MORPHOLOGICAL CHOICE OF PLANAR MECHANISMS IN ROBOTICS

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Abstract: In this paper a morphological confined choice for kinematic mechanisms in robotics is presented. It is based on symmetries of structures. Pairs of groups of mutually symmetrical mechanisms are detected. Thus, the number of possible configurations is confined by eliminating the symmetrical ones. Different cases of symmetries have been studied. Expressions for the calculation of the number of frames and end-effectors are presented. It enables the reduction of the number of structures by avoiding those that are isomorphic. Following this, examples for applications for various kinematic structures are presented, enabling the field of research to be restricted to the possible solutions.

1 INTRODUCTION

The choice of a kinematic mechanism applied in robotics is conditioned by the number of degrees of freedom of the task to be carried out by the robot. The task itself imposes a kinematic chain compatible with its number of degrees of freedom. The kinematic chain thus imposed will be compatible with the task if it possesses a number and type of links and joints as those defined by the mobility and connection laws of Mechanism and Machine Theory (MMT). MMT supplies lists of possible mechanisms. As there may be a large number of these mechanisms, it is usually difficult to make a choice amongst the available structures in the initial design phase of the robot chain. In fact taking into account the symmetries it can be noticed that there are a significant number of isomorphic structures as far as the position of the frame and of the end-effector of the robot. MMT contributed greatly to planar and spatial mechanism synthesis with different degrees of freedom (Hervè, 1982).

The morphological (topological) synthesis of kinematic chains has, for a long time, been the subject of many papers. There are different methods for the kinematic synthesis of planar chains with simple revolute joints, with different degrees of mobility and different numbers of links and joints. These methods which enabled the lists of chains, called A_i lists, to be obtained are: intuition and inspection (Crossley, 1964), graph theory (Dobrjanskyi 1967, Woo 1967). Others consist of transformation of binary chains (Mruthyunjaya 1984a, Mruthyunjaya 1984b) the concept of Assur groups (Manulescu, 1987), or Franke's notation (Davies 1966, Crossley 1966). New methods based on genetic algorithms or neuronal networks are also used (Chedmail 1995, Yannou 1997). These A_i lists are subdivided into many sub-lists, called B_i, taking into account the position of the frame and of the end-effector of the robot.

The problem is how to choose amongst the possible structures provided by MMT as far as the position of the frame and the end-effector. The objective is to find planar mechanisms with revolute joints that provide guidance of a moving frame e.g. the end-effector of an industrial robot, relative to a base frame with a given degree of freedom. The aim of this paper is to present a new method enabling the reduction of the number of kinematic structures provided by the MMT which are suitable for robotics applications. It is based on the exploitation of symmetries of the mechanisms. The sub-lists B_i are then studied in order to extract the minimum number of possible structures for the initial design of kinematic chains of industrial robots, the two criteria being the position of the frame and of the end-effector of the robot.

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2 NOTIONS AND RESTRICTIONS

MMT proposes various ways of representing kinematic structures. The most common, the kinematic graph, consists in conserving a shape for the links in order to better appraise the topology of the structure. Nevertheless this presentation is difficult to manage. Any kinematic structure may by transformed into Crossley's inverse graph (Crossley, 1964) replacing every link (binary, ternary…) by a point. The joints themselves are represented by a line linking the points concerned. We note that the kinematic graph expresses geometrical dimensions. Obviously the inverse graph does not. But this letter expresses better the symmetries of the structures if there are any.

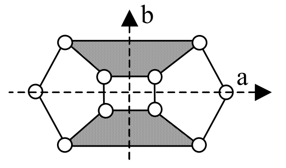
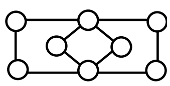
kinematic graph	inverse graph
	

Figure 1: Representation of a structure by kinematic and Crossley's inverse graph.

