In memoriam
NICOLAE I. MANOLESCU, *Corespondent member of the Romanian Academy*

BI-MOBILE PLANAR MECHANIS FOR ROBOTICS OBTAINED THROUGH INVERSE MODELLING

ADRIANA COMANESCU[1], DORU BOBLEA [2], ANTONIA ONACA[3]

Abstract. Bi-mobile planar mechanisms are commonly used in various fields of robotics. By adding additional degrees of mobility (rotation and/or translation) to the basis, multi-mobile systems for manipulators or pedipulators (legs) found in various fields are obtained. The paper aims to highlight these mechanisms using bi-mobile planar kinematic linkages described in the classical literature of mechanism theory [1–5,16,17,23,25] in which the basis and the effector are nominated by inverse modelling [8–12,13,15]. The effector extremity of such mechanism may describe any trajectory in its field. This is equivalent to introduce a pair with two constrains which determines the structure to have zero degree of mobility, its inverse structural model could have only passive modular groups. All basis-effector solutions for planar bi-mobile mechanisms obtained from linkages with five degrees of mobility and two and three independent contours are mentioned. The mechanism mobility is given by two active kinematic pairs suitably placed in the same chain [8–15]. The structural algorithm included in the paper offers the possibility to create various optimal solution for bi-mobile mechanisms. At the same time, the base-effector structural solutions mentioned in the paper are useful in designing these systems, and can be used to verify or adopt appropriate solutions.

Key words: bi-mobile linkage, bi-mobile robot mechanism, optimal solution, baranov truss, passive modular group, Inverse model, direct model, inverse modelling, direct modelling.

1. THEORETICAL CONSIDERATIONS

Any bi-mobile planar mechanism may be obtained from kinematic linkages with five degrees of freedom and consequently with two degrees of mobility. In the traditional literature [1–5, 17, 23, 25, 29] there are mentioned a single linkage with five elements and one independent contour, four linkages with seven elements and two independent loops (Fig. 1) and forty systems L_k with nine links and three independent contours (Table 1).

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The following theorems must be fulfilled to achieve the mechanism model [8, 11]:

- The effector must have a planar motion depending on both independent parameters as to the system has two degrees of mobility;

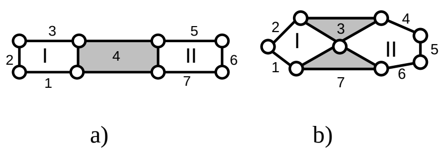
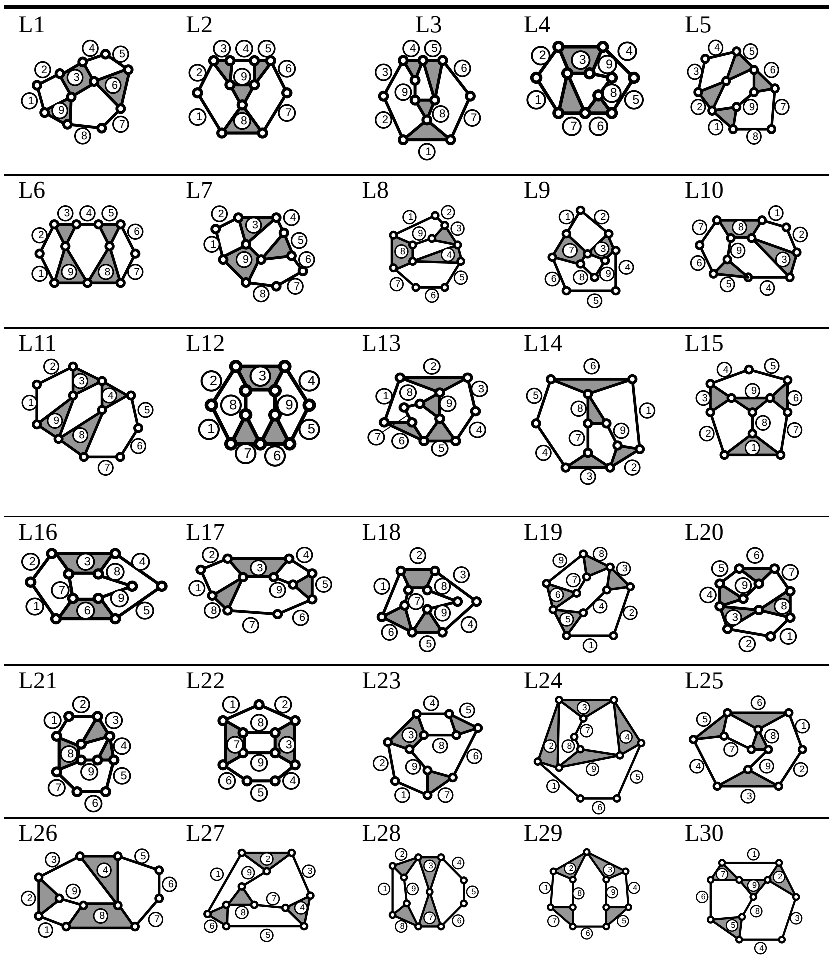
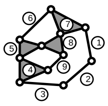
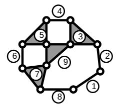
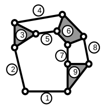
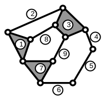
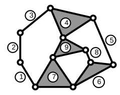
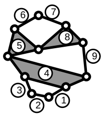
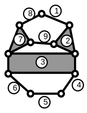
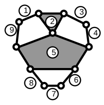
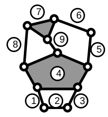
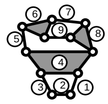


Fig. 1 – Bi-mobile and bi-looped planar kinematic linkages.

Table 1

Bi-mobile and three looped linkages



L31	L32	L33	L34	L35
				
L36	**L37**	**L38**	**L39**	**L40**
				

- The effector cannot belong to a four-bar linkage, Watt or Stephenson structures (Fig. 2);

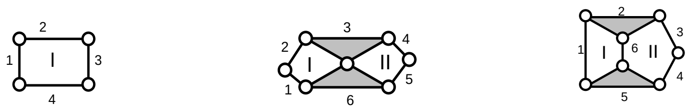


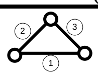
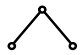
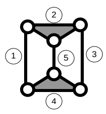
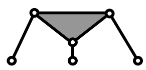
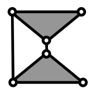
Fig. 2 – Four-bars linkage, Watt and Stephenson linkage.

The possible solutions for basis-effector in a linkage L_k with n elements may be mentioned in $A(i, j)$ square and symmetrical matrix ($n \times n$) with Boolean values components;

- Each solution for basis-effector must be verified through its inverse model with zero degrees of mobility. Imposing any position on a trajectory for the effector extremity is equivalent to introduce a kinematic pair with two constrains between the link extremity and the basis, which determines zero mobility for the structure.
- Consequently, the inverse model must have only passive modular groups (GMP) named Assur groups [2, 5, 17, 23] derived from Baranov trusses with 3, 5, 7 elements (Table 2).

Table 2

Passive modular groups (Assur groups)

Baranov truss (BT)	Passive modular group (GMP)
 **BT 1**	 **GMP 1**
 **BT 2**	 **GMP 2**
	 **GMP 3**

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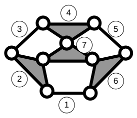
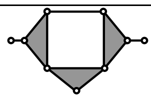
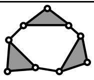
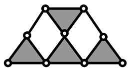
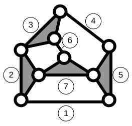
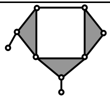
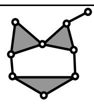
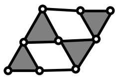
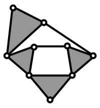
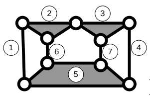
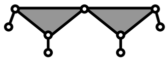
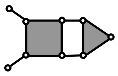
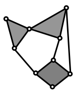
<tr><td rowspan="3"> BT 3</td><td> GMP 5</td></tr>
<tr><td> GMP 9</td></tr>
<tr><td> GMP 11</td></tr>
<tr><td rowspan="4"> BT 4</td><td> GMP 6</td></tr>
<tr><td> GMP 8</td></tr>
<tr><td> GMP 10</td></tr>
<tr><td> GMP 12</td></tr>
<tr><td rowspan="3"> BT 5</td><td> GMP 4</td></tr>
<tr><td> GMP 7</td></tr>
<tr><td> GMP 13</td></tr>
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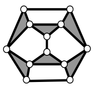
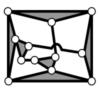
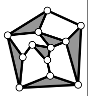
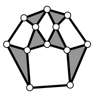
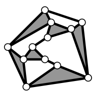
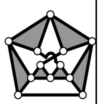
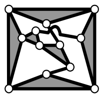
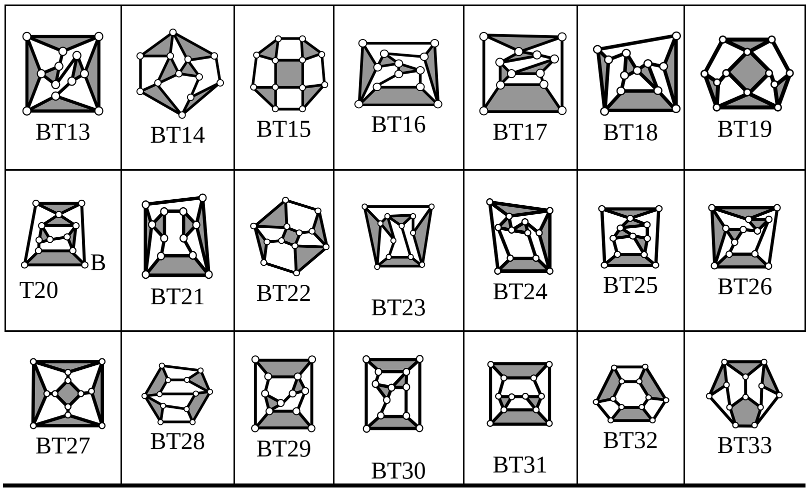
The best solutions for basis-effector include a minimum number of passive groups, ideally a single one. In this last case the inverse model is a Baranov truss (Table 3).

