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CLASS OF REDUNDANT SERIAL ROBOTS WITH 7 UP TO 12 AXES – DEFINITION, STRUCTURAL SYNTHESIS AND WORKSPACE

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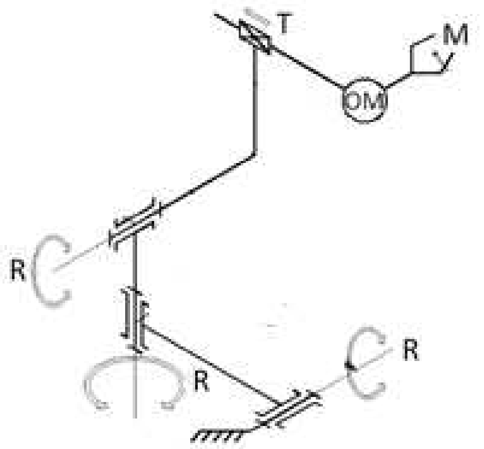
Abstract: *In this paper, for the first time, serial kinematic chains of industrial robots are classified into: minimal serial kinematic chains (6 axes), redundant serial kinematic chains (7 to 12 axes) and hyper-redundant serial kinematic chains (more than 12 axes). Redundant serial robot kinematic chains with 7 till 12 axes are an extension of classical 6-axis ones. The structural synthesis of these structures is useful to provide a working basis, including for the promotion of new structures with 7 or more axes, besides some already existing and applied structures. This paper summarizes kinematic chain structures using a combinatorial method by listing all possible variants of the structures with 7 till 12 axes, obtained by adding a rotational or translational coupling, in a parallel or perpendicular position, against the guiding structure with 6 axes consisting of two distinct modules: positioning module (PM:3 axes) and orientation module (OM:3 axes). Representation of proper workspaces can help the designer in choosing the structure with maximum functionality for a given application.*
Keywords: *industrial robot, structural synthesis, redundant kinematic chain, workspace*

1. INTRODUCTION

In this paper, first we propose the classification of industrial robots serial kinematic chains into: *minimal serial kinematic chains*, *redundant serial kinematic chains* and *hyper-redundant serial kinematic chains*. Minimal kinematic chains, specific to *minimal serial robots*, are kinematic chains with 6 axes of rotation (R) and / or translation (T) in series (3 axes of the positioning kinematic chain: PM, plus 3 axes of the orientation kinematic chain: OM), whose comprehensive structural synthesis and non-degenerate workspaces representation was presented in [1]. Through a minimal kinematic chain, unambiguous positioning and orientation is provided, accurately rigorous, so guiding an object in space, in a three-dimensional orthogonal reference system, Oxyz type(x,y,z are axes and O being the origin point of the reference system). There was a period when it was considered that serial kinematic chains with more than 6 axes are of no interest. They have unnecessary mobility, and increasing dramatically the computation time of the kinematics along the desired trajectories. After this period, we began to make, practically, out of real needs in the industrial production, industrial robots with seven axes, 8 axes, 9 axes and even more axes. One reason is the significant decrease in the calculation duration of the kinematics, due to considerable growth of computing power of computers used, which have evolved a lot in the last 10-15 years in this respect, and therefore significantly costs decrease.
This paper proposes to define the class of *redundant serial kinematic chains of redundant industrial robots* as consisting of those kinematic chains that have series of 7 to 12 axes including axes of rotation and / or translation. We consider the relative positions of perpendicularity or parallelism between these axes, the relative positions of the axes that are characteristic of most industrial robots made so far.
The situations in which between two consecutive axes there is an angles other than 0 or 90 degrees, obviously result therefrom. We limited the number of axes to 12 because thus we get to the doubling of the axes, minimum 6 and so there is a significant redundancy: doubling each axis of a minimal structure. This is a principle used in nature too. Kinematic chains with more than 12 serial axes form *the class of hyper-redundant serial industrial robots*, where the maximum number of axes is not limited and they form the structures of trunk-like and vertebrae-like robots, detailed in [2].