A robot being a complex mechanical system (MS) characterised by a very important interaction between its links, we define its architecture by (Mitrouchev 1999): *the main structure*, which generates the main motion of the robot and upon which, stands the rest of the MS, *the regional structure*, consisting of the arm and the forearm of the robot (mechanical arm) and the *local structure* usually consisting of three axes concurrent at one point, and representing the wrist of the robot.

It is noted at this stage that the structure presented by one or other ways (kinematic or inverse graph) only presents the main structure of the robot (cf. fig. 2).

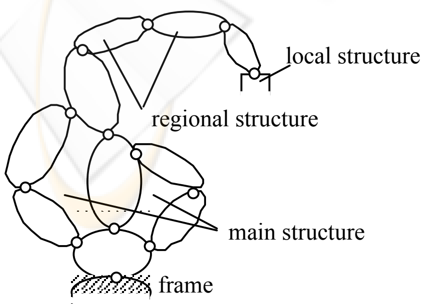


Figure 2: Topological structure of a robot.

Let us consider a mechanism with M degree of mobility, N links of any type, joined to each other by C simple revolute joints. In this paper only mechanisms having main planar structures with simple revolute joints usually applied in robotic design will be studied. We note that the objective is not to find among the mechanisms available a particular one that fits well to a given task, but to reduce the number of possible structures, the two criteria being the position of the frame and the end-effector of the robot.

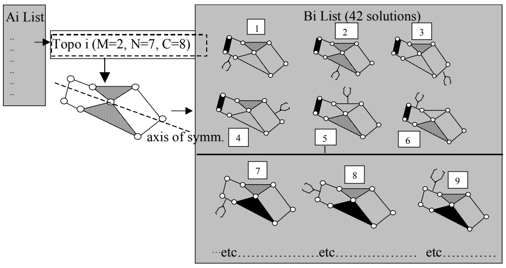
3 MECHANISM DESIGN

MMT, being a part of the technological sciences, is at the base of mechanism design in robotics. The question is: amongst the available kinematic structures supplied by MMT, how many of these are suitable for application in kinematic chain design in robotics? In order to reply to the above question it is interesting to answer the following questions: why and how?

Why ? Obviously it is not possible to dimension a mechanism without being familiar with its topology. The topological choice is normally made before the dimensioning phase. It is this stage that presents the most difficult problem in mechanism synthesis. It is currently impossible to place the dimensioning equations on the same level as the choice of topology, because this choice is not governed by equations i.e. assigning design variables for this or that topology, except for: degree of mobility M, number of links N and number of joints C (e.g. M=2, N=7 and C=8).

How? Let us consider a list of mechanisms provided by MMT and defined by the three following parameters : number of links, number of joints and number of degree of freedom. As we said, we call this list A_i list. We define also the B_i list, issued from an A_i list taking into account the position of the frame and of the end-effector. The problem is to decide which structures may be removed from the A_i list, without restricting the choice of available structures taking into account the position of the frame and of the end-effector.

Let us consider an A_i list of P topologies Topo i extracted from a complete list of mechanisms with respect to some parameters (e.g. mechanisms with two degrees of mobility M=2, seven links N=7 and eight joints C=8). Firstly from this list, B_i sub-lists are extracted with respect to criterion 1 "fixing a frame" or "frame choice". Then each topology Topo i gives several possibilities for attaching an end-effector (pincers, paint gun, welding electrode). This is the second criterion "fixing an end-effector" or "end-effector choice" with regard to the choice of the frame used in the elaboration of the confined B_i lists. For example, the B_i list of fig. 3 below, contains N.(N-1)=7.6 = 42 possible solutions but it is noted that some of them appear twice: solutions 1 and 6, 2 and 5, 4 and 3 for the first possibility to fix a frame. For the other possibilities it is reasonable to suppose that there will be other dual (isomorphic) solutions.



key: black element – frame; —⊂ - end -effector

Figure 3: Elaboration of the B_i list.

