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Passive Modular Groups for Inverse Structural Modelling of Bimobile Systems

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Abstract

The passive modular groups mentioned in the classical theory of mechanisms are the basis modules in the construction of planar mechanisms with one degree of mobility corresponding to their linkages with four degrees of freedom. Even if thirteen solutions are presented [3, 4, 5, 6] only some of them are found in practice and apparently there are groups never met in the mechanisms structure.

The effectors extremity of bi mobile mechanisms describes any curve in an adequate domain. When the bi mobile mechanisms become main mechanical structures for robot arms and legs for mobile platforms two new notions are put into evidence - the inverse and the direct modelling. The inverse structure modelling of bi mobile mechanisms is based on the passive modular groups. By using the numerical operators such new structures with zero degree of mobility obtained from Baranov trusses may be obtained. In the paper there are also presented such new groups and their applying for the design of optimal bi mobile mechanisms. The paper is the result of intensive research to obtain new solutions applied and designed for various branches of robotics. The bi mobile systems thus obtained are patentable.

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Keywords: passive group; Baranov truss; inverse structural model; numerical operator; numerical synthesis;

1. Introduction

The inverse problem in robotics has the main purpose to establish the characteristics of the active pairs (actuators) in function of the parameters required to the effector [1, 8]. From structural point of view this situation is

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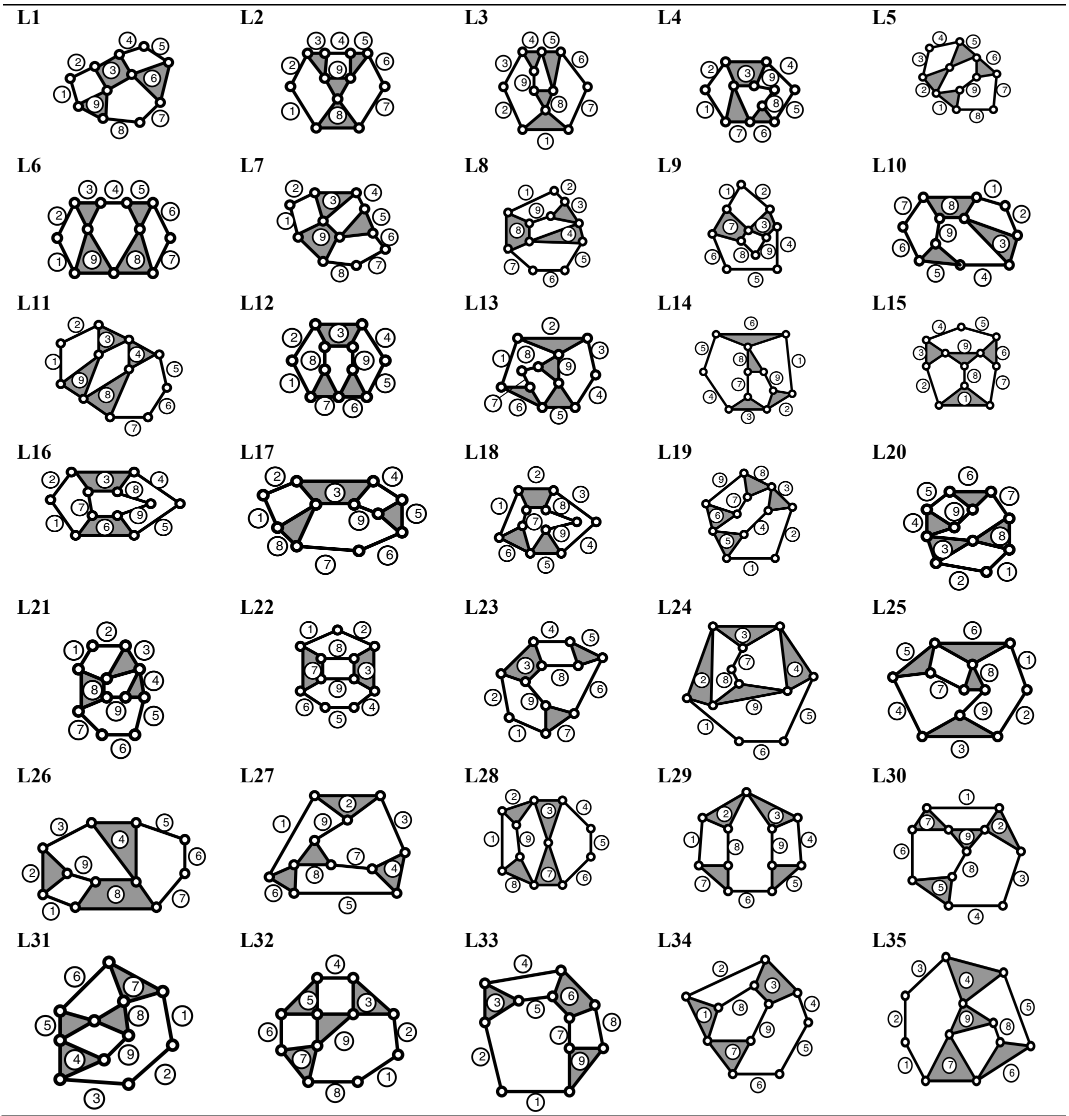
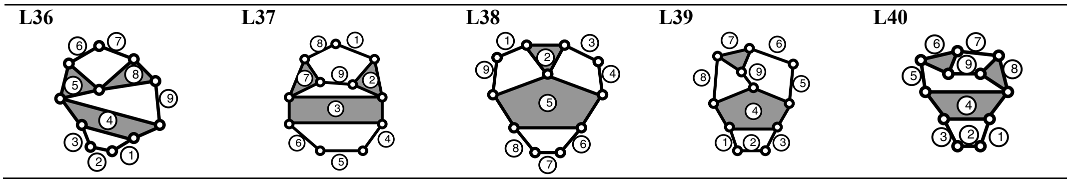
equivalent to have for the robot arm or pedipulator mechanical system an instantaneous degree of mobility equal to zero. In the case of the bi-mobile systems [2] the mobility instantaneously becomes zero due to the placing a connection between the basis and the extremity of the effectors and this connection being equivalent to a lower pair with two constrains and a single mobility [2].