Table 3

Baranov trusses for robot mechanisms modeling

 BT6	 BT 7	 BT8	 BT9	 BT10	 BT11	 BT12



The robot mechanism is finally obtained by introducing two active pairs in the linkages structure through its direct model [12, 13, 15].

The structural algorithm previously mentioned is synthetized in Fig. 3. Here the authors only developed the first part of the algorithm concerning the inverse model optimization.

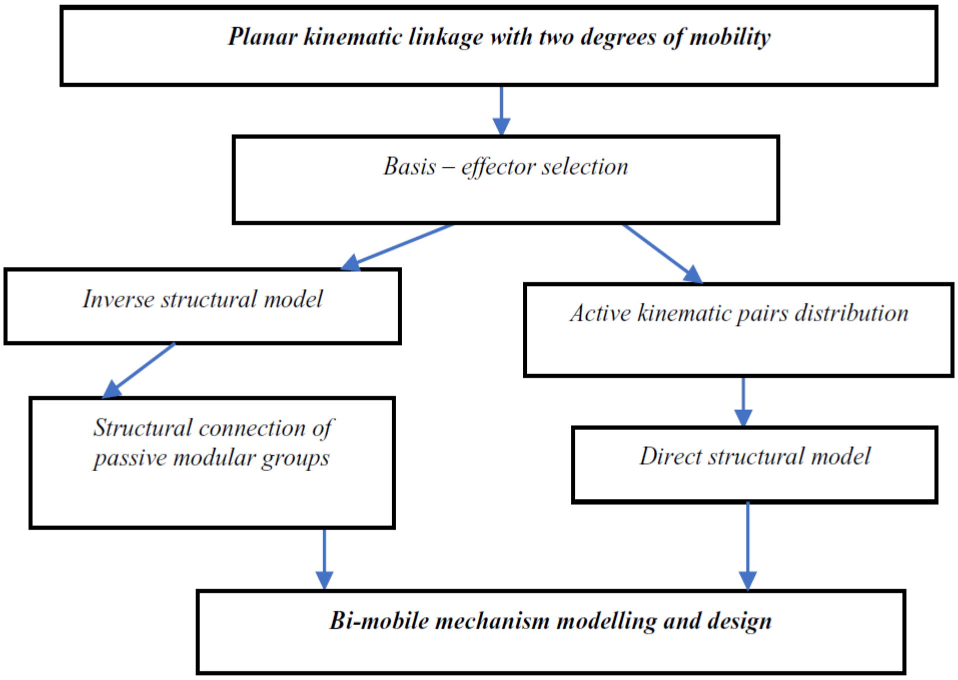


Fig. 3 – Structural algorithm for bi-mobile robot mechanism modelling.

A final remark concerns the component of inverse models associated with chains made according to the theorems outlined above. They consist of passive modular groups with a structure as follows:

– For chains with 7 elements, inverse models could have the following passive modular structures: with 2+2+2, 2+4, 4+2, 6 elements (Table 2);

– For chains with 9 elements, modular passive structures can have respectively 2+2+2+2 (Appendix 1), 2+2+4 (Appendix 2), 2+4+2 (Appendix 3), 4+2+2 (Appendix 4), 2+6 (Appendix 5), 6+2 (Appendix 6), 4+4 (Appendix 7), 8 elements.

2. OPTIMAL INVERSE MODELS FOR BI-MOBILE AND BI-LOOPED PLANAR LINKAGE

A classic example of a mechanism with two degrees of mobility and two independent contours is the Stewart's foot (Fig. 4a), which often equips stepping platforms. The mechanism has 6 moving elements and 8 kinematic pairs of rotation and translation, so that the degree of mobility is $M = 2$. The kinematic translation pairs (1, 2) and (4, 5) are active pairs that ensure well-defined system movement. The fundamental decomposable plane kinematic chain (Fig. 4b), which formed the basis of the direct structural model, is shown in Fig. 5a.

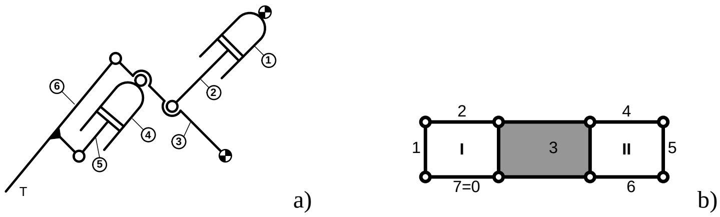


Fig. 4 – Stewart foot.

Point T belonging to execution element 6 not adjacent to basis 7 and not belonging to the same quadrilateral contour as the basis (Fig. 4a), has a trajectory dependent on the parameters of both active translation pairs. Consequently, *the direct structural model* of the mechanism is given in Fig. 4a, to which corresponds the connection of the modular groups in Fig. 5b. It consists of two active modular groups of RTRR type linked in parallel to the basis 0 = 7 of the mechanism.

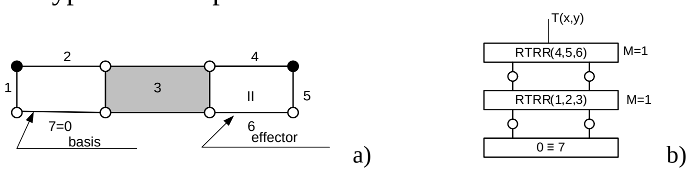
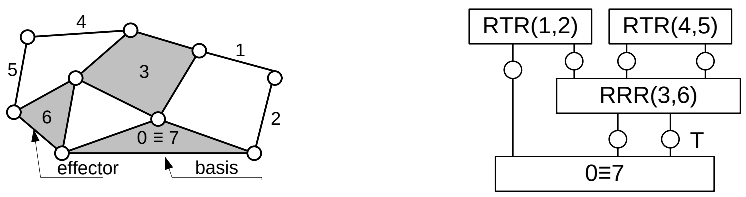


Fig. 5 – Direct structural model of Stewart foot.

Consequently, the *direct structural model* highlights the two parameters of the tracer point T according to the two parameters of the active pairs.
Imposing successive point positions on the T point in relation to the fixed element is equivalent to introducing an instantaneous kinematic pair with two restrictions $k=2$ between the execution element and the basis. In this case, the degree of mobility instantly becomes $M_{inst}=3m-2(c+1)$ *i.e.* $M_{inst}=0$ and is characteristic *of the inverse structural model of the mechanism*, Fig. 6 a), which corresponds to the connection of the modular groups in Fig. 6 b.



a) b)

Fig. 6 – Inverse structural model of Stewart foot.

The bi-mobile and bi-looped planar linkages (Fig. 1), may be characterized by their classes of the independent contours (loops). The linkages from Fig. 1a, b, c, d are described as follows: 4–4, 4–5, 5–5, and 4–6.

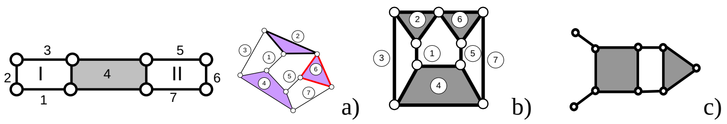
Using the previously mentioned theorems (§1) the basis-effector matrix with Boolean values for each linkage is important to be correctly achieved. Its matrix element $A(i,j)$ gives the basis i and the effector j. The matrix $(n\times n)$, n being the number of the linkage links is square and symmetrical one with zero values for the principal diagonal.

In the case of the 4–4 linkage (Fig. 1a), the matrix $A(i,j)$ is as follows:

A(i, j) =

element	1	2	3	4	5	6	7
1	0	0	0	0	1	1	1
2	0	0	0	0	1	1	1
3	0	0	0	0	1	1	1
4	0	0	0	0	0	0	0
5	1	1	1	0	0	0	0
6	1	1	1	0	0	0	0
7	1	1	1	0	0	0	0

For the first linkage 4–4 (Fig. 7), the inverse models [23, 24] reveal only one optimal solution (Fig. 7a), for $A(2,6)$, which is equivalent to Baranov truss BT5 (Fig. 7b). By eliminating basis 2 in the inverse model the classical modular passive group GMP7 is found (Fig. 7c).



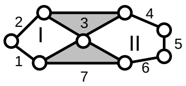
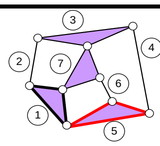
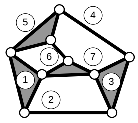
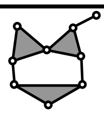
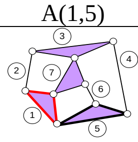
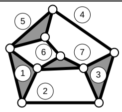
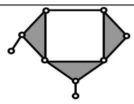
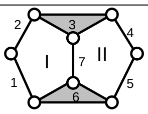
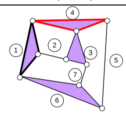
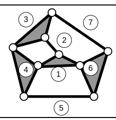
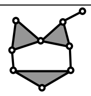
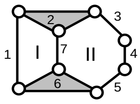
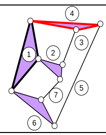
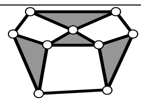
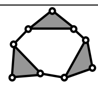
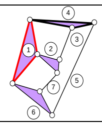
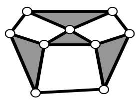
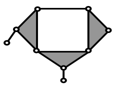
4–4 A(2,6) → BT 5 → GMP7(1,3,4,5,6,7)

Fig. 7 – Structural modelling for the bi-mobile and bi-looped linkage 4-4.

