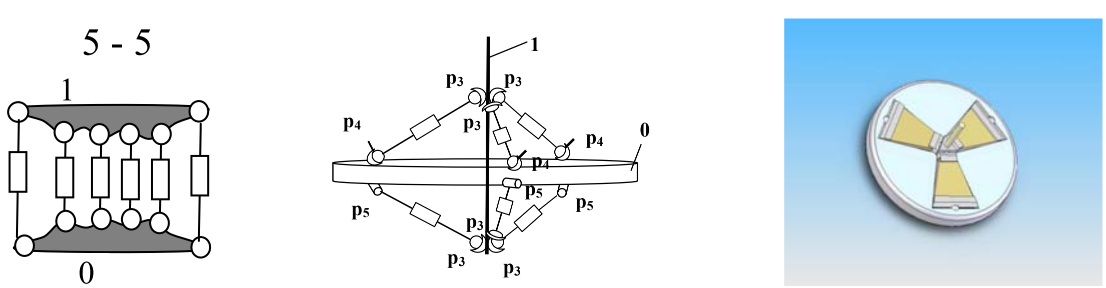
a) b) c)

Fig.3**.** Device with structured piezo-ceramics with $\mathbf{n_B^0=2}$ (type B) and **h=m=3**.

The basic chain includes two links mark as 0 and 7 , connected by means of one elastic couple $\mathbf{p_3,}$ allow one linear and two rotational movements. Link 0 is chosen as immovable one. A simulation of a device prototype with structured piezo-ceramics built up this scheme is shown on Fig.3 c)

5.2. To be synthesized device with two links of the basic serial chain $\mathbf{n^0=2}$ (structure type A) and three degrees of freedom **h=3.** The number of the actuators to be bigger to the number of the device degrees of freedom **m = h +r,** or **m=3+3 = 6.**

According equation (5) and Table 3 structure **6 – 6** corresponds to the above parameters. The structure is symmetric and each basic link can be chosen as immovable one as is shown in Fig.4 a). After equations (12) , (13) or results in Table 6, the possible revolution couples distributions are the next $\mathbf{p_3=3, p_4=9;}$ $\mathbf{p_3=4, p_4=7, p_5=1;}$ $\mathbf{p_3=5, p_4=5, p_5=2;}$ $\mathbf{p_3=6, p_4=3, p_5=3}$ and $\mathbf{p_3=7, p_4=1, p_5=4.}$ On the above a kinematics scheme with couples $\mathbf{p_3=6, p_4=3, p_5=3,}$ is build as shown in Fig.4 б). Actuator chains in the scheme are chosen according Fig.2.



a) b) c)

Fig.4. Device with structured piezo-ceramics with $\mathbf{n^0=2}$ (type A) and **h=3, m=6**.

The basic two links are indicated as 0 and 1, while link 0 is chosen as immovable one. A simulation of a device prototype with structured piezo-ceramics built up this scheme is shown on Fig.4 c).

6.Conclusions.

Devices with closed kinematical structure have a number of advantages as high stiffness, compactness and redundant actuation possibility. In the paper an approach is presented for synthesis of closed structures suitable for devices for micro- and nano-applications using structured piezo-ceramics or single ceramic actuators. The presented synthesis includes three case studies: a) when the structure includes basic links connected in between, only by means of the actuators, b) when the structure includes basic links connected in between in a serial chain to which are connected the actuators and c) when the structure includes basic links connected in between in a parallel chain to which are connected the actuators. The synthesised three case structures are suitable for devisces based on the structured piezo-ceramics, including polarised and non-polarised areas or for devices using piezo stack actuators and single ceramic actuators. It is shown with given examples of mechatronic handling devices for micro- and nano-applications based on synthesised structures.

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