A bi-mobile linkage with 9 links and three loops (Table 1) may have an inverse model constituted by the following passive modular groups formed by: 2+2+2+2, 2+4+2, 2+2+4, 4+2+2, 4+4, 2+6, 6+2 or 8 elements. Some groups with 8 links are deduced from the Baranov trusses (Table 2) and presented in the next paragraphs. From these structures the passive modular groups already known are obtained by eliminating a link and the pairs are placed to its adjacent links [3].

Consequently such passive modular group is an open, non-composed linkage with an even number of links. An optimal structure used either for a robot arm or for a leg of a walking robot must contain a minimum number of modular passive groups for the inverse model and also a minimum number of modular groups for the direct model.

Table 1. The bi-mobile planar linkages with nine elements.





2. Numerical structural analysis and synthesis relations

The numerical analysis of the planar linkages was mainly developed by Christian Pelecudi in his reference book entitled "Mechanisms Analysis Bases" published by the printing house of the Romanian Academy in 1967. He used the contributions of F.R.E.Crossley [5] and N.I.Manolescu [6] in the field of the mechanisms structure.

The linkage is an assembly of links connected by kinematic pairs. The degree of freedom for a linkage is calculated as the difference between the degrees of freedom of the elements considered free and the connected conditions imposed by kinematic pairs.

For the fundamental linkage (linkage included only pairs with two restrictions in the relative motion of links) with n links and c lower pairs the degree of freedom L is given by

$$L = 3n - 2c \quad (1)$$

The links and the independent loops are defined by their class imposed by the number of the adjacent pairs. Consequently the number n of links and the number c of pairs are the following:

$$n = \sum_{i=2} n_i \quad ; \quad c = \frac{\sum_i i n_i}{2} \quad (2)$$

From (1) and (2) the degree of freedom L becomes

$$L = n_2 - \sum_{i=4} (i-3) n_i \quad (3)$$

The number N of the independent loops for a linkage is given by the ciclomatic number of the associated graph

$$N = c - n + 1 \quad (4)$$

and by using (2) and (3) one may obtained

$$N = 1 + \frac{1}{2} \sum_{i=3} (i-2) n_i \quad (5)$$

The previous relations reveal the following conclusions:

- the total number of the odd classes elements is an even number, that is $\sum_{k=1} n_{2k+1} = 2h$
- the degree of freedom L is independent relative to the number of the ternary elements

The general equations for the systematization of planar linkages have the following forms:

$$n = 2(N-1) + L = 2N + M + 1$$
$$c = 3(N-1) + L = 3N + M \quad (6)$$

$$n_2 - L = \sum_{i=4} (i-3)n_i$$
$$n - L = \sum_{i=3} (i-2)n_i = 2(N-1) \quad (7)$$

The mobility degree M of a linkage or a mechanism expresses the degree of freedom relative to one of its own link being L-3=M.

The solutions of the equations (7) are positive integers [4] and consequently the following relations are relevant for the structural synthesis of the planar linkages regardless their degree of freedom.

$$n > n_2 \geq L > 0 \;; \qquad \min\left[n, \frac{n_2 - L}{i-3}, \frac{n-L}{i-2}\right] \geq n_i \geq 0 \quad i \geq 3 \quad (8)$$

For the linkages with M=0 and L=3 the following relations [4] are deduced

$$n = 2N + 1 \qquad c = 3N \quad (9)$$

and by using (7) one may obtain

$$n_2 - 3 = \sum_{i=4} (i-3)n_i \;; \qquad n - 3 = \sum_{i=3} (i-2)n_i = 2(N-1) \quad (10)$$

The relations (7) may be written as

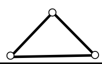
$$n - 1 = 2N + M \quad ; \quad c = 3N + M \quad (11)$$

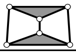
and $m = 2N + M \qquad c = 3N + M$ (12)

where m is the number of the mobile elements, $(m = n - 1)$ and $N > 0$, $M \geq 0$.

The relations (12) and (10) have been used to systematization the linkages with M=0 and N=1, 2, 3, 4 known as Baranov trusses (Table 2).

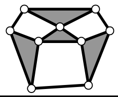
Table 2. Baranov trusses (BT) and their characteristics .

	n	n_2	n_3	n_4	n_5
	3	3	0	0	0
BT1					
	5	3	2	0	0
BT2					

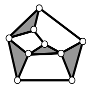


7	**3**	**4**	**0**	**0**

BT3

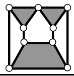


BT4



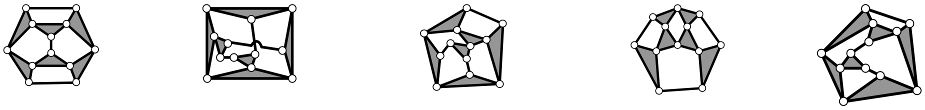
7	**4**	**2**	**1**	**0**

BT5



9	**3**	**6**	**0**	**0**

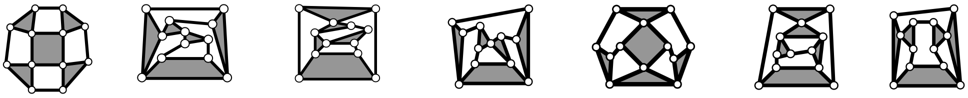
BT 6 **BT 7** **BT 8** **BT 9** **BT 10**



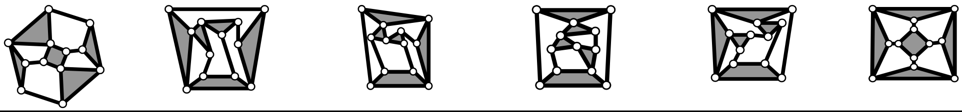
BT 11 **BT 12** **BT 13** **BT 14**

9	**4**	**4**	**1**	**0**

BT 15 **BT 16** **BT 17** **BT 18** **BT 19** **BT 20** **BT 21**



BT 22 **BT 23** **BT 24** **BT 25** **BT 26** **BT 27**

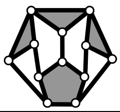


9	**5**	**2**	**2**	**0**

BT 28 **BT 29** **BT 30** **BT 31**

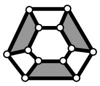
9	**5**	**3**	**0**	**1**

BT 33



9	**6**	**0**	**3**	**0**

BT 32



The following relations for a linkage relative to the number N of the independent loops may be written [4, 5]

