Classification of industrial robots according to the number of degrees of mobility-structural synthesis and useful configurations

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Abstract. Industrial serial robots can be classified according to several criteria, the most important being: the number of mobility degrees or independent movements, the number of independent kinematic axes, the shape of the workspace, the value of the useful load, the precision of touching a predetermined point, etc. Among these criteria, the number of degrees of mobility directly determines the structure of the kinematic chain corresponding to the robot and implicitly its construction, functionality and utility. In this paper, we define the three classes of industrial serial robots according to the degree of mobility: the class of industrial serial robots of minimum configuration, the class of redundant industrial serial robots and the class of hyper-redundant industrial serial robots. For each class of industrial serial robots the structural synthesis method is presented and representative examples of structures are given.

1. Introduction

Serial industrial robots currently exist in multiple variants in continuous diversification. So far, however, there has not been a classification of serial industrial robots to be useful to both designers and users. Obviously, it is first necessary to establish the main criterion or criteria for classification.

By analyzing the technical datasheets of the already manufactured industrial robots, we can note that the main classification criterion is the number of degrees of mobility, respectively the number of independent movements, of independent kinematic axes. Thus, we obtained the structural synthesis of open series cinematic chains with 3 or 6 independent movements. Therefore, the category or class of minimal configuration serial industrial robots has been defined [1] required and sufficient to guide (position and orient) an object in the three-dimensional space relative to an Oxyz three-orthogonal reference system. In time, one or more axes corresponding to independent movements have been added to the minimally configured serial robotic kinematic chains to increase the workspace and enhance the robot functionality. Such structures have been practically obtained individually without systematization and are now available on the industrial robotics market. If we consider the situations where the minimum configurations reach a double number of independent movements, a reasonable degree of redundancy, a second category of industrial robots is defined, namely the category or class of redundant serial industrial robots [2] characterized by 7 to 12 independent movements, respectively, mobility degrees or independent kinematic axes. However, structures with over 12 independent kinematic axes were imagined by the addition of a large or very large serial number of independent movements, resulting in robotic trunk-like serial structures [3] or type spine [1], obtained
by adding, in series, a single cinematic coupling or a limited number of kinematic couplings. These structures with more than 12 independent movements, generating non-degenerated workspaces, form the category or class of hyper-redundant serial industrial robots. The paper presents for the first time the general structural synthesis of each class of industrial serial robots and gives suggestive examples of structures specific to each class.

2. Class of industrial serial robots with minimal configuration

As it has already been shown for positioning an object in three-dimensional space, three independent movements are required to obtain the three linear coordinates corresponding to the three Ox, Oy and Oz axes of an Oxyz three-orthogonal reference system. According to [1] in order to obtain the possible variants of these structures, we distinguish the repeating arrangements of \( m \) distinct elements grouped by \( n \), namely, arrangements of two rotation or translational couples (R, T) grouped by three (XZY), X, Z, Y \( \in \{ R, T \} \) of two relative positions: perpendicular or parallel (\( \perp, \parallel \)), grouped by two (\( \perp, \parallel \)), X, Z, Y \( \in \{ R, T \} \) of two relative positions: perpendicular or parallel (\( \perp, \parallel \)), grouped by two (\( \perp, \parallel \)), and respectively two values (\( \alpha, \beta \)) assigned to three sizes: \( a_1, a_2, b \). We obtain \( \alpha_2 = a_2 = 2^\perp = 8 \) and \( \alpha_2 = a_2 = 2^\parallel = 4 \). It also follows that two couplings \( R \) and \( T \) can be grouped in threes (XZY) in eight modes, of which four XRY groups: \( \alpha_{(R,T)} \alpha_{(XY)} \alpha_2 = 2^\perp = 8 \) and \( \alpha_{(R,T)} \alpha_{(XY)} \alpha_2 = 2^\parallel = 4 \). A kinematic chain of the XRY type is determined if the relative position of the coupling \( R \) reported to the X coupling and the position of the coupling \( Y \) reported to \( R \) is known, so four kinematic positioning chains (PC) can be formed with the XRY-type group: \( \alpha_{(R,T)} \alpha_{(XY)} \alpha_{(XY)} \alpha_{(XY)} \). Similarly, PC type XTY are obtained. Thus the four XTY variants: \( \alpha_{(R,T)} \alpha_{(XY)} \alpha_{(XY)} \alpha_{(XY)} \) correspond, however, to 5 variants depending on the relative position: \( \perp, \parallel, \perp, \parallel, \parallel, \parallel \). So there are \( 4 \times 5 = 20 \) XTY type PC variants. In total, we obtain \( 16 + 20 = 36 \) kinematic positioning chains, of which 20 describe non-degenerated workloads [1]. Figure 1 gives three examples of PC describing non-degenerated workloads.

The kinematic orientation chain (OC) provides the orientation of an object in space according to the three angles \( \alpha, \beta \) and \( \gamma \) and consists of three rotation couplings with perpendicular axes: \( R \perp R \perp R \). Depending on the relative position of the three axes, we obtain \( \alpha^2 = a^2 = 2^\perp = 8 \) and \( \alpha^2 = a^2 = 2^\parallel = 4 \). Figure 2 gives 4 examples of OC of the 32 variants [1]. By adding to the kinematic positioning chain (PC) the kinematic orientation chain (OC), the kinematic guiding chain (GC) is obtained, which ensures the unambiguous positioning and orientation of an object in the space associated to an Oxyz tri-orthogonal reference system. If for the 20 PCs that correspond to non-degenerated workspaces, the

![Figure 1. Positioning chains(PC) with minimal configuration.](image_url)
32 OC variants are considered, that results in 20 * 32 = 640 variants of GC that correspond to non-degenerated workspaces.