4 PROPOSED METHOD

We indicate by:
- N_{sc} number of the links of a sub-chain,
- n_c the number of links cut by an axis of symmetry coincident with their axis of symmetry,
- n_{nc} the number of links not cut by an axis of symmetry or cut, but not along their axis of symmetry,
- n_a the number of links cut solely by the axis of symmetry a (cf. fig. 4 and figures below), or the number of links containing the centre of symmetry in the case of a central symmetry,
- n_b the number of links cut solely by the axis of symmetry b,
- n_{ab} the number of links cut both by the axes of symmetry a and b,
- s the number of symmetries .

In order to present the method, various cases will be demonstrated with respect to their type and to their number of symmetries.

4.1 Different cases of symmetries

4.1.1 No symmetry

The simplest case is the one without any symmetry (fig. 4a.). In this case there are N possibilities to fix the frame. Thus Fc = N. Concerning the position of the end-effector there are (N-1) possibilities to attach it for each position of the frame. Thus to each frame choice belong (N-1) end-effector choices.

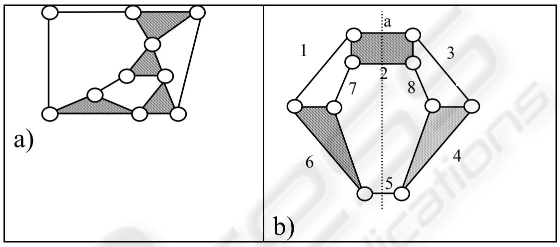


Figure 4: Structures without and with symmetries.

The structure of fig. 4a. above has the peculiarity of having no symmetry, then:

$$Fc = N \qquad (1)$$

and

$$Ec = N(N-1) \qquad (2)$$

4.1.2 Only one symmetry

We define the axis of geometrical symmetry in the kinematic graph like the axis of topological symmetry in the inverse graph. If a link is cut by an axis of symmetry in the kinematic graph, the same link is cut by the same axis (called axis of topological symmetry) in the inverse graph.

Many mechanisms, like the structure in fig. 4b., have one axis of symmetry noted “a”. There are two sub-chains 1276, 2348 and each of them has a symmetry of links 1 and 7 for the furst sub-chain 1276 and 3 and 8 for the second one (2348). As regards the position (choice) of the frame Fc, symmetry dictates that the case where the frame is on link 1 is the same as the cases when it is on 3, 7 or 8. It is the same for the links 6 and 4. Therefore an inventory of two possibilities (solutions) are taken to which must be added the two possibilities: links 2 and 5. The latter two have the particularity of being cut by the axis of symmetry. The first two possibilities correspond to $((N-n_c)/2)-1$ solutions, consequently for Fc we have:

$$Fc = \frac{N + n_c}{2} \qquad (3)$$

Concerning the number of possibilities for the attachment of an end-effector Ec, as a function of the frame position:
- in the case where the frame is not situated symmetrically, the number of possibilities for the attachment of an end-effector is (N-1),
- in the case where the frame is placed symmetrically, the same problem as the one treated previously is found; that is to say the positions 1,3,7 and 8 are identical, as are 6 and 4. Consequently there are $(N-n_c)/2+(n_c-1)$ possibilities for Ec.

It should be noted that the number of cases when the frame is placed symmetrically corresponds to the number of the links cut by the axis of symmetry. Thus for Ec we have:

$$Ec = \frac{N - n_c}{2}\left(N - 1\right) + n_c\left(\frac{N + n_c - 2}{2}\right) \qquad (4)$$

4.1.3 Two symmetries

Two cases are to be considered for the two symmetries.

4.1.3.1 None of the links are cut by an axis of symmetry

The structure in fig. 5a below has two axes of symmetry but they do not cut each other in a link. As regards the choice of frame Fc:
- in the case of a link that is not cut, each link is found four times by the system of symmetries, for example links 2-1-4-5,

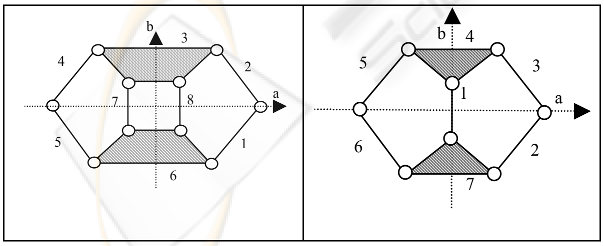


Figure 5: Structures with two symmetry.