2. STRUCTURAL SYNTHESIS OF REDUNDANT SERIAL INDUSTRIAL ROBOTS

For the structural synthesis of redundant serial industrial robots kinematic chains, we propose as a synthesis method adding one axis of rotation or translation oriented perpendicular or parallel to the corresponding structures of minimal serial industrial robots, respectively reported to positioning modules (PM) or orientation modules (OM), to obtain structures with 12 axes. Keeping the positioning module (PM) and the orientation module (OM), we obtain positioning and orientation in a three-orthogonal space, avoiding getting to degenerate structures that cannot provide these minimum requirements. Another variant of the structural synthesis would be highlighting all possible combinations between 7 couplings, of rotation and / or translation, up to 12 rotation and / or translation couplings' combinations, with perpendicular or parallel relative positions. In this situation, however, we face great complications highlighting all the possible variants and difficulties in identifying the variants that provide positioning and orientation and therefore non-degenerate workspaces. According to the method proposed, 7-axis structures are obtained by adding one T or R axis, perpendicular or parallel to the positioning module (PM) or to the orientation module (OM) of a minimal structure. The structures as follows: R⊥(PM)(OM), R||(PM)(OM) or T⊥(PM)(OM), T||(PM)(OM). By highlighting all possible situations there are 12 redundant structures with 7 axes: R⊥(PM)(OM), R||(PM)(OM), T⊥(PM)(OM), T||(PM)(OM), (PM)⊥R(OM), (PM)||R(OM), (PM)⊥T(OM), (PM)||T(OM), (PM)(OM)⊥R, (PM)(OM)||R, (PM)(OM)⊥T, (PM)(OM)||T. To maintain the structural similarity we consider one reporting of the extra coupling, either to the positioning module or to the orientation module. In Fig. 1a there is an example of structural diagram of a kinematic chain with seven axes, type: R⊥(PM)(OM), respectively, by detailing the structure of the positioning module R ⊥(PM:R⊥R⊥T)(OM). The structures with eight axes are obtained by adding an additional axis R or T in perpendicular or parallel position to the structures with 7 axes obtained in the previous step, resulting in structures such as: R⊥[R⊥(PM)(OM)], R||[R⊥(PM)(OM)], T⊥[R⊥(PM)(OM)], T||[R⊥(PM)(OM)]. By highlighting all possible situations of variants with 8 axes, type: R⊥R⊥(PM)(OM),..., T||T||(PM)(OM), we obtain 96 combinations, 16 for each combination type (R/T)(⊥/||)(R/T)(⊥/||)(PM)(OM), (R/T)(⊥/||)(PM)(⊥/||)(R/T)(OM), (R/T)(⊥/||)(PM)(OM)(⊥/||)(R/T), (PM)(⊥/||)(R/T)(OM)(⊥/||)(R/T), (PM)(⊥/||)(R/T)(⊥/||)(R/T)(OM) and (PM)(OM)(⊥/||)(R/T)(⊥/||)(R/T). In Fig. 1b there is an example of structure with 8 axes, type: R⊥R|| (PM:R||R⊥R)(OM:R⊥ R⊥ R).



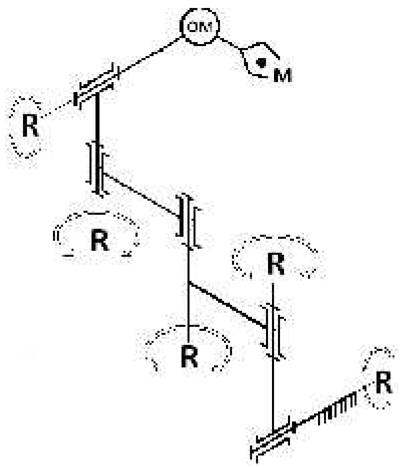
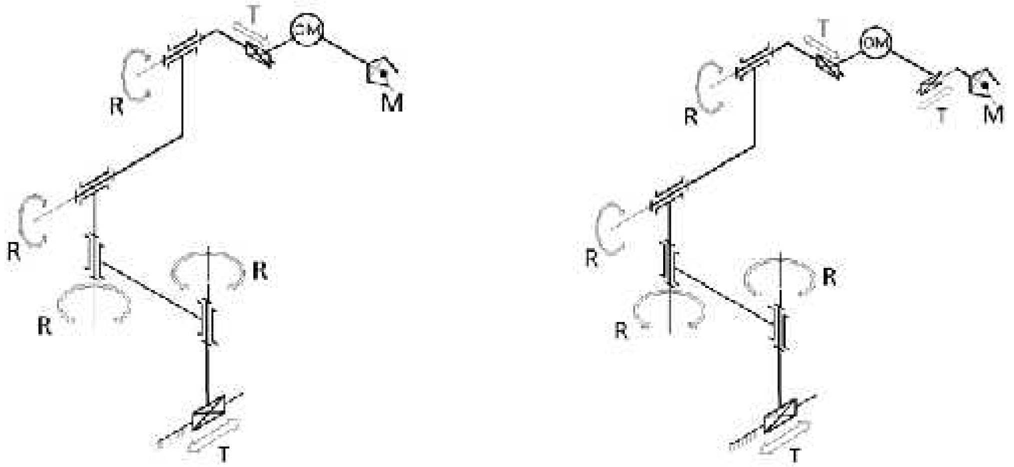