Likewise, for the bi-mobile linkages 4–5, 5–5, 4–6 (Fig. 1b, c, d) the solutions for optimal structures are found in Table 4.

Table 4

Optimal solutions for linkages 4–5, 5–5 and 4–6

 4-5	 A(1,5)	 BT4	 GMP8(2,3,4,5,6,7)
	 A(5,1)	 BT4	 GMP6(1,2,3,4,6,7)
 5-5	 A(1,4)	 BT4	 GMP8(2,3,4,5,6,7)
 4-6	 A(1,4)	 BT3	 GMP9(2,3,4,5,6,7)
	 A(4,1)	 BT3	 GMP6(1,2,3,4,6,7)

Their inverse models are characterized by passive modular groups GMP with 6 links known from mechanisms literature [2, 5, 23] and derived from previously mentioned Baranov trusses, Table 3. These mechanisms with basis-effector solutions mentioned in Table 4 are also optimal from technological and precision point of view.

3. OPTIMAL INVERSE MODELS FOR BI-MOBILE AND THREE-LOOPED PLANAR LINKAGES

The structural algorithm presented above, Fig. 3 for determining by inverse modelling the basis-effector solutions for bi-mobile and three-contour mechanisms highlights a number of 941 solutions, the models having 9 elements consisting of passive modular groups with the following characteristics of the elements (Table 2): 2+2+2+2, 2+4+2, 2+2+4, 4+2+2, 4+4, 2+6, 6+2, 8 details of which are shown in the paper appendixes.

The optimal basis-effector solutions for the non-decomposable linkages (L1-L35) shown in Table 1 are mentioned in Table 5.

Table 5

Basis-effector solutions for non-decomposable kinematic linkages

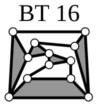
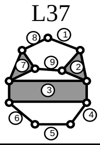
No	BT	The bi-mobile and three looped planar linkages	Optimal solution for the basis-effector
1.	BT 6	L3	A(3,7), A(7,3)
		L9	A(2,6)
2.	BT 7	L13	A(4,8)
		L15	A(4,8), A(8,4)
		L27	A(1,7)
		L35	A(2,8), A(8,2)
3.	BT 8	L2	A(2,8)
		L5	A(3,7), A(7,3)
		L15	A(2,5), A(5,2)
		L28	A(3,7), A(7,3)
4.	BT 9	L6	A(1,6), A(6,1), A(1,7)
		L29	A(1,4)
		L30	A(1,6), A(6,1)
		L31	A(2,6), A(6,2)
5.	BT 10	L2	A(1,6), A(6,1)
		L3	A(2,6), A(6,2)
		L20	A(1,5), A(5,1)
		L30	A(3,6), A(6,3)
		L35	A(2,5), A(5,2)
6.	BT 11	L13	A(3,7)
7.	BT 12	L13	A(3,8)
		L14	A(4,9), A(9,4)
		L24	A(6,7), A(7,6)
		L25	A(2,7), A(7,2)
8.	BT 13	L20	A(2,5), A(5,2)
		L25	A(1,4), A(4,1)
		L32	A(1,4), A(4,1)
9.	BT 14	L3	A(3,6), A(6,3)
		L5	A(3,8), A(8,3)
		L11	A(1,6), A(6,1)
		L14	A(1,4), A(4,1)
		L19	A(1,7), A(7,1)
		L30	A(3,6), A(6,3)

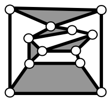
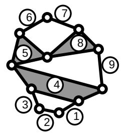
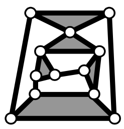
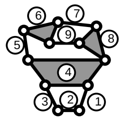
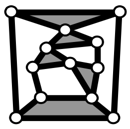
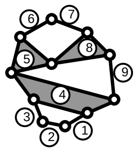
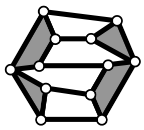
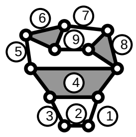
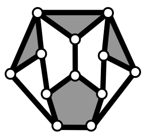
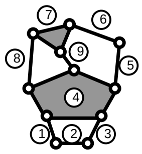
10.	BT	L32							
	15	A(1,9)				A(9,1)			
11.	BT	L17		L19		L28			
	16	A(2,6)	A(6,2)	A(1,8)	A(8,1)	A(2,5)			
12.	BT	L18		L29		L33		L34	
	17	A(3,9)	A(3,9)	A(1,5)	A(5,1)	A(1,4)	A(4,1)	A(5,9)	A(9,5)
13.	BT	L7		L30		L31		L35	
	18	A(1,7)	A(7,1)	A(4,8)	A(8,4)	A(2,5)	A(5,2)	A(2,9)	A(9,2)
14.	BT	L26		L27		L32			
	19	A(1,6)	A(6,1)	A(3,6)	A(6,3)	A(1,5)	A(5,1)		
15.	BT	L20		L23		L26			
	20	A(2,6)	A(6,2)	A(2,6)	A(6,2)	A(3,6)	A(6,3)		
16.	BT	L21				L25			
	21	A(1,6)		A(6,1)		A(2,5)		A(5,2)	
17.	BT	L8				L30			
	22	A(1,6)		A(6,1)		A(4,7)		A(7,4)	
18.	BT	L7		L10		L14		L35	
	23	A(2,7)	A(7,2)	A(1,6)	A(6,1)	A(2,5)	A(5,2)	A(2,6)	A(6,2)
19.	BT	L8		L10		L12		L15	
	24	A(2,6)	A(6,2)	A(2,6)	A(6,2)	A(1,4)	A(4,1)	A(1,4)	A(4,1)
20.	BT	L17				L20			
	25	A(1,6)		A(6,1)		A(1,6)		A(6,1)	
21.	BT	L21		L23		L27		L34	
	26	A(2,6)	A(6,2)	A(1,4)	A(4,1)	A(1,4)	A(4,1)	A(2,5)	A(5,2)
22.	BT	L12							
	27	A(1,5)							
23.	BT	L26							
	29	A(2,6)				A(6,2)			
24.	BT	L22				L23			
	30	A(1,5)		A(5,1)		A(1,5)		A(5,1)	
25.	BT	L34							
	31	A(1,5)				A(5,1)			

Applying the same structural procedure the basis-effector optimal solutions for decomposable linkages are shown in Table 6.

Table 6

Basis-effector solutions for decomposable kinematic linkages

No.	BT	The bi-mobile and three looped planar linkages Optimal solution for the basis-effector	
1.	BT 16 	L37 	
		A(1,5)	A(5,1)

2.	BT 17 	L36 	
		A(2,6)	A(6,2)
3.	BT 20 	L40 	
		A(2,7)	A(7,2)
4.	BT 25 	L36 	
		A(2,7)	A(7,2)
5.	BT 28 	L40 	
		A(2,6)	A(6,2)
6.	BT 33 	L39 	
		A(2,6)	A(6,2)

The optimal solutions for basis-effector selected through Baranov trusses [(BT6-BT33) – (BT32)] have in view only 27 of them, the 28th is a particular one (BT 32) with symmetry properties.

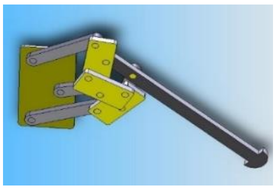


Fig. 8 – Manipulator with the inverse model defined by Baranov truss BT 24 from the linkage L15 with the basis 1 and the effector 4 (Table 5).

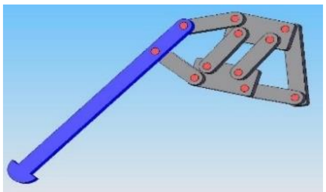


Fig. 9 – Manipulator with the inverse model defined by Baranov truss BT 30 from the linkage L22 with the basis 1 and the effector 5 (Table 5).

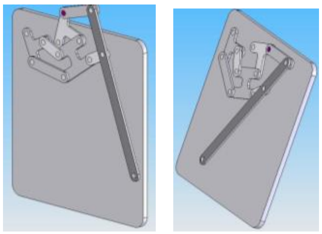


Fig. 10 – Manipulator with the inverse model defined by Baranov truss BT 20 from the linkage L26 with the basis 3 and the effector 6 (Table 5).

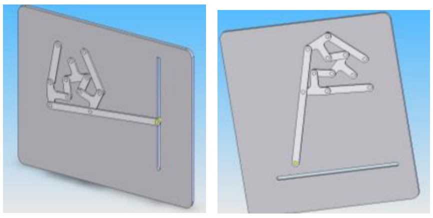


Fig. 11 – Manipulator with the inverse model defined by Baranov truss BT 19 from the linkage L27 with the basis 6 and the effector 3 (Table 5).

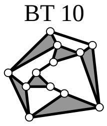
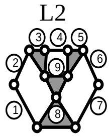
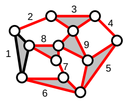
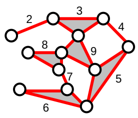
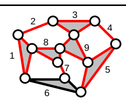
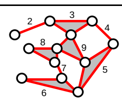
The experimental robot mechanisms (Figs. 8–11) are achieved by means of previously presented theoretical researches.