- in the case of a link, which is cut, each link is found twice, for example 7-8, 3-6, thus:

$$Fc = \frac{n_{nc}}{4} + \frac{n_a}{2} + \frac{n_b}{2} = \frac{N + n_c}{4} \qquad (5)$$

Then, as regards choice Ec, working in discriminately with symmetry a or b, requires two identical methods (reflections):
- in the case where the frame is not situated symmetrically, the number of possibilities to attach the end-effector is (N-1), so there are $n_{nc}/4$ cases thus described,
- in the case where the frame is placed symmetrically with respect to symmetry a, the number of possible solutions for the attachment of an end-effector is $(N-n_a)/2+n_a-1$, so there are $n_a/2$ cases thus described.

Finally, after simplification, for Ec we have:

$$Ec = \frac{N - n_c}{4}(N - 1) + \frac{n_a}{2}\left(\frac{N + n_a - 2}{2}\right) + \frac{n_b}{2}\left(\frac{N + n_b - 2}{2}\right) \qquad (6)$$

4.1.3.2 Links are cut by two axes of symmetry

The structure of fig. 5.b has two axes of symmetry that cross on a link. To fix the frame the same reasoning as in the previous case can be adapted, taking care to add the links cut by *a* and *b* symmetries which are counted neither in n_a nor in n_b, consequently:

$$Fc = \frac{N + n_c + 2n_{ab}}{4} \qquad (7)$$

It is the same process concerning the position of the end-effector:

$$Ec = \frac{N - n_c}{4}(N - 1) + \frac{n_a}{2}\left(\frac{N + n_a - 2 + n_{ab}}{2}\right) + \frac{n_b}{2}\left(\frac{N + n_b - 2 + n_{ab}}{2}\right) + n_{ab}\left(\frac{N + n_a + n_b + 3n_{ab} - 4}{4}\right) \qquad (8)$$

4.1.4 Central symmetry

This is the case for the structure below. To fix the frame, the difference between two cases must be made:

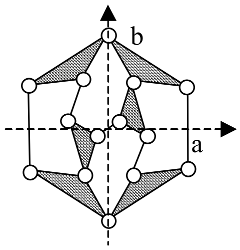


Figure 6: Structure with central symmetry.

- the centre of symmetry belongs to n_c links, so there are $(N-n_c)/2+n_c$ possibilities,
- the centre of symmetry does not belong to a link, so there are N/2 possibilities.

Finally for Fc we have:

$$Fc = \frac{N + n_c}{2} \qquad (9)$$

As regards the Ec choice we have:

$$Ec = \frac{N - n_c}{2}(N-1) + n_c\left(\frac{N + n_c - 2}{2}\right) \qquad (10)$$

We can note that the equations (9) and (10) are the same as the equations (3) and (4).

4.1.5 Three or more symmetries

Only one case of three symmetries is present in the mechanisms studied (cf. fig 7.). This is the number 60 mechanism of the A_i list of mechanisms, with M=3, N=10 and C=12.

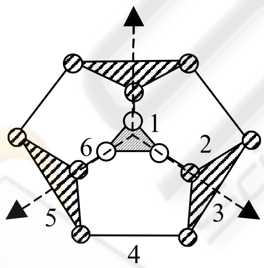


Figure 7: Structures with three symmetries.

In this particular case there are three symmetrical sub-chains (1,2,3,4,5,6) with s=3. As regards the position of the frame Fc (frame choice), we can note that each sub-chain contains two symmetrical triples of links (1,3,5 and 2,4,6) which correspond to (N_{sc}/s) solutions. Consequently for Fc we have: Fc= (N_{sc}/s)=2.