Figure 1: Structural scheme for structure with 7 axes(a) and with 8 axes(b)

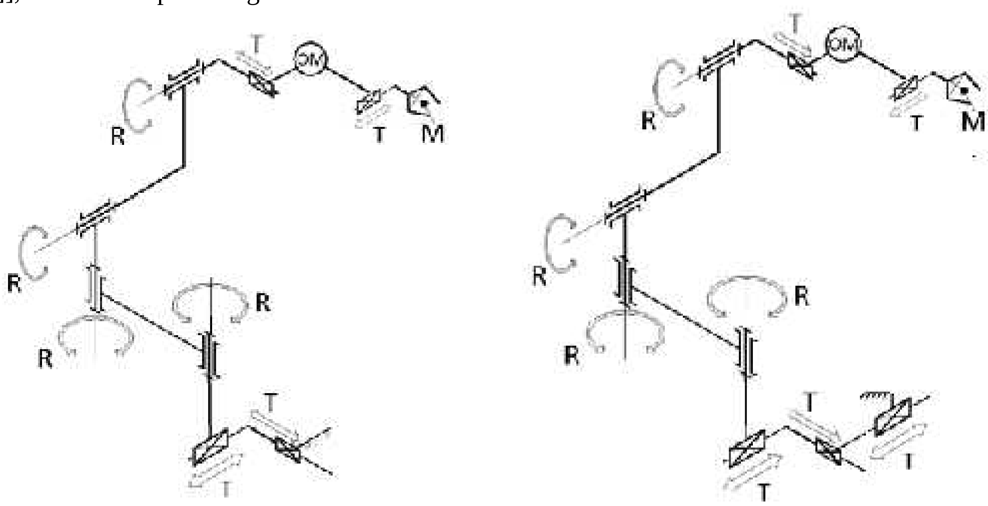
Structures with 9 axes are obtained by adding a further axis of R or T in perpendicular or parallel position to the structures with 8 axes, resulting in structures such as: R⊥[R⊥[R⊥(PM)(OM)]], R||[R⊥[R⊥(PM)(OM)]], T ⊥[R⊥[R⊥(PM)(OM)]], T|| [R⊥[R⊥(PM)(OM)]]. An example of structure with 9 axes is shown in Fig. 2a.
Structures with 10 axes are obtained by adding a further axis of R or T in perpendicular or parallel position to the structures with 9 axes, resulting in structures such as: R⊥[R⊥[R⊥[R⊥(PM)(OM)]]], R||[R ⊥[R⊥[R⊥(PM)(OM)]]], T⊥[R ⊥[R⊥[R⊥(PM)(OM)]]], T||[R ⊥[R⊥[R⊥(PM)(OM)]]]. An example of structure with 10 axes is shown in Fig. 2b.



a b

Figure 2: Structural scheme for structure with 9 axes(a) and with 10 axes(b)