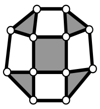
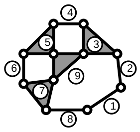
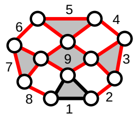
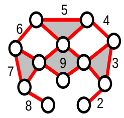
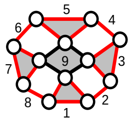
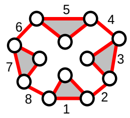
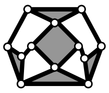
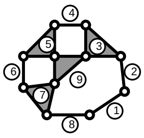
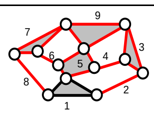
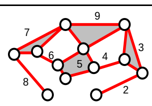
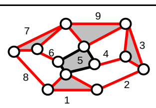
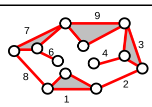
4. PASSIVE MODULAR GROUPS IDENTIFIED BY MEANS OF INVERSE MODELS FOR BI-MOBILE AND THREE-LOOPED PLANAR LINKAGES

Most of the solutions for inverse models from Table 4 and Table 5 give new distinct passive modular groups with eight elements. Some significant examples are mentioned in Table 7, others will be presented in a future paper.

Table 7

Passive modular groups with 8 elements

Baranov truss	Linkage	Basis-effector solution	Inverse model	Passive modular group (new configuration)
BT 10 	L2 	A(1,6)		
		A(6,1)		

BT 15 	L 32 	A(1,9)		
		A(9,1)		
BT 19 	L 32 	A(1,5)		
		A(5,1)		

5. CONCLUSIONS

The paper makes available to researchers and designers of robotic mechanical systems the assembly of bi-mobile and bi-contour mechanisms obtained from kinematic chains with five degrees of freedom. By nominating the base and effector, the correct and chosen inverse modular structure is ensured so as to achieve optimal control of the structure. A small number of passive modular groups in the reverse model influence the accuracy of motion and its control through a small number of sensors.

This consideration justifies the development of recent research on Baranov trusses with 11 and 13 elements [6, 18, 19, 27, 28, 30].
Further research will focus on minimizing the number of active modular groups in these mechanisms, which raise the performance of precision and control of movements.

The paper synthesizes the all bi-mobile mechanisms with two and three independent contours for robotic systems, being useful in design, similar to the famous atlas J.A.Hrones and G.L.Nelson, dedicated to the synthesis of four-bar mechanisms according to their coupler curves [21].

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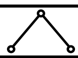
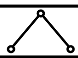
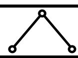
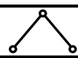
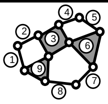
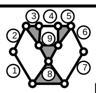
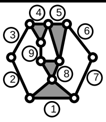
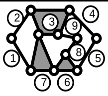
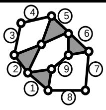
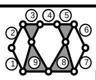
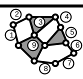
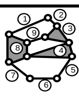
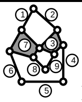
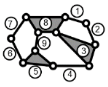
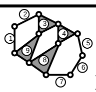
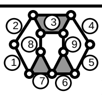
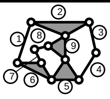
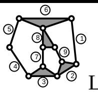
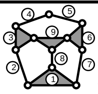
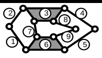
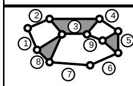
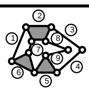
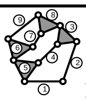
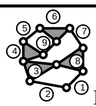
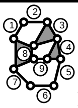
APPENDICES

Appendix 1

Base-effector structural solutions from inverse models
with 2+2+2+2 passive modular groups connection

2+2+2+2											
 L1	A(1,8)	A(8,1)	A(2,4)	A(2,6)	A(6,2)						
	A(3,7)	A(7,3)	A(6,8)	A(8,6)	A(6,9)						
 L2	A(1,3)	A(3,1)	A(1,9)	A(9,1)	A(2,4)	A(4,2)					
	A(2,8)	A(8,2)	A(2,9)	A(9,2)	A(3,8)	A(8.3)					
 L3	A(1,5)	A(5,1)	A(1,6)	A(6,1)	A(1,9)	A(9,1)	A(3,5)	A(5,3)	A(3,9)		
	A(9,3)	A(4,6)	A(6,4)	A(5,7)	A(7,5)	A(6,8)	A(8,6)	A(7,8)	A(8,7)		
 L4	A (1,6)	A(6,1)	A(2,4)	A(4,2)	A(3,5)	A(5,3)	A(3,6)				
	A(6,3)	A(4,6)	A(6,4)	A(4,7)	A(7,4)	A(5,7)	A(7,5)				
 L5	A(1,3)	A(3,1)	A(1,5)	A(5,1)	A(1,6)						
	A(1,7)	A(7,1)	A(2,9)	A(9,2)	A(7,9)	A(9,7)					
 L6	A(1,8)	A(8,1)	A(2,4)	A(4,2)	A(3,5)	A(3,8)	A(8,3)	A(4,8)	A(8,4)		
 L7	A(1,8)	A(8,1)	A(3,8)	A(8,3)	A(4,6)	A(6,4)	A(5,7)	A(7,5)			
	A(5,8)	A(8,5)	A(6,8)	A(8,6)	A(6,9)	A(9,6)	A(7,9)	A(9,7)			
 L8	A(3,5)	A(5,3)	A(4,6)	A(6,4)	A(4,7)	A(7,4)	A(5,7)				
	A(7,5)	A(5,8)	A(8,5)	A(6,8)	A(8,6)	A(7,9)	A(9,7)				
 L9	A(1,6)	A(6,1)	A(3,5)	A(5,3)	A(3,6)	A(6,3)	A(4,6)				
 L10	A(1,9)	A(9,1)	A(2,4)	A(4.2)	A(3,5)	A(5,3)	A(3,9)	A(9,3)	A(4,8)	A(8,4)	A(4,9)
	A(9,4)	A(5,7)	A(7,5)	A(5,8)	A(8,5)	A(6,8)	A(8,6)	A(6,9)	A(9,6)	A(7,9)	A(9,7)
 L11	A(3,5)	A(5,3)	A(4,6)	A(6,4)	A(4,7)	A(7,4)	A(5,7)				
 L12	A(1,3)	A(3,1)	A(1,8)	A(8,1)	A(2,7)	A(7,2)	A(2,8)				
	A(8,2)	A(3,6)	A(6,3)	A(6,8)	A(8,6)	A(8,9)	A(8,2)				

 L13	A(1,5)	A(5,1)	A(2,4)	A(4,2)	A(2,5)	A(2,6)
	A(3,5)	A(5.3)	A(3,9)	A(9,3)	A(4,9)	A(9,4)
 L14	A(1,8)	A(8,1)	A(1,9)	A(2,6)		
 L15	A(1,3)	A(3,1)	A(1,9)	A(9,1)	A(2,9)	
	A(8,2)	A(2,9)	A(9,2)	A(3,8)	A(8,3)	
 L16	A(1,3)	A(3,1)	A(1,7)	A(7,1)	A(3,6)	
 L17	A(2,4)	A(4,2)	A(4,6)	A(6,4)	A(4,8)	A(8,4)
 L18	A(1,3)	A(3,1)	A(1,5)	A(5,1)		
 L19	A(3,7)	A(7,3)				
 L20	A(3,5)	A(5,3)	A(5,7)	A(7,5)		
 L21	A(1,7)	A(7,1)	A(3,5)	A(5,3)	A(3,7)	
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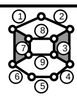
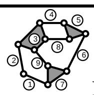
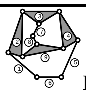
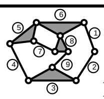
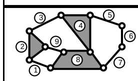
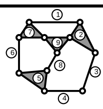
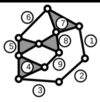
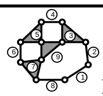
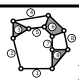
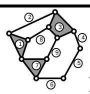
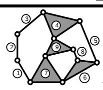
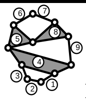
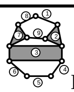
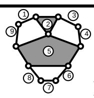
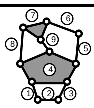
 L22	A(4,8)	A(8,4)				
 L23	A(4,6)	A(6,4)	A(4,9)	A(9,4)		
 L24	A(1,3)	A(3,1)				
 L25	A(4,6)	A(6,4)	A(4,7)	A(7,4)	A(7,9)	A(9,7)
 L26	A(1,7)	A(7,1)				

 L30	A(1,6)	A(6,1)	A(2,9)	A(9,2)	A(5,7)	A(7,5)	
	A(5,8)	A(8,5)	A(6,8)	A(8,6)	A(6,9)	A(7,9)	A(9,7)
 L31	A(1,6)	A(6,1)	A(1,8)	A(8,1)			
 L32	A(2,4)	A(4,2)	A(2,9)	A(9,2)			
 L33	A(4,7)						
 L34	A(2,4)	A(4,2)					
 L35	A(1,6)	A(6,1)	A1,9)	A(9,1)			
 L36	A(1,5)	A(5,1)	A(1,9)	A(9,1)			
 L37	A(2,4)	A(4,2)					
 L38	A(2,6)	A(6,2)	A(4,6)	A(6,4)			
 L39	A(1,8)	A(8,1)					

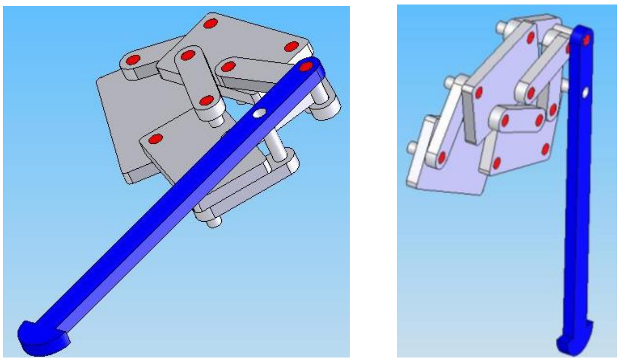
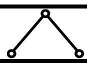
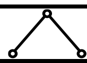
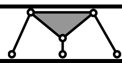


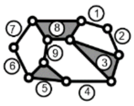
Fig. 12 – Bi-mobile mechanism with 2+2+2+2 inverse modular structure (basis 1 and effector 3) from the linkage 16.