Figure 2. Kinematic orientation chain (OC).

Figure 3 gives 3 examples of such GC(orientation chain(OC: 3 rotations R || R || R ) is symbolically represented).

Figure 3. Example of kinematic guiding chain (GC).

3. Redundant serial industrial robots class
Any serial industrial robot that adds at least a degree of mobility, so an independent movement beyond the 6 necessary minimum mobility degrees, becomes a redundant robot because the additional degree of mobility or degrees of mobility are not necessary for univocal positioning and orientation of an object in the three-dimensional space, but only increase the working space and the functionality of the robot by increasing the capacity of accessing additional areas of these structures to structures with minimal configuration. After some time it was considered that robots with more than 6 degrees of mobility, so 6 axes, are not necessary, but 7-degree mobility, so 7, 8, even 9-axis structures were made [4-13], without a systematization of the possible variants and implicitly a method of rigorous structural synthesis. In the paper [2] a method of structural synthesis of redundant serial robots has been proposed and described, of which all structures with 7 to 12 degrees of mobility, i.e. 7 to 12 independent kinematic axes, are considered to belong. Thus, for redundant robots with 7 degrees of mobility, i.e. 7 independent kinematic axes, there are structures of the type: R (PM)(OM), R||| (PM)(OM), R||| (PM)(OM), R||| (PM)(OM). By highlighting all the possible situations, there are 12 redundant structures with 7 axes: R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM). As a result, the 20 positioning structures (PM) characterized by non-degenerated workspaces correspond to 20 * 12 = 240 redundant structures with 7 degrees of mobility.

In Figure 4 there are two variants of redundant structures with 7 degrees of mobility and 7 independent kinematic axes: R || (R || R || T) (OM: R || R || R) și T || (R || R || T) (OM: R || R || R). Structures with 8 axes are obtained by adding an additional axis of R or T in position || or || to the structures with 7 axes obtained in the previous step, resulting in structures of the type: R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM), R (PM)(OM).
Figure 4. Two variants of redundant structures with 7 degrees of mobility.

Figure 5 gives two examples of structures with 8 axes.

Figure 5. Structures with 8 degrees of mobility- 8 independent axes.

9-axis structures are obtained by adding an additional R or T axis in ⊥ or || position to structures with 8 axes, resulting in structures of the type: \( R\perp[R\perp[R\perp(PM)(OM)]], R\parallel[R\perp(RPM)(OM)] \), \( T\perp[R\perp(RPM)(OM)] \), \( T\parallel[R\perp(RPM)(OM)] \). Two examples of nine-axis structures are shown in Figure 6.

Figure 6. Structures with 9 degrees of mobility- 9 independent axes.

Structures with 10 axes are obtained by adding an additional axis of R or T in \( \perp \) or || to structures with 9 axes, resulting in structures of the type: \( R\perp[R\perp[R\perp(RPM)(OM)]], R\parallel[R\perp(RPM)(OM)] \), \( \perp[R\perp(RPM)(OM)] \), \( \parallel[R\perp(RPM)(OM)] \).

Figure 7 gives two examples of structures with 10 axes. Structures with 11 axes are obtained by adding an additional axis of R or T in \( \perp \) position or || to structures with 10 axes, resulting in structures of the type: \( R\perp[R\perp[R\perp[R\perp(RPM)(OM)]]] \), etc.
Figure 7. Structures with 10 degrees of mobility - 10 independent axes.

In Figure 8 there are two examples of structures with 11 axes.

Figure 8. Structures with 11 degrees of mobility - 11 independent axes.

Structures with 12 axes are obtained by adding an additional axis of R or T in position \perp or || to structures with 11 axes, resulting in structures of the type: R\perp|R\perp [ R\perp [ R\perp [ R\perp [ R\perp [ R\perp [ R\perp [R\perp(PM)(OM))]]]]], etc. Two examples of structures with 12 axes are given in Figure 9.

Figure 9. Structures with 12 degrees of mobility - 12 independent axes.

4. The class of serial industrial hyper-redundant robots

Industrial serial hyper-redundant are characterized by more than 12 degrees of mobility, so 13 or more independent kinematic axes. The structures of these robots are obtained by adding a degree of mobility, i.e. an independent axis corresponding to a mono-mobile rotation (R) or translation (T) coupling in a parallel (||) or perpendicular (\perp) relative position to structures with 12 independent kinematic axes. For hyper-redundant structures, the number of independent axes above 12 is not limited. These structures are also known as trunk-like or type spine structures [1].

Obviously, any redundant serial structure to which one or more degrees of mobility are added, so one or more kinematic independent axes of rotation or translation becomes a hyper-redundant
structure. In Figure 10, two hyper-redundant structures are represented, derived from a redundant structure with 12 degrees of mobility.

5. Conclusions
On the basis of the facts presented in this paper, the following conclusions can be drawn:
1. After a systematization of the minimum configuration serial industrial robot structures with 6 degrees of mobility was completed in the 1980s, the continuation of such systematization for serial robot structures with 7 or more degrees of mobility was given up, but later such structures have emerged through disparate practical achievements.
2. The author of this paper proposed for the first time the definition of the class of redundant serial industrial robots with 7 to 12 degrees of mobility for which he proposed a method of structural synthesis, which allows highlighting the most useful structures possible.
3. Serial robots with 13 or more degrees of mobility form the class of hyper-redundant robots.

6. References
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