Structures with 11 axes are obtained by adding a further axis of R or T in perpendicular or parallel position to the structures with 10 axes, resulting in structures such as: R⊥[R⊥[R ⊥[R⊥[R⊥(PM)(OM)]]]], R|| [R⊥[R ⊥[R⊥[R⊥(PM)(OM)]]]], T⊥[R⊥[R ⊥[R⊥[R⊥(PM)(OM)]]]], T|| [R⊥[R ⊥[R⊥[R⊥(PM)(OM)]]]], see an example in Fig. 3a.
Structures with 12 axes are obtained by adding a further axis of R or T in perpendicular or parallel position to the structures with 11 axes, resulting in structures such as: R⊥[R⊥[R⊥[R ⊥[R⊥[R⊥(PM)(OM)]]]]], R||[R⊥[R⊥[R⊥[R⊥[R⊥(PM)(OM)]]]]],T⊥[R⊥[R⊥[R⊥[R⊥[R⊥(PM)(OM)]]]]],T||[R⊥[R⊥[R⊥[R⊥[R⊥(PM)(OM)]]]]], see an example in Fig. 3b.



a b

Figure 3: Structural scheme for structure with 11 axes(a) and with 12 axes(b)

The structures of serial redundant robots include all the present robots versions that can move in translational movement along one to three mutually perpendicular axes, if the entire assembly is considered as a whole and all axes are controlled by a unitary computing system.

3. WORKSPACES CORRESPONDING TO SERIAL REDUNDANT INDUSTRIAL ROBOTS

The workspace of industrial robots is generated by possible movements in component couplings. In rotation couplings, to the limit, we can perform a complete rotation movement of 360 degrees, and in translational couplings, we can carry out a translation along a predetermined distance. We exemplify the workspace for a variant of 7-axis serial redundant robot:R⊥(PM: R⊥R⊥T)(OM:R⊥R⊥R) (Fig. 4 a1-a6) and for an 8-axis serial redundant robot: R⊥R||(PM:R||R⊥R)(OM:R⊥R⊥R) (Fig. 4 b1-b7). We considered a rotation of 360 degrees in rotation couplings and translation along predetermined distances limited in translational couplings.