Appendix 2

Base-effector structural solutions from inverse models
with 2+2+4 passive modular groups connection

2+2+4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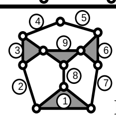
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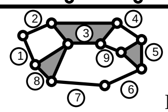
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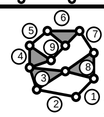
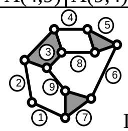
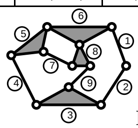

L20

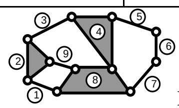
A(1,7)	A(7,1)	A(3,5)	A(5,3)	A(3,6)	A(4,9)	A(9,4)	A(1,7)	A(7,1)	A(2,4)	A(4,2)


L23

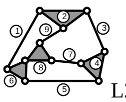
A(1,3)	A(3,1)	A(1,9)	A(9,1)	A(2,4)	A(4,2)	A(2,7)	A(7,2)	A(2,9)	A(9,2)	A(3,7)	A(7,3)


L25

A(1,5)	A(5,1)


L26

A(4,6)	A(6,4)	A(4,7)	A(7,4)	A(5,7)	A(7,5)	A(5,8)	A(8,5)	A(6,8)	A(8,6)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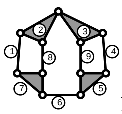
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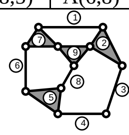
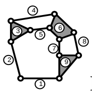

L30

A(1,8)	A(8,1)	A(2,6)	A(6,2)	A(1,3)	A(3,1)	A(1,3)	A(3,1)	A(3,8)	A(8,3)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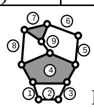
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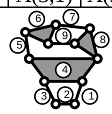
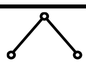
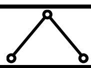
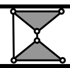
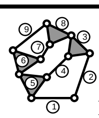

L40

A(1,7)	A(7,1)	A(1,5)	A(5,1)	A(1,8)	A(8,1)

2+2+4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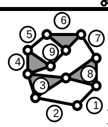
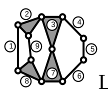

L20

A(1,3)	A(3,1)	A(1,4)	A(4,1)	A(3,5)	A(1,7)	A(7,1)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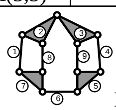
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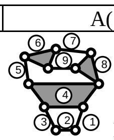
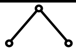
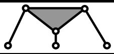
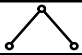
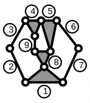
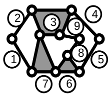
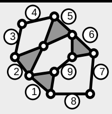
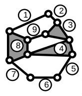

L40

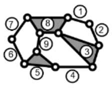
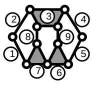
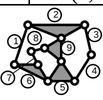
A(3,5)	A(5,3)	A(3,6)	A(6,3)	A(4,6)	A(1,6)	A(6,1)	A(1,5)	A(5,1)

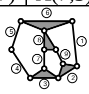
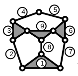
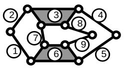
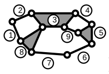
Appendix 3

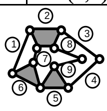
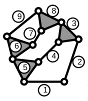
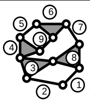
Base-effector structural solutions from inverse models
with 2+4 +2 passive modular groups connection

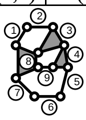
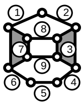
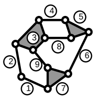
2+4+2			

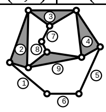
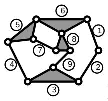
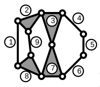
 L3				 L4		 L5		 L8	
A(2,4)	A(4,2)	A(2,8)	A(8,2)	A(4,9)	A(5,8)	A(2,8)	A(8,2)	A(1,7)	A(7,1)

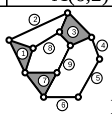
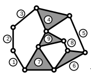
 L10				 L12				 L13			
A(3,7)	A(7,3)	A(4,6)	A(6,4)	A(1,6)	A(6,1)	A(2,9)	A(9,2)	A(1,3)	A(3,1)	A(2,8)	A(8,2)

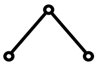
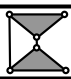
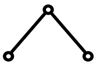
 L14		 L15	 L16			 L17			
A(1,3)	A(3,1)	A(2,7)	A(1,5)	A(5,1)	A(4,8)	A(3,7)	A(7,3)	A(5,7)	A(7,5)

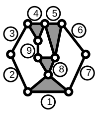
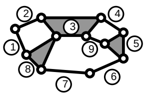
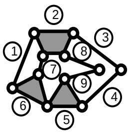
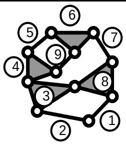
 L18				 L19		 L20			
A(2,4)	A(4,2)	A(4,6)	A(6,4)	A(4,6)	A(6,4)	A(4,8)	A(8,4)	A(6,8)	A(8,6)

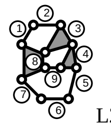
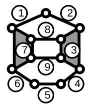
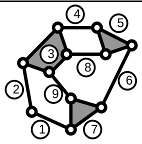
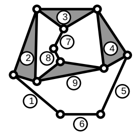
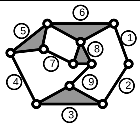
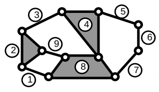
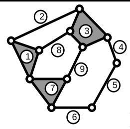
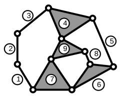
 L21				 L22				 L23	
A(4,6)	A(6,4)	A(6,8)	A(8,6)	A(1,6)	A(6,1)	A(3,5)	A(5,3)	A(5,7)	A(7,5)

 L24		 L25		 L28	
A(2,6)	A(6,2)	A(3,5)	A(5,3)	A(2,4)	A(4,2)

 L34				 L35	
A(1,6)	A(6,1)	A(4,9)	A(9,4)	A(3,9)	A(9,3)

2+4+2			

 L3		 L17		 L18		 L20	
A(1,3)	A(3,1)	A(6,8)	A(8,6)	A(3,5)	A(5,3)	A(3,7)	A(7,3)

 L21	 L22	 L23	 L24
A(5,7) A(7,5)	A(4,6)	A(6,9) A(9,6)	A(1,5)
 L25	 L26	 L34	 L35
A(4,9) A(9,4)	A(3,5) A(5,3)	A(6,9) A(9,6)	A(3,5) A(5,3)

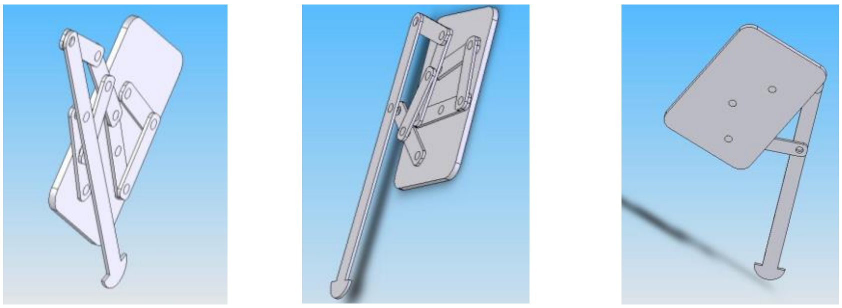
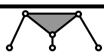
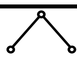
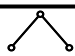
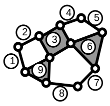
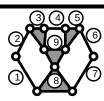
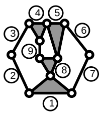
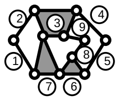
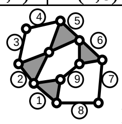
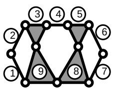
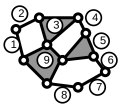
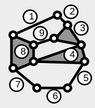
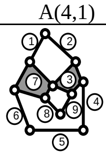
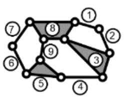
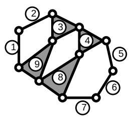
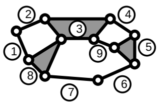
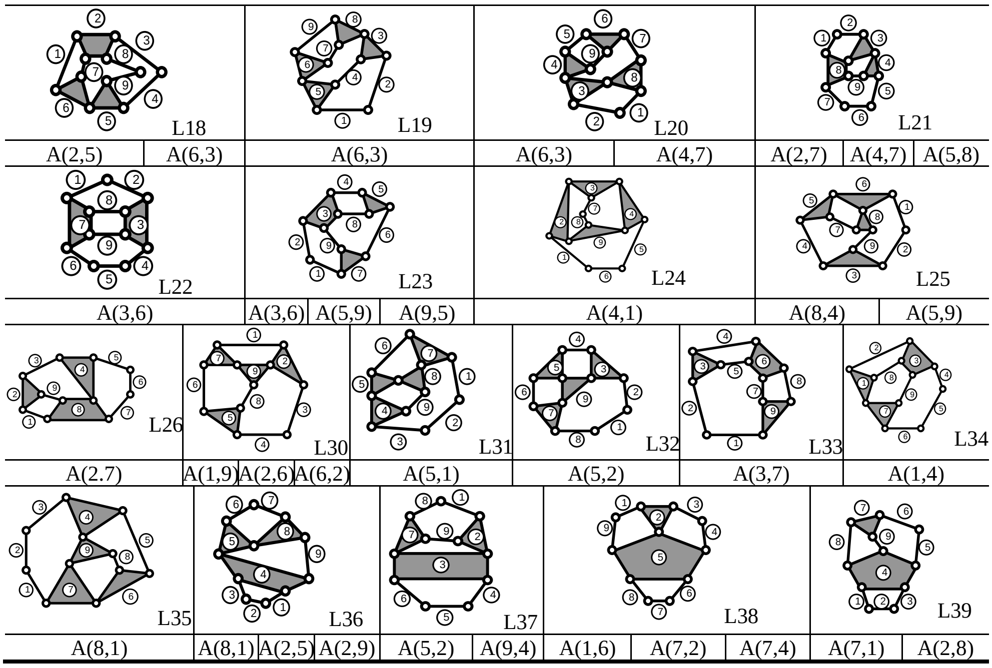