$$N = N_4 + N_5 + N_6 + \ldots + N_i \quad ; \quad c = \frac{4N_4 + 5N_5 + \ldots . iN_i + k}{2} \tag{13}$$

where

N_i - the number of independent loops having the i class;

c – the number of the lower pairs in a linkage;
k – the class of the external loop for a linkage.
Having in view the relations for the degree of mobility M and the number of the independent loops N one may deduce

$$2M = -2N_4 - N_5 + N_7 + 2N_8 + \ldots + (i-6)N_i + k \tag{14}$$

$$2(N+M) = N_5 + 2N_6 + 3N_7 + \ldots + (i-4)N_i + k \tag{15}$$

From equation (15) it is noted that total number of loops having odd class and including the external contour is even, that is $N_5 + N_7 + \ldots\ldots = 2h$.

The degree of mobility M is independent of the number N_6 of the class 6 loops (17), and the sum N+M is independent of the number N_4 for the class 4 loops (15).

From (13,14,15) one may note that the number of loops N_i is less than the smaller of

$$N_i < \min\left(N, \frac{2M + 2N_4 + N_5 - k}{i-6}, \frac{2(N+M) - k}{i-4} \right) \tag{16}$$

In order to determine the maximum class of the external loop $k \geq i$ it is adopted $N_5 = N_6 = \ldots = N_i = 0$ and from (15) it results $N = N_4$ and from (18) it is obtained $k_{max} = 2(N+M)$.

From $M = 3m - 2c$ and $N = c - m$ there are obtained

$$M = c - 3N \qquad \text{or} \qquad M = m - 2N \tag{17}$$

The maximum class of the external loop is limited by the number n of the linkage links, which would be totally placed at the external loop of the linkage and by using (20) it is deduced $k'_{max} = n = 2N + M + 1$ [4,5].

If the linkage is decomposable into separate loops and the reference links contribute to the external loop with several sides then $k''_{max} > k'_{max}$ is obtained. To avoid the decomposable linkages it is necessary that $k_{max} \leq k'_{max}$ or $M \leq 1$.

By analogy for the linkages with M>1 it is adopted $N_6 = N_7 = \ldots = N_i = 0$ and from (15) $N = N_4 + N_5$ is deduced, that is $k_{max} = 2(N+M) - N_5$ up to $M \leq 1 + N_5$ when the linkages with distinct parts reappear [4].

For M=2 the value $N_5 = 1$ is adopted and consequently the class of the external loop is $k_{max} = 2(N+M) - 1$.

By considering $k_{min} \geq i_{max}$ and $N_{i\,max} \leq N$ the minimum value of the external loop is obtained and having in view (15) $k_{min} \geq 2(N+M) - (k_{min} - 4)N$ is established from which

$$k_{min} \geq 6 - \frac{2(3-M)}{1+N} \tag{18}$$

is deduced.

3. Numerical operators for the structural analysis and synthesis

The numerical solutions of the equations (7) and (8) reveal the following properties [4]:

- from (7) for the linkages with the same degree of freedom L and the same number N of the independent loops and consequently with the same number of links n and pairs c the solutions are obtained by applying the numerical operator $\pm[1,-2,1]$ or by repeated application of the derived operators to the first ones, that is $\pm[1,-1,-1,1]$. For Baranov trusses (with M=0 and L=3) with relations (11) there are obtained the solutions (Table 3) by applying the previous operators.

Table 3. Numerical element solutions for Baranov trusses.

n	n_2	n_3	n_4	n_5	Numerical operator			
					n_2	n_3	n_4	n_5
3	3	0	0	0	-			
5	3	2	0	0	-			
7	3	4	0	0	1	-2	1	
	4	2	1	0				
9	3	6	0	0	1	-2	1	
	4	4	1	0	1	-2	1	
					1	-1	-1	1
	5	2	2	0	1	-2	1	
	5	3	0	1				
	6	0	3	0				

- for linkages with different degrees of freedom and the same number N of the independent loops the same solutions for $n_3, n_4, ..., n_i$ are obtained from (7). The number of binary elements n_2 must vary in the same direction as the difference of degrees of freedom.
- from (7) it is also noted that for the same number of independent N contours are the same number of possible variants of linkages regardless their degree of freedom.
- for linkages with the same degree of freedom L and N + 1 number of independent loops the solutions (7) are obtained from the lower class by raising the two units of the total number of elements or respectively ternary elements by applying the operators [4,5].