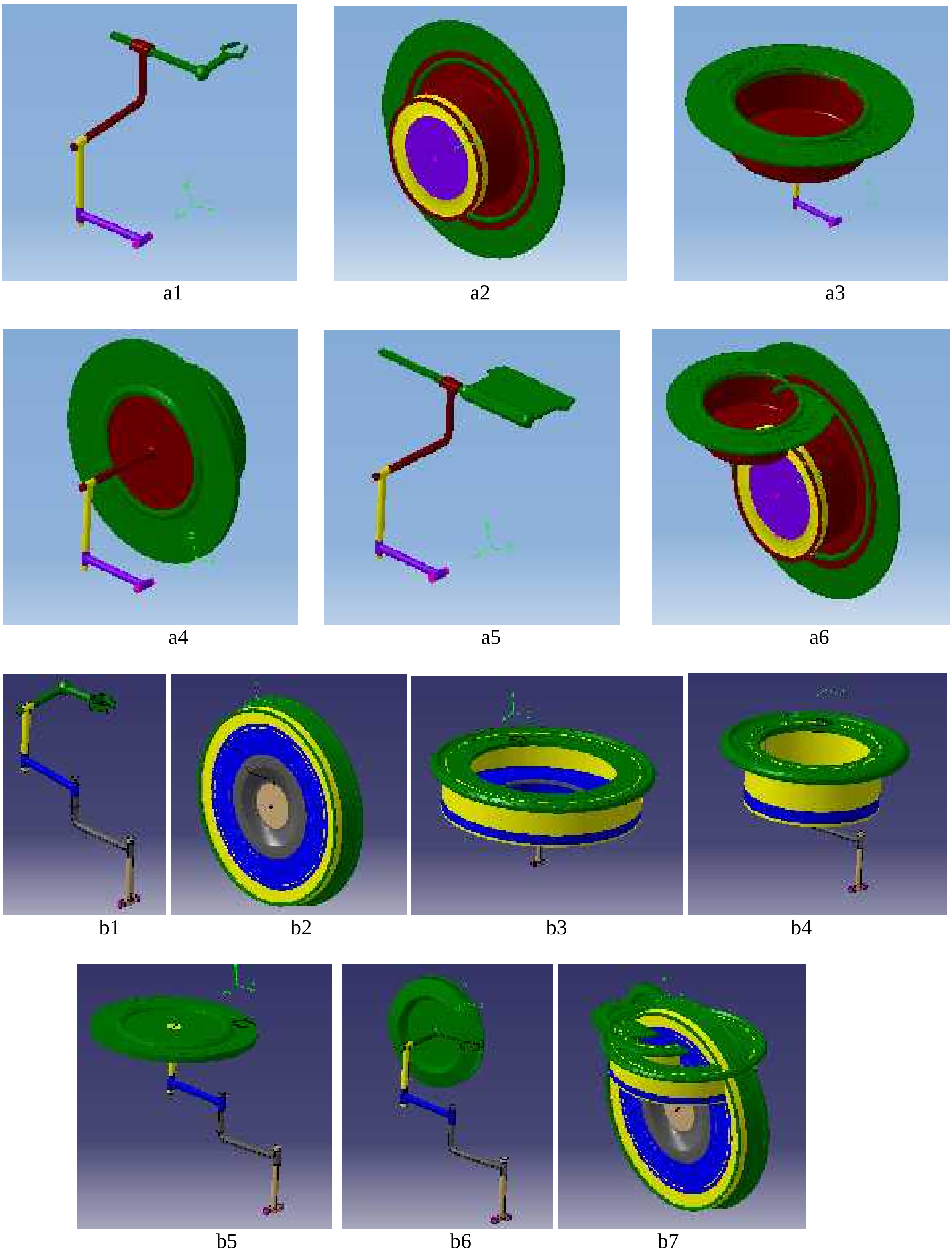


Figure 4: Representations of workspaces of serial redundant industrial robots kinematic chains: with 7 axes: R⊥(PM: R⊥R⊥T)(OM:R⊥R⊥R) (a1-a6), and with 8 axes: R⊥R||(PM:R||R⊥R)(OM:R⊥R⊥R) (b1-b7)

4. EXAMPLES OF SERIAL REDUNDANT ROBOTS WITH 7 OR MORE AXES

So far, there were made and there are already on the market several variants of redundant serial robots with more than 6 axes[3,4,5,6,7,8,9,10,11]. Thus, there is an example of a robot Cloos, with seven axes [10] (Fig. 5a, b), to which it was added a 7th axis(R7). It is a vertical axis of rotation, parallel to the first axis of the positioning kinematic chain, which is of type R⊥R||R, and we obtain a structure of the type: R||(PM:R⊥R||R)(OM:R⊥R⊥R). To this robot, by adding from one to three translation axes, we obtain versions with up to 10 axes, which correspond totally to one of the variants obtained by the structural synthesis proposed in this paper. An example of a 9-axis robot is IGM type: R|| (PM:R⊥R⊥R) ⊥ R(OM: R⊥R⊥R)||R [12] (Fig.5c, d), which, with one to three axes of translation, will have 12 axes, variant that also corresponds to one of the versions obtained through the above structural synthesis.