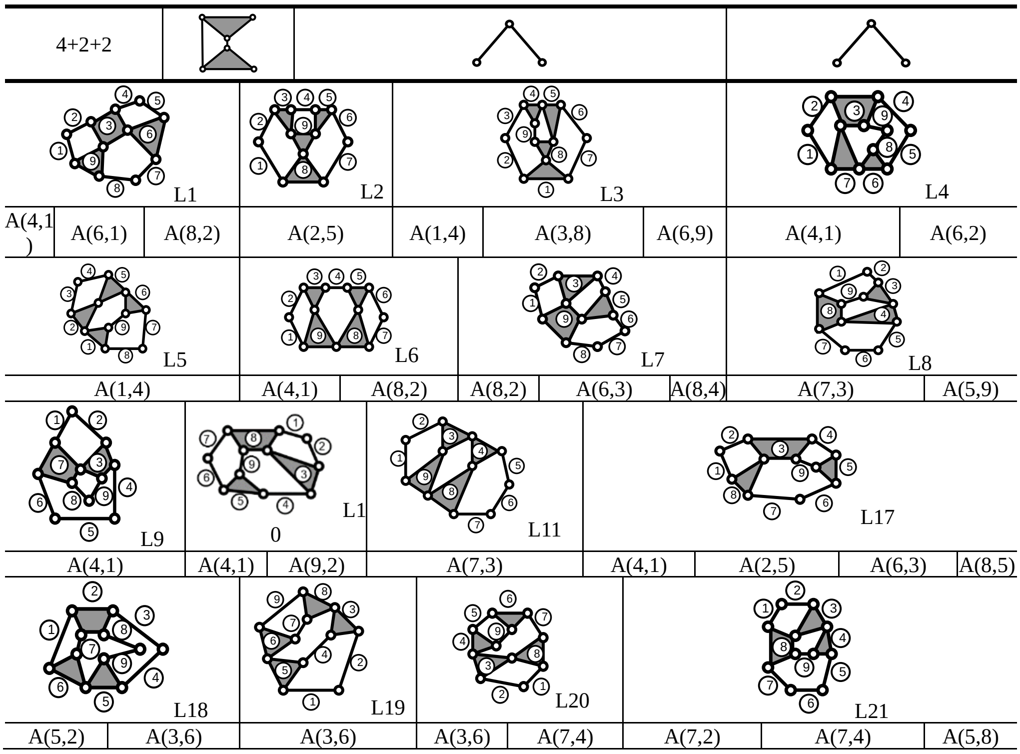
Fig. 13 – Bi-mobile mechanism with 2+4+2 inverse modular structure
(basis 2 and effector 8) from L5 linkage.

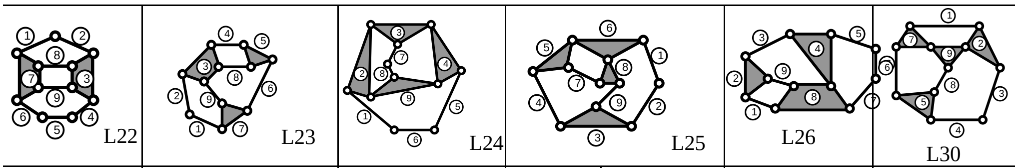
Appendix 4

Base-effector structural solutions from inverse models
with 4+2+2 passive modular groups connection

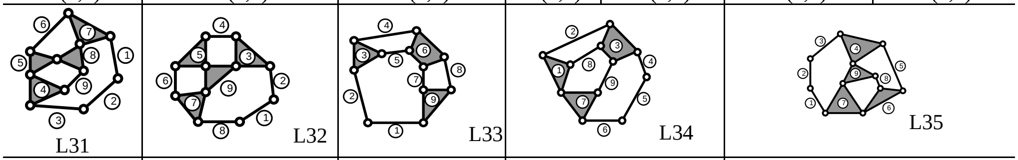
4+2+2			
 L1	 L2	 L3	 L4
A(1,4) A(1,6) A(2,8)	A(5,2) A(4,8) A(8,4)	A(4,1) A(8,3) A(9,6)	A(1,4) A(2,6)
 L5	 L6	 L7	 L8
A(4,1)	A(1,4) A(2,8)	A(2,8) A(3,6) A(4,8)	A(3,7) A(9,5)
 L9	 L10	 L11	 L17
A(1,4)	A(1,4) A(2,9)	A(3,7)	A(1,4) A(5,2) A(3,6) A(5,8)


L18
L19
L20
L21
A(2,5)
A(6,3)
A(6,3)
A(6,3)
A(4,7)
A(2,7)
A(4,7)
A(5,8)
L22
L23
L24
L25
A(3,6)
A(3,6)
A(5,9)
A(9,5)
A(4,1)
A(8,4)
A(5,9)
L26
L30
L31
L32
L33
L34
A(2.7)
A(1,9)
A(2,6)
A(6,2)
A(5,1)
A(5,2)
A(3,7)
A(1,4)
L35
L36
L37
L38
L39
A(8,1)
A(8,1)
A(2,5)
A(2,9)
A(5,2)
A(9,4)
A(1,6)
A(7,2)
A(7,4)
A(7,1)
A(2,8)

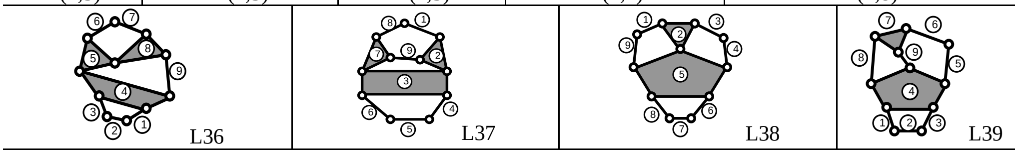

4+2+2
L1
L2
L3
L4
A(4,1)
A(6,1)
A(8,2)
A(2,5)
A(1,4)
A(3,8)
A(6,9)
A(4,1)
A(6,2)
L5
L6
L7
L8
A(1,4)
A(4,1)
A(8,2)
A(8,2)
A(6,3)
A(8,4)
A(7,3)
A(5,9)
L9
L10
L11
L17
A(4,1)
A(4,1)
A(9,2)
A(7,3)
A(4,1)
A(2,5)
A(6,3)
A(8,5)
L18
L19
L20
L21
A(5,2)
A(3,6)
A(3,6)
A(3,6)
A(7,4)
A(7,2)
A(7,4)
A(5,8)



A(6,3)	A(6,3)	A(1,4)	A(4,8)	A(9,5)	A(7,2)	A(9,1)



A(1,5)	A(2,5)	A(7,3)	A(4,1)	A(1,8)



A(1,8)	A(5,2)	A(9,2)	A(2,5)	A(4,9)	A(6,1)	A(2,7)	A(4,7)	A(1,7)	A(8,2)

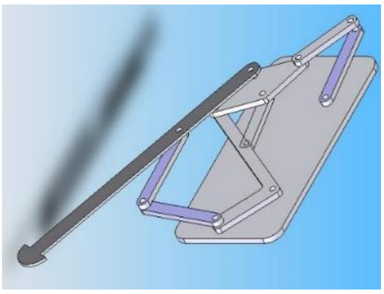
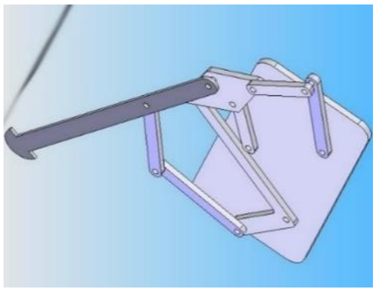
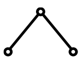
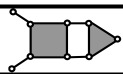
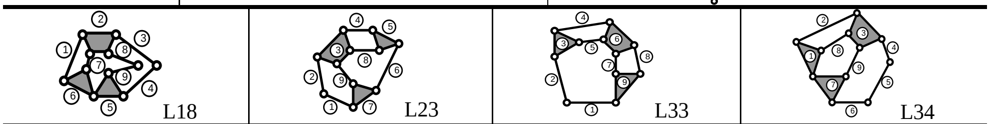
 

Fig. 14 –Bi-mobile mechanism with 4+2+2 inverse modular structure (basis 3 and effector 7) from L8 linkage.