In order to fix the end-effector, for a given position of the frame, there are $(N_{sc}-1)-n_{sc}$ solutions. Consequently for the Fc positions of the frame we have : $E_c=F_c[(N-1)-n_{sc}]=12$ positions of the end-effector.

5 GENERAL CASE

It is possible to bring together most of the equations above in one equation as regards Fc and Ec. It is only necessary to add the variable *s* indicating the number of symmetries. As a result it is relatively easy for the choice of the frame to present only one formula for the cases studied above.

$$Fc = \frac{N + n_c + 2n_{ab}}{2s} - 1, \quad s = 1,2 \qquad (11)$$

For the choice Ec:

$$Ec = \frac{N - n_c}{2s}(N-1) + \frac{n_a}{2s}\left(N + n_a - 2 + n_{ab}\right) + \\ + \frac{n_b}{2s}\left(N + n_b - 2 + n_{ab}\right) + n_{ab}\left(\frac{N + n_a + n_b - n_{ab}}{2s}\right)$$

$$s = 1, 2 \qquad (12)$$

Only one case is different, this is the case without symmetry (s = 0) because the equations (11) and (12) have no mathematical significance. Thus it is found that the two equations as far as the cases without symmetries are mainly the equations *(1)* and *(2)*.

6 EXAMPLES FOR APPLICATIONS

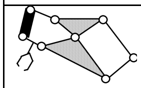
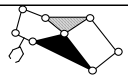
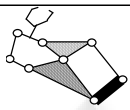
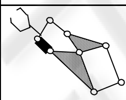
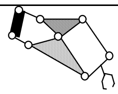
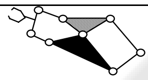
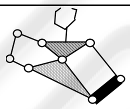
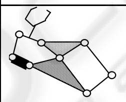
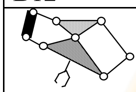
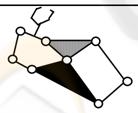
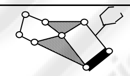
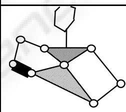
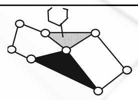
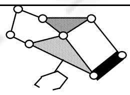
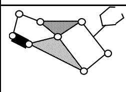
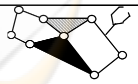
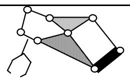
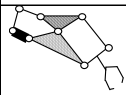
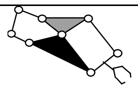
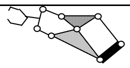
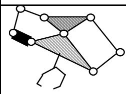
In order to illustrate the expressions thus presented, they are applied for some structures with different degrees of mobility. As has already been said, the proposed help does not allow the optimum solution to be found, but reduces the field of research for this solution. This is what will be shown by the following examples applied to descriptions of the main structures of industrial robots.

6.1 Structures with two degrees of mobility, seven links and eight joints

Let us consider the structure below found on an A_i list provided by MMT with M=2, N=7 and C=8. The B_i list contains N(N-1) = 7.6 = 42 solutions (cf. fig. 3). Firstly the description file N=7, s=1, n_a=1, n_b=0, n_{ab}=0, n_c=1 is established. The created program computes the the Fc and Ec variables. When there is a central symmetry and not an axial one, this is noted as a note in the respective line of the tables. The confined B_i list contains Ec=21 solutions, where the four possibilities for Fc are distinguished (cf. Table 1)

Amongst the twenty one possibilities, solution number B23 from the table below was chosen by a robot manufacturer in order to design the main structure of the AKR-3000 robot presented in fig. 8 (Ferreti, 1981). In this case the frame was transformed in to a quaternary link and the binary link, where the end-effector was attached, in to a ternary one.