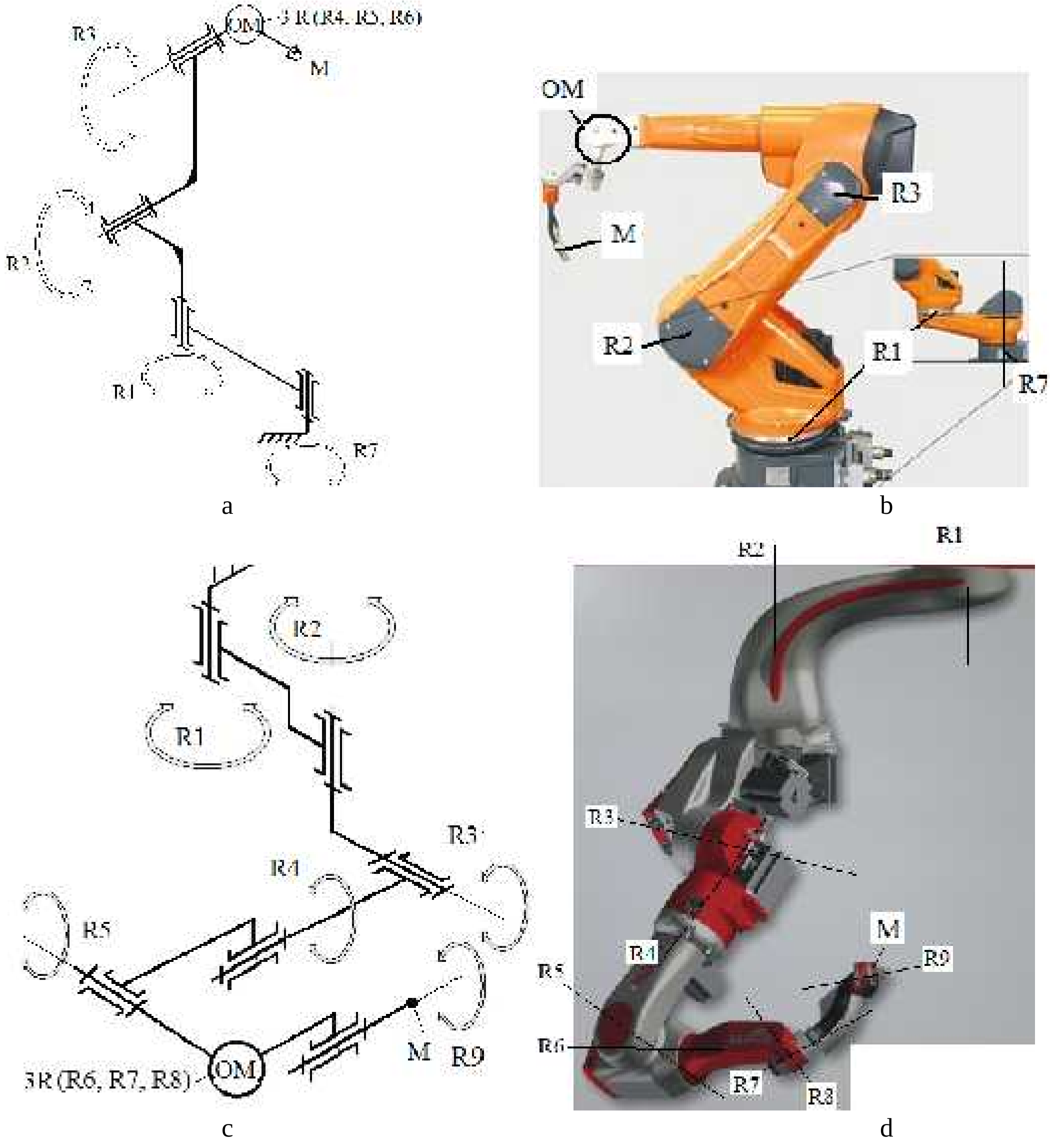


Figure 5: Redundant serial kinematic robotic chain with 7 axes(a-structural scheme: R||(PM: R⊥R||R)(OM:R⊥R⊥R) and b-real version) and with 9 axes(c-structural scheme: R|| (PM:R⊥R⊥R) ⊥ R(OM: R⊥R⊥R)||R and d-real version)

5. CONCLUSIONS

Based on the information presented in this paper, we can be draw the following conclusions:

1. Serial robots kinematic chains may be classified as: *minimal serial kinematic chains*, obtained by series of 6 rotation and / or translation couplings, *redundant serial kinematic chains,* which are obtained by adding to the minimal serial kinematic chains one to 6 rotation and / or translation couplings with the position perpendicular or parallel to the initial or final coupling of the positioning kinematic chain(PM), or the orientation kinematic chain (OM), taking into account only one reporting of the extra coupling to the positioning module (PM) or the orientation module (OM) and *hyper-redundant serial kinematic chains,* which are obtained through series of more than 12 axes of rotation and / or translation.
2. In the future we will achieve more and more variants of serial redundant robots, usually modular, thanks to their two main advantages:
- substantial increase in volume of the workspace and maneuverability to reach a point of it, even bypassing certain obstacles;
- reducing the time of calculation of optimal trajectories even in the case of a large number of axles, axes such versions with 12 axes, due to further increase of the computing power of specialized software for the calculation of their kinematics.

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