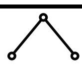
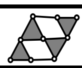
Appendix 5

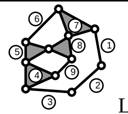
Base-effector structural solutions from inverse models with 2+6 passive modular groups connection

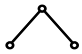
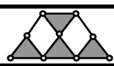
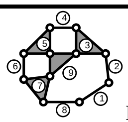
2+6		

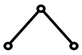
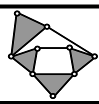
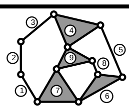


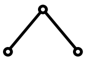
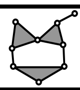
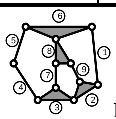
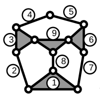
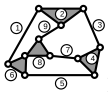
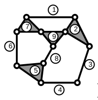
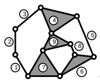
A(4,9)	A(1,6)	A(6,1)	A(1,3)	A(3,1)	A(5,7)	A(7,5)

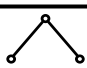
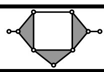
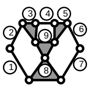
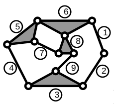
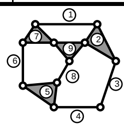
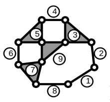
2+6		

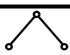
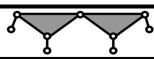
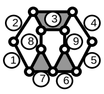
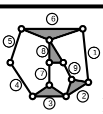
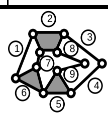
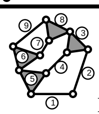
 L31
A(1,3)

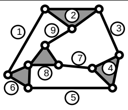
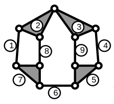
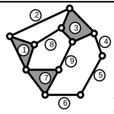
2+6		
 L32		
A(2,8)		

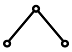
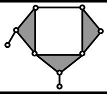
2+6		
 L35		
A(1,3)	A(3,1)	

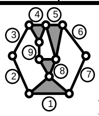
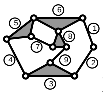
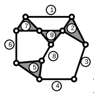
2+6										
 L14				 L15			 L27	 L30		 L35
A(1,5)	A(5,1)	A(3,5)	A(5,3)	A(2,4)	A(4,2)	A(1,3)	A(3,1)	A(2,4)	A(4,2)	A(2,7)	A(7,2)

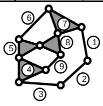
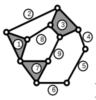
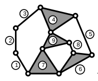
2+6						
 L2	 L25		 L30		 L32	
A(1,7)	A(1,3)	A(3,1)	A(4,9)	A(9,4)	A(1,3)	A(3,1)

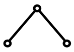
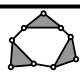
2+6					
 L12	 L14		 L18	 L19	
A(2,4)	A(2,4)	A(4,2)	A(3,8)	A(1,6)	A(6,1)

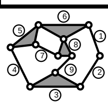
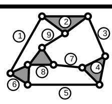
 L27	 L29	 L34	
A(2,4)	A(5,7)	A(3,5)	A(5,3)

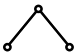
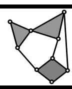
2+6		

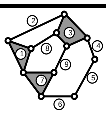
 L3		 L25		 L30			
A(2,7)	A(7,2)	A(2,4)	A(4,2)	A(3,5)	A(5,3)	A(4,6)	A(6,4)

 L31		 L34		 L35	
A(2,4)	A(4,2)	A(3,5)	A(5,3)	A(2,4)	A(4,2)

2+6		

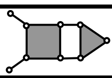
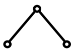
 L25		 L27
A(2,6)	A(6,2)	A(1,5)

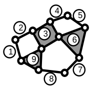
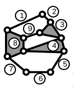
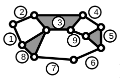
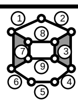
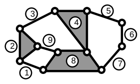
2+6		

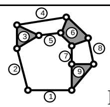
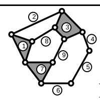
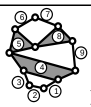
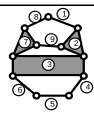
 L34	
A(4,6)	A(6,4)

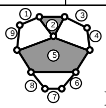
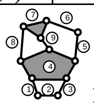
Appendix 6

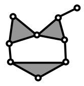
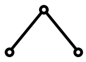
Base-effector structural solutions from inverse models
with 6+2 passive modular groups connection

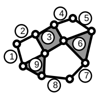
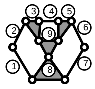
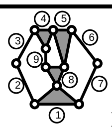
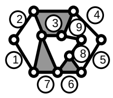
6+2		

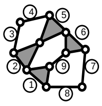
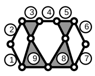
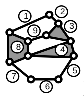
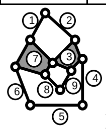
 L1	 L8	 L17		 L22	 L26
A(1,5)	A(2,7)	A(1,5)	A(5,1)	A(1,4)	A(3,7)

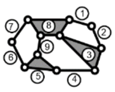
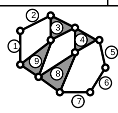
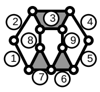
 L33	 L34	 L36		 L37	
A(3,9)	A(7,4)	A(2,8)	A(8,2)	A(5,9)	A(9,5)

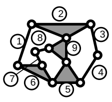
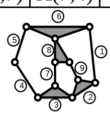
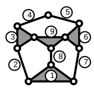
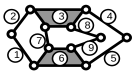
 L38		 L39		
A(1,7)	A(7,1)	A(6,1)	A(2,7)	A(7,2)

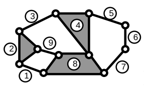
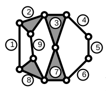
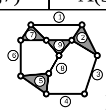
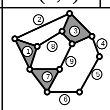
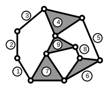
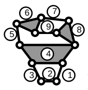
6+2		

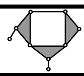
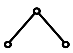
 L1		 L2		 L3		 L4			
A(1,7)	A(2,7)	A(4,1)	A(5,1)	A(4,7)	A(9,7)	A(1,5)	A(2,5)	A(4,8)	A(8,4)

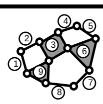
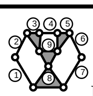
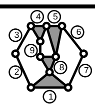
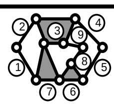
 L5			 L6		 L8		 L9
A(2,7)	A(7,2)	A(3,9)	A(1,5)	A(2,5)	A(3,6)	A(9,6)	A(1,5)

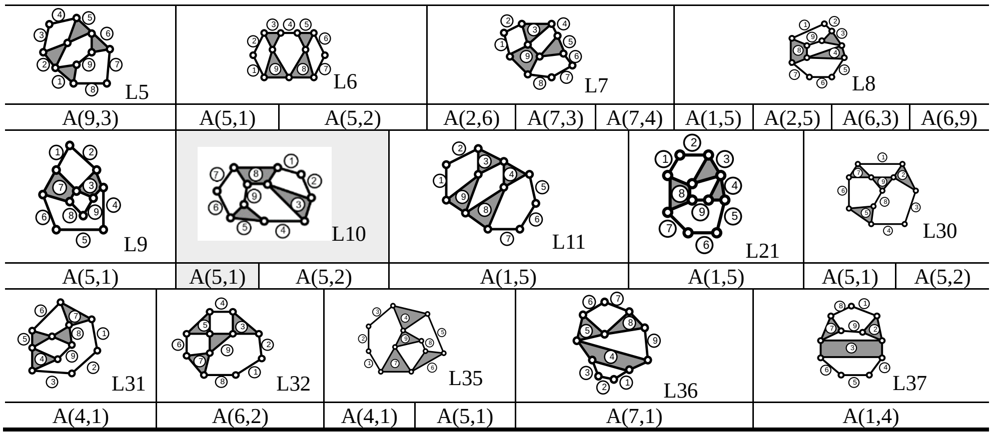
 L10						 L11	 L12			
A(1,5)	A(2,5)	A(3,6)	A(6,3)	A(4,7)	A(7,4)	A(3,6)	A(1,9)	A(9,1)	A(2,6)	A(6,2)

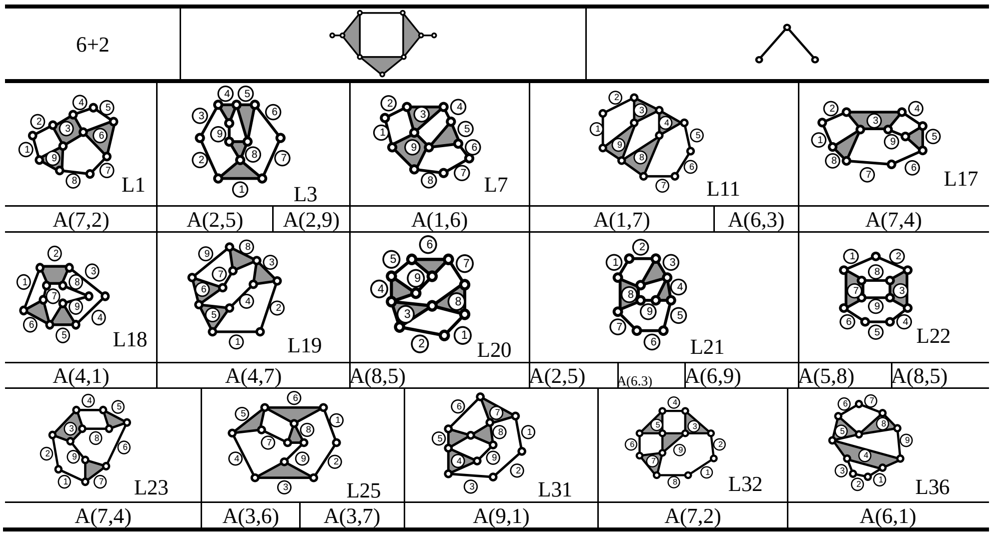
 L13				 L14		 L15		 L16		
A(1,4)	A(4,1)	A(2,7)	A(7,2)	A(1,7)	A(3,6)	A(2,6)	A(6,2)	A(1,4)	A(4,1)	A(4,9)