Table 1: Confined Bi list of structures with two degrees of mobility, seven links and eight joints

List B1	List B2	List B3	List B4
 B11	 B21	 B31	 B41
 B12	 B22	 B32	 B42
 B13	 B23	 B33	 B43
	 B24	 B34	 B44
	 B25	 B35	 B45
	 B26	 B36	 B46

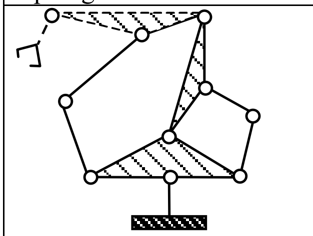
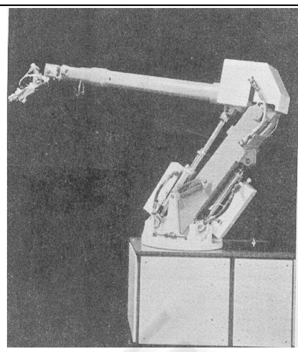
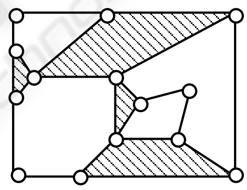
topological structure	AKR-3000 robot
	

Figure 8: AKR-3000 robot.

6.2 Structures with two degrees of mobility, eleven links and fourteen joints

The kinematic graph for a structure from an A_i list created by MMT (M=2, N=11, C=14) is presented below (description file N=11, s=0, n_a=0, n_b=0, n_{ab}=0). The Excel table gives the following results: Fc=11 and Ec=110.



Amongst the one hundred and ten available structures, a robot manufacturer has applied one solution in order to design the main structure of the Andromat robot presented below.

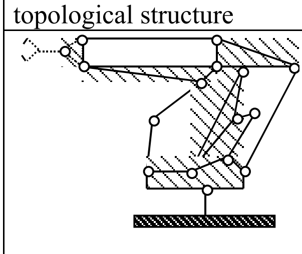
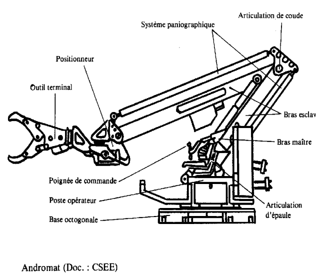
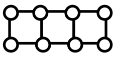
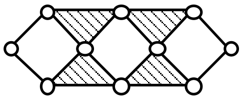
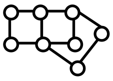
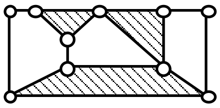
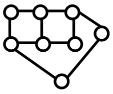
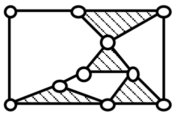
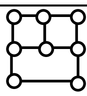
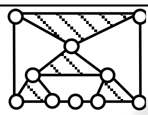
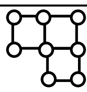
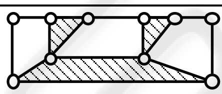
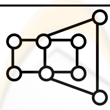
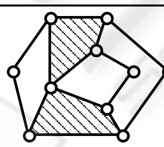
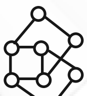
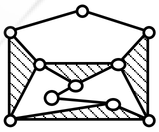
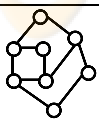
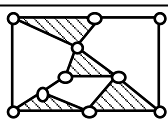
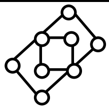
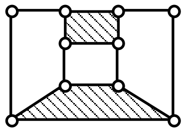
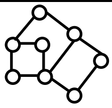
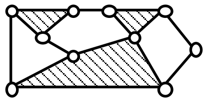
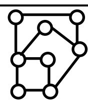
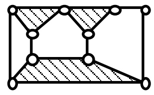
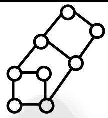
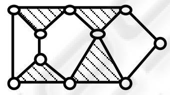
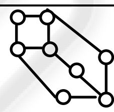
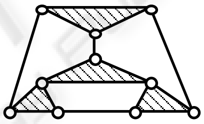
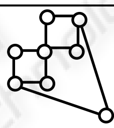
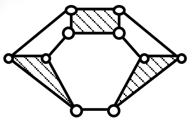
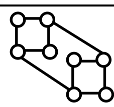
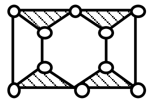
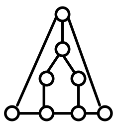
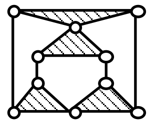
topological structure	Andromat robot
	

Figure 9: Topological structure of Andromat robot.

