Mechatronic Approaches for Functional Structural Synthesis of Mechanical Systems of Industrial Robots
Part IV Approaches for Structural Synthesis of Motion-generator Mechanisms

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Abstract: *In this part of the study are introduced two mechatronic approaches for functional structural synthesis of mechanical systems of industrial robots, where the main manipulation mechanism is motion generator. There are directly defined a limited number structures that meet the set technical objectives and requirements for the designed mechanisms. Emphasis is placed on the tasks of passive control of the manipulation systems associated with the specialised robotics.*

Keywords: *Goal motions, structural synthesis, motion-generator mechanisms*

1. Introduction

The manipulation mechanisms are an essential part of various robotic modules and systems [6]. These mechanisms usually guide a body (end effector - an instrument or gripper) on a given trajectory of the characteristic point of the body, together with its orientation [15], [16], [3], [14]. The known methods of synthesis are mainly for highly constrain motion-generator (guidance) mechanisms with a four-unit topological structure [2], [13], [8], [7], [9]. For synthesis of multi-loop lever linkages are also used different methods, among which the optimisational ones take a significant place.

The relatively complete review in the publications of Chedmail [10] and Galabov [5] shows that the methods of synthesis of multi-loop lever linkages are primarily of a scietific and research nature and therefore are rarely applied in practice. An exception is the developed functional approach for structural and dimensional synthesis of multi-loop linkages [5]. It is based on an original idea for the structure of the manipulation mechanisms such as the overlaying of one main *primary kinematic chain* (PKC) with other functional types of kinematic chains [12], which results in the formation of control mechanisms [11] with stands on the mobile link of the primary chain.

In Part I of the study is justified the necessity for new approaches to structural synthesis of mechanical systems, via which are directly identified a limited number of structures that carry a potential for solving technical problems raised, related to the design of specialised robots. In Part II were identified five types of kinematic chains with different functionalities, which allows to determine structure of manipulation mechanisms according to defined goal tasks and specific functional requirements for these manipulation mechanisms, consistent with the control of industrial robots. On this basis, in Part III were introduced two mechatronic approaches for functional structural synthesis of mechanical systems for industrial robots [4, 1] where the main manipulation mechanism is path generator [16]. In this Part IV a smilarly formed structural synthesis will be introduced for manipulation motion-generator mechanisms (for rigid body guidance).

2. Goal motions and structures of motion-generator mechanisms

In Part I of the eponymous research the goal motion constituted of three components - a movement curve of the characteristic point of the end effector (gripper or working instrument), its velocity , and angular velocity of the effector.

In this formulation the kinematic components of the goal motion of the end effector, respectively the main tasks for structural synthesis of manipulation systems of industrial robots and for synthesis their active and (or) passive kinematic control were formally divided into eight groups. In part III for the manipulation path-generator mechanisms groups are three (A, B and C), since they do not take into account the angular velocity of the effector. Accordingly, the components of the goal motion in this section IV the *manipulation motion-generator mechanisms* will be again classified into three groups, but will also include subgroups, since the angular velocity of the effector is taken into account:

groups	(A)	(B)	(C)
τ	(var)	(invar)	(invar)
V_H	(var)	(var)	(invar)
ω_{ef}	(var)	(var)	(invar).

Again the approaches for structural development of the manipulation mechanisms are two.

First approach to build structures of motion-generator mechanisms (table 1)

Group A. The trajectory τ, velocities V_H and $\omega_{ef} \in \omega_{3,0} \in \dot{\varphi}_{3,0}$ belong to preset classes of functions, defined by the sets T, V and Ω: $\tau ::= \mathrm{var}\,\mathrm{O}\,T$; $V_H ::= \mathrm{var}\,\mathrm{O}\,V$,. $\omega_{3,0} ::= \mathrm{var}\,\mathrm{O}\,\Omega_{3,0}$. This goal task for generating programmably changable trajectory and orientation is most common and characteristic for the universal robots, where the functions of the velocities are independent $(V_H / \omega_{ef} ::= \mathrm{var})$, due to which the minimum number of moveable links, degrees of freedom, required input parameters of their open kinematic chain and respective manageble engies is 3. This task can be solved by mechanisms with four-link open *primary kinematic chain*, guided by a system for active kinematic control of three generalised coordinates or velocities:

(1)
$$\dot{\varphi}_{1,0}(t) ::= \text{var} О \dot{\Phi}_{1,0} \text{ Ь } (T, V, \Omega_{3,0}),$$
(2)
$$\dot{\varphi}_{2,1}(t) ::= \text{var} О \dot{\Phi}_{2,1} \text{ Ь } (T, V, \Omega_{3,0}),$$
(3)
$$\dot{\varphi}_{3,2}(t) ::= \text{var} О \dot{\Phi}_{3,2} \text{ Ь } (T, V, \Omega_{3,0}).$$

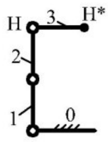
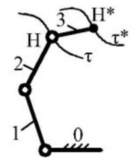
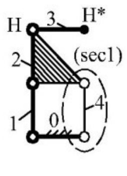
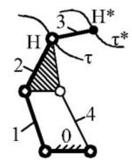
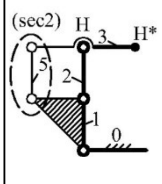
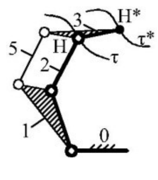
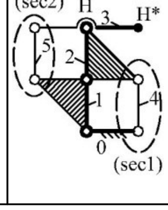
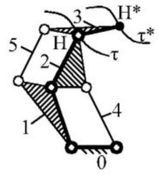
The open structure of the mechanism allows for decoupled propulsion of the three moveable links. This is achieved by the die casting supply robots of the type FEEDMAT 3 of the Bulgarian- German firm SPESIMA, where the third moveable link is the ladle itself, which scoops and doses melted aluminum alloy.

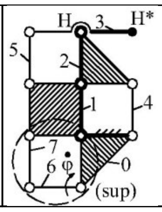
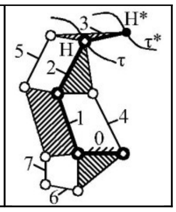
Group B. In contrast to *group A* in the tasks of these groups is not expected a change of the target trajectory ($\tau ::= \text{invar}$). They can be solved with mechanical and control systems, typical for the tasks of *group A*. A specific for the tasks from *group B* solution is part of the control of the motion of point H along the curve τ to be fulfilled by the mechanism itself.

Subgroup B1. One *secondary kinematic chain* (sec1) is formed by the base 0, link 2 of *the primary chain* and one new intermediate link 4. A new control four-bar linkage is formed with a relative base link 1. The reverse kinematic task is solved, in which are derived correlations between the relative motions of the links 0, 1 and 2 in the shape of a displacement function $\varphi_{2,1} = f(\varphi_{0,1})$ and the kinematic transfer functions $i_{2,0}^{(1)}$, $i_{2,0}^{(1)}$, ..., representing consecutive derivatives of the displacement functions $\varphi_{2,1}$ related to $\varphi_{0,1}$. With the help of these functions is synthesised the aforementioed control transfer mechanism for passive kinematic control. In reality the trajectory τ is generated by the formed four-bar path-generator linkage, typical for many of the specialised robots of the type GRIPMAT, which are designed to extract casts of horizontal machines for pressure casting, as well as for other purposes. The fourth, also separately moved link, is a translational module, equipped with a gripper.

The generalised velocities (1) and (2) should be synchronised in such a way, that at defined permanent geometric parameters of the motion-generator mechanism to be achieved the set components V_H and $\omega_{3,0}$ of the goal moition.

Table 1

N	Components of the goal motion	Topologic structures	Necessary input paramenters	Dependencies in the related movements	Sample motion-generator mechanisms
A				N/A	
B				- - - - - - - - -	
				- - - - - - - - -	
				- - - - - - - - - - - - - - - - - -	

C				- -	

Subgroup B2. A *secondary kinematic chain* (sec2) is formed by the links 1, 3 of the *primary chain* and one new intermediary link 5. A four-bar path-generator linkage is formed with a relative stand link 2. The reverse kinematic problem is solved, where are derived correlations between the relative motion of the links 1, 2 and 3 in the shape of the displacement function $\varphi_{3,2} = f(\varphi_{1,2})$ and the kinematic transfer functions $i_{3,1}^{(2)}$, $iў_{3,1}^{(2)}$, ..., representing consecutive derivatives of the displacement function $\varphi_{3,2}$ in relation to $\varphi_{1,2}$. With the aid of these functions is synthesised the aforementioned motion-generator mechanism for passive kinematic control.