The first solutions in positive integers are determined considering

$$n_4 = n_5 = ... = n_i = 0 \tag{19}$$

and by means of (7)

$$n_{2\min} = L \quad \text{and} \quad n_3 = n - L = 2(N-1) \tag{20}$$

The last solution is obtained from (8) as follows:

$$n_{2\max} = n\,,\; n_3 = n_4 = ... = n_i = 0 \qquad \text{and} \qquad n_{2\max} = n_{2\min}\,;$$

$n_{2\max} = n - 1$ require to have a single element class i >2 with the maximum value $i_{\max} = 2N$;

$n_{2\max} = n - 2$ requires only two elements of class i >2, j >2 corresponding to the $i_{\max} + j_{\max} = 2(N+1)$.

If $i_{\max}$ <N+1 then it follows $j_{\max}$ >N+1, but for the links of the same class $i_{\max} = j_{\max} = N + 1$.

4. New passive modular groups for the inverse structural models of bi-mobile mechanisms

A bi-mobile mechanism deduced from linkages with 9 links and three loops (Table 1) may have an inverse model constituted by the following passive modular groups formed by: 2+2+2+2, 2+4+2, 2+2+4, 4+2+2, 4+4, 2+6, 6+2 or 8 elements [2].

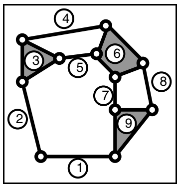
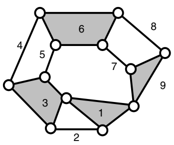
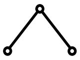
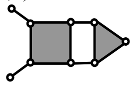
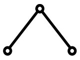
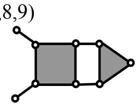
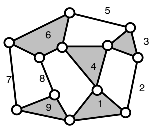
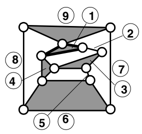
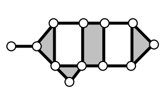
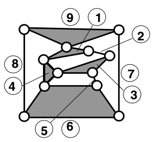
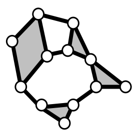
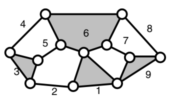
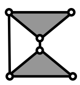
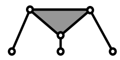
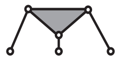
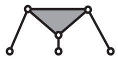


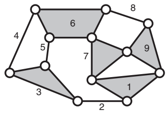
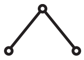
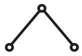
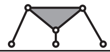
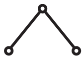
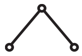
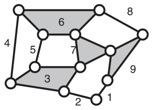
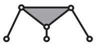
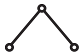
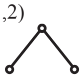
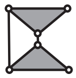
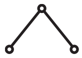
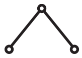
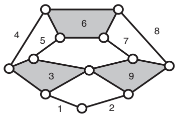
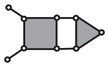
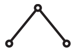
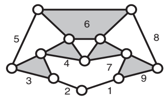
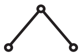
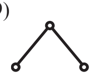
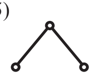
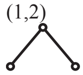
Fig. 1. The adopted linkage for a bi-mobile mechanism.

Most of these variants are found for the linkage L33 (Fig. 1) which has 12 distinct solutions for the basis and the effector (Table 4).

Table 4. The inverse structural models for L33.

No.	Basis – effector (Fig. 1.)	Inverse model	Passive modular groups			
1.	1-3		(2-3)		(4,5,6,7,8,9)	
2.	3-1		(1-2)		(4,5,6,7,8,9)	
3.	1-4		BT 17		→	 (2,3,4,5,6,7,8,9)
4.	4-1		BT 17		→	 (1,2,3,5,6,7,8,9)
5.	1-6		(6,7,8,9)		(2,3,4,5)	
6.	6-1		(1,7,8,9)		(2,3,4,5)	

7.	1-7		(7,9) 	(6,8) 	(2,3,4,5) 
8.	7-1		(1,9) 	(6,8) 	(2,3,4,5) 
9.	3-7		(4,5,6,7) 	(8,9) 	(1,2) 
10.	7-3		(3,4,5,6) 	(8,9) 	(1,2) 
11.	3-9		(4,5,6,7,8,9) 	(1,2) 	
12.	4-7		(6,7)  (8,9) 	(3,5) 	(1,2) 

By adopting the basis 4 and the effector 1 for which the 8 elements passive modular group is used in its inverse structural model the following constructive solution possible applied for a mobile platform [7] is given in Fig. 2.