6.3 Structures with one degree of mobility, eight links and ten joints

The table below groups the A_i list of the sixteen kinematic structures with one degree of mobility represented by their kinematic and inverse graphs and their description files.

Table 2: A_i list of structures with one degree of mobility, eight links and ten joints.

notat.	inverse graph	kinematic graph	descrip. file
G1-8[1]			N=8, s=2, n_a=0, n_b=0, n_{ab}=0
G1-8[2]			N=8, s=0, n_a=0, n_b=0, n_{ab}=0
G1-8[3]			N=8, s=0, n_a=0, n_b=0, n_{ab}=0
G1-8[4]			N=8, s=1, n_a=2, n_b=0, n_{ab}=0
G1-8[5]			N=8, s=1, n_a=2, n_b=0, n_{ab}=0
G1-8[6]			N=8, s=1, n_a=0, n_b=0, n_{ab}=0
G1-8[7]			N=8, s=1, n_a=4, n_b=0, n_{ab}=0
G1-8[8]			N=8, s=0, n_a=0, n_b=0, n_{ab}=0
G1-8[9]			N=8, s=2, n_a=2, n_b=2, n_{ab}=0
G1-8[10]			N=8, s=0, n_a=0, n_b=0, n_{ab}=0
G1-8[11]			N=8, s=0, n_a=0 n_b=0, n_{ab}=0
G1-8[12]			N=8, s=1, n_a=2, n_b=0, n_{ab}=0
G1-8[13]			N=8, s=1, n_a=2, n_b=0, n_{ab}=0
G1-8[14]			N=8, s=1, n_a=2, n_b=0, n_{ab}=0
G1-8[15]			N=8, s=2, n_a=4, n_b=0, n_{ab}=0
G1-8[16]			N=8, s=1, n_a=2, n_b=0, n_{ab}=0

The possible choices for the frame and the end-effector obtained by the proposed method are presented in table 3.

6.4 Other examples

An application under Silicon Graphics /UNIX has been created based on the method presented. Enabling the restriction of the number of structures it is applied to other structures as examples with:
- one degree of mobility, ten links and thirteen joints,

- two degrees of mobility, nine links and eleven joints ,
- three degrees of mobility, ten links and twelve joints.

In the majority of cases the kinematic structure has axial symmetry. This symmetry is not mentioned in the tables presented. However, the central symmetry (not as much presented in the structures) is mentioned, as previously stated in paragraph 6.1.

Table 3: Frame and the end-effector choices.

Structures with one degree of mobility, eight links and ten joints

n°	N	s	nsc	Nsc	nsp	nc	Fc	Ec
1	8	2	2	4	2	0	2	14
2	8	0	0	0	0	0	8	56
3	8	0	0	0	0	0	8	56
4	8	1	2	4	0	2	5	29
5	8	1	2	4	0	2	5	29
6	8	1	0	0	2	0	3	21
7	8	1	2	5	0	4	2	10
8	8	0	0	0	0	0	8	56
9	8	2	2	5	0	4	3	15
10	8	0	0	0	0	0	8	56
11	8	0	0	0	0	0	8	56
12	8	1	0	0	0	2	5	29
13	8	1	2	5	0	2	6	34
14	8	1	2	4	2	2	4	16
15	8	2	2	4	2	4	3	17
16	8	1	2	5	0	2	5	29
							total	total
							83	518

7 SUMMARY

The method presented in this paper enables the morphological restriction for planar kinematic mechanisms in robotics by avoiding those that are isomorphic. It is based on the exploitation of symmetries. The different cases of symmetry studied provide expressions allowing the number of possible structures to be calculated as regards the position of the frame and of the end-effector. The proposed expressions are then applied to different examples. The results of this study may be useful to robot-designers enabling them to limit the field of research to the possible solutions.

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