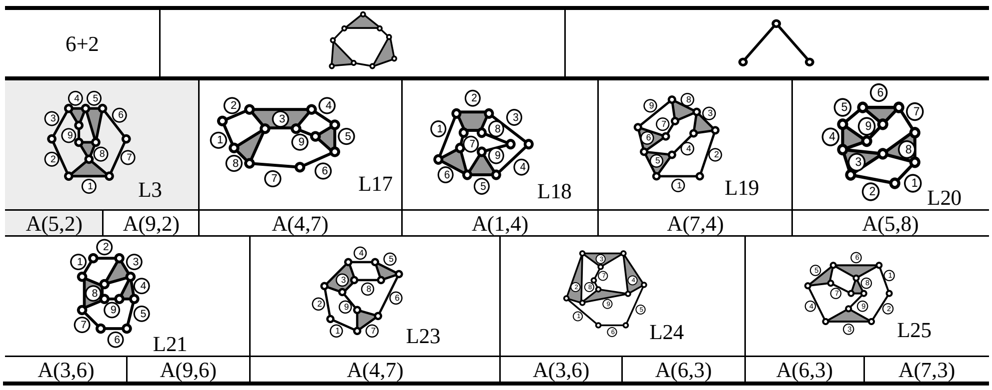
 L26	 L28	 L30		 L34	 L35		 L40
A(1,5)	A(1,4)	A(1,5)	A(2,5)	A(2,6)	A(7,3)	A(8,3)	A(7,1)

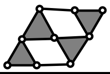
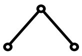
6+2		

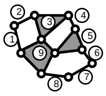
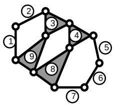
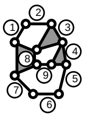
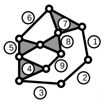
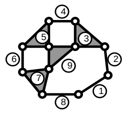
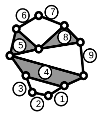
 L1	 L2		 L3		 L4	
A(7,1)	A(1,4)	A(1,5)	A(7,4)	A(7,9)	A(5,1)	A(5,2)

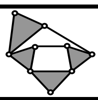
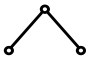

L5
L6
L7
L8
A(9,3)
A(5,1)
A(5,2)
A(2,6)
A(7,3)
A(7,4)
A(1,5)
A(2,5)
A(6,3)
A(6,9)
L9
L10
L11
L21
L30
A(5,1)
A(5,1)
A(5,2)
A(1,5)
A(1,5)
A(5,1)
A(5,2)
L31
L32
L35
L36
L37
A(4,1)
A(6,2)
A(4,1)
A(5,1)
A(7,1)
A(1,4)

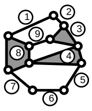
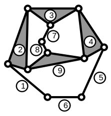
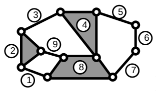
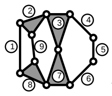
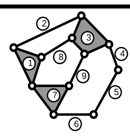

6+2
L1
L3
L7
L11
L17
A(7,2)
A(2,5)
A(2,9)
A(1,6)
A(1,7)
A(6,3)
A(7,4)
L18
L19
L20
L21
L22
A(4,1)
A(4,7)
A(8,5)
A(2,5)
A(6.3)
A(6,9)
A(5,8)
A(8,5)
L23
L25
L31
L32
L36
A(7,4)
A(3,6)
A(3,7)
A(9,1)
A(7,2)
A(6,1)

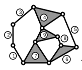
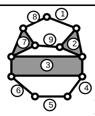
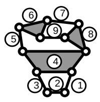

6+2
L3
L17
L18
L19
L20
A(5,2)
A(9,2)
A(4,7)
A(1,4)
A(7,4)
A(5,8)
L21
L23
L24
L25
A(3,6)
A(9,6)
A(4,7)
A(3,6)
A(6,3)
A(6,3)
A(7,3)

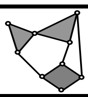
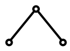
6+2		

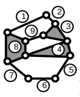
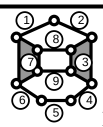
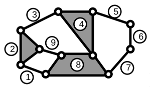
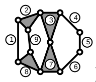
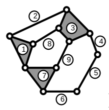
 L7	 L11	 L21	 L31	 L32	 L36
A(6,2)	A(5,1)	A(5,1)	A(1,4)	A(2,6)	A(1,7)

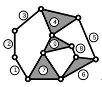
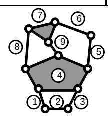
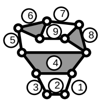
6+2		

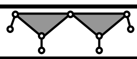
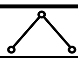
 L8		 L24		 L26	 L28	 L34
A(5,1)	A(5,2)	A(1,7)	A(7,1)	A(5,1)	A(4,1)	A(6,2)

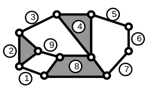
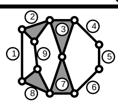
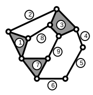
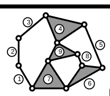
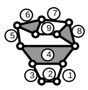
 L35				 L37	 L40
A(1,4)	A(1,5)	A(3,7)	A(3,8)	A(4,1)	A(1,7)

6+2		

 L8	 L22	 L26		 L28	 L34	
A(7,2)	A(4,1)	A(5,2)	A(7,3)	A(6,2)	A(6,3)	A(4,7)

 L35	 L39	 L40
A(3,6)	A(1,6)	A(1,6)

6+2		

 L26	 L28	 L34	 L35	 L40
A(2,5)	A(2,6)	A(3,6)	A(6,3)	A(6,1)

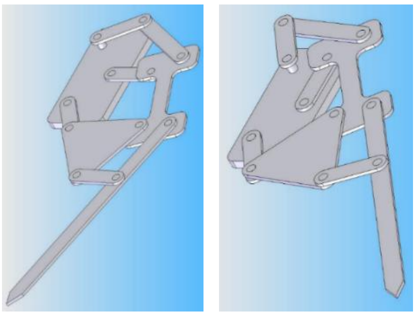


Fig. 15 – Bi-mobile mechanism with 6+2 inverse modular structure (basis 5 and effector 1) from L10 linkage.

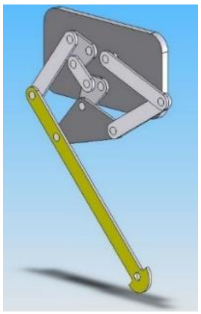


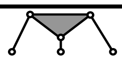
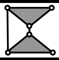
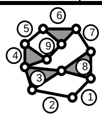
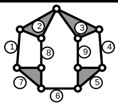
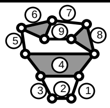
Fig. 16 – Bi-mobile mechanism with 6+2 inverse modular structure(basis 5 and effector 2) from L3 linkage.

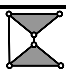
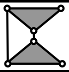
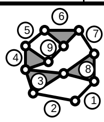
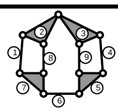
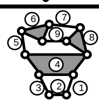
Appendix 7

Base-effector structural solutions from inverse models with 4+4 passive modular groups connection

4+4				
L10	L17	L20	L23	L29
A(2,7)	A(2.7)	A(1,4)	A(5,2)	A(5,2)
L30	L33	L39	L40	
A(7,3)	A(6,1)	A(2,5)	A(2,8)	

4+4			
L10	L17	L20	L23
A(7,2)	A(7,2)	A(4,1)	A(2,5)
L25		L29	
A(1,7)	A(7,1)	A(2,5)	
L30	L33	L39	L40
A(3,7)	A(1,6)	A(5,2)	A(8,2)

4+4		
 L20	 L29	 L40
A(2,7)	A(2,6)	A(2,5)

4+4		
 L20	 L29	 L40
A(7,2)	A(6,2)	A(5,2)

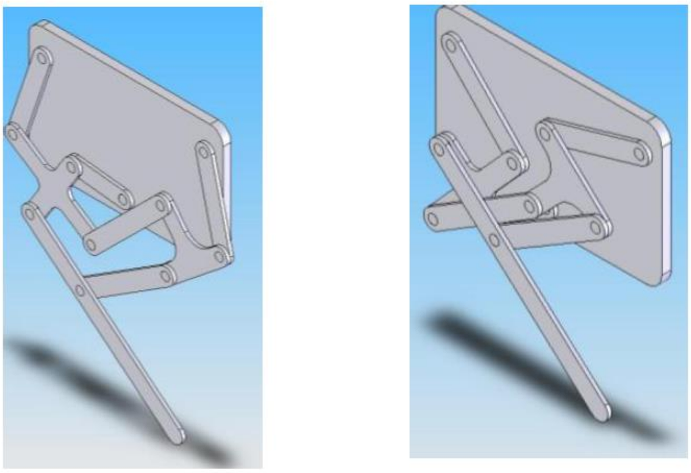


Fig. 17 – Bi-mobile mechanism with 4+4 inverse modular structure (basis 5 and effector 2) from L23 linkage.