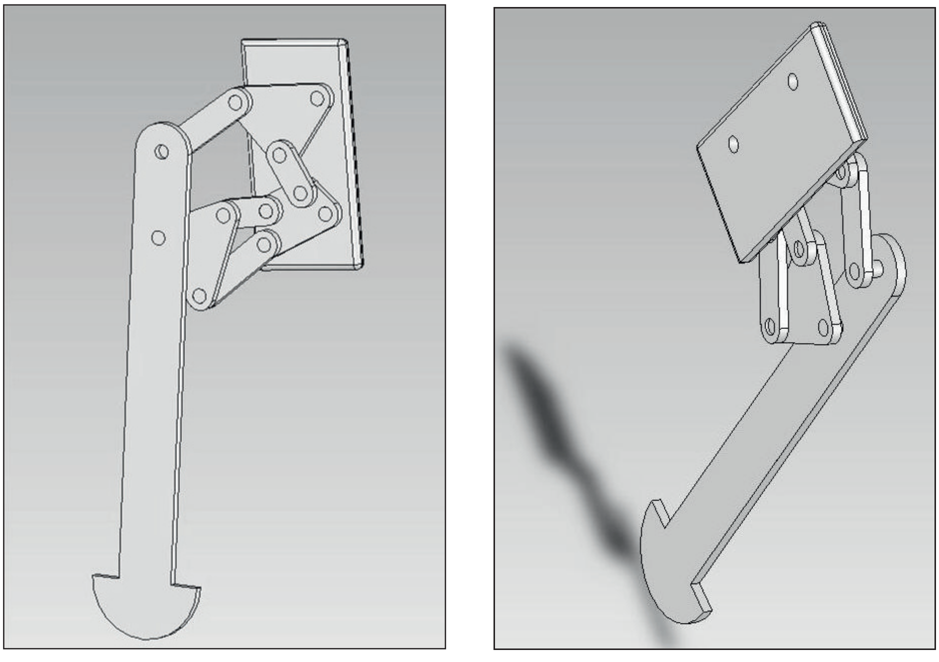


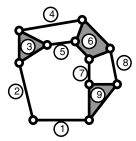
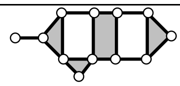
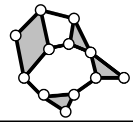
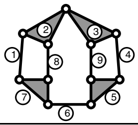
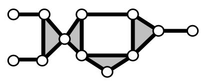
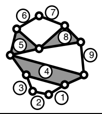
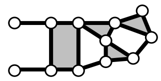
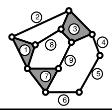
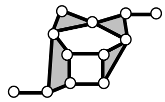
Fig. 2. The constructive solution for a mobile platform leg.

By applying to all linkages from Table 1 the method for the structural design of bi-mobile mechanisms [2] the

Baranov truss BT 17 is involved in five new passive modular groups with eight links.

In the next table there are mentioned these new groups.

Table 5. The passive modular groups from the Baranov truss BT 17.

Baranov truss	Linkage	Basis/ effector	Passive modular groups with 8 links
BT 17	**L33** 	1/4	
		4/1	
	L29 	1/5	
	L36 	2/6	
	L34 	5/9	

Conclusion

The paper brings in attention some aspects connected to the structural synthesis of bi-mobile planar mechanisms. This class of mechanisms is applied in robotics for robot-arms or legs-pedipulators for walking or stepping robots. The inverse structural models are based on the passive groups [1, 2] obtained from structures named Baranov trusses with zero degrees of mobility. The theoretical approach implies the numerical analysis generally made on planar linkages and especially on Baranov trusses and the generation of some new passive groups similar to those mentioned in the literature. The paper also includes suggestive constructive applications. In the next future all these new structures will be included in a scientific data basis.

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