This structure *B2* is identical to *B1* under the condition, that the base 0 and the end-link 3 are inversed. Regardless of this, the motion-generator mechanism with structure *B2* can not fulfill the goal motion of a mechanism with structure *B1,* in particular the condition $\omega_{3,0} ::= \text{varО}\Omega_{3,0}$. The function $\omega_{3,0}$ is dependent on the functions $\omega_{1,0}$ є $\dot{\varphi}_{1,0}$, $\omega_{2,1}$ є $\dot{\varphi}_{2,1}$ and the dimensions of the motion-generator mechanism with a relative stand 2, input link 1 and output link 3. By changing V_H are changed $\omega_{1,0}$ and $\omega_{2,1}$. Therefore $\omega_{3,0}$ can not be independently controlled.

Subcategory B3. The trajectory τ is generated by a path-generator mechanism, typical for *B1*, while the orientation of the end effector (unit 3) is achieved by a second control transfer mechanism, typical for group *B2.* In practise the structure of *subgroup B3* can be observed as a combination of hte subgroups *B1* and *B2,* derived by overlaying a primary kinematic chain with two secondary chains, where a structure of the type Watt II is formed, which is a particular case o f the so-called $Q-$manipulators [11], among which is the one of the robot SPEEDMAT of the Bulgarian-German firm SPESIMA. The actively controled generalized velocity $\omega_{1,0}$ є $\dot{\varphi}_{1,0}$ of the mechanism, represented by the indication (1), is derived as a solution of the reverse kinematic chain under certain permanent paramenters of the kinematic scheme of the mechanism and the given function of the output velocity V_H.

Group C. In contrast to the subgroups of *group B* in the tasks of *group C* is not expected a change of the functions, defining respectively the velocity of poin H ($V_H ::= \text{invar}\,\text{О}\,\text{V}$) and the angular velocity of the end effector ($\omega_{3,0} ::= \text{invarО}\Omega_{3,0}$). The tasks of this group can be solved with the help of mechanical and control systems, typical for the groups A and B. Specifically for *group C* a solution is achived entirely with the help of the mechanical system. The movement of point H along the curve τ is achieved by the path-generator mechanism, as was described by the tasks of *group* B. The required function of the generalised velocity

(4)

$$\dot{\varphi}_{1,0}(t) ::= \text{invarО}\dot{\Phi}_{1,0} \text{ Ь } (\tau, V_H), \omega_{3,0}$$

At $\tau ::= \text{invarО}T$; $V_H ::= \text{invarО}V$, $\omega_{3,0} ::= \text{invarО}\Omega_{3,0}$, will be derived by the means of the *subsidiary kinematic chain* (sub), which with two binary links 6 and 7 connects kinematically the base link 0 with link 1. A four-bar topolotical structure is formed of a subsidiary transfer mechanism with input velocity

(5)

$$\dot{\varphi} ::= \text{constО}\dot{\Phi} \text{ Ь } (\tau, V_H, \omega_{3,0}).$$

The mechanism is synthesised with the function $\varphi_{1,0} = f(\varphi)$ and its derivative transfer functions, defined by solving a reverse kinematic chain at a set law of motion of the output $V_H = f(t)$ and the linear coordinate $\varphi(t)$ at the entry of the mechanism [5]. The overall structure of the mechanism is of an eight-bar type of the class of the Q-manipulators.

Second approach to build structures of motion-generator mechanisms (table 2)

Similar to approach firstly is observed a structure of a mianpulation mechanism with three degrees of freedom, after which the levels of mobility are reduced, by inputting other functional types of chains, where are derived four-bar loops of control transfer mechanisms for passive control.

Group A. It is comprised of three subgroups, represented by table 2, where are provided (as in table 1) the components for the goal motoin, the topological structures, the necessary input parameters, the dependencies between the relative motions and sample motion-generator mechanisms, where, in contrast to the ones of table 1, are included higher kinematic pairs.

Subgroup A1. A four-bar *primary kinematic* chain is initially closed by a *parallel* one (par). The structure of a manipulation mechanism with a parallel topology and three degrees of freedom is formed. Two of the three adjustable-speed motors are to be appropriately mounted on the frame.

Subgroup A2. One additional kinematic chain (add1) is formed by the links 1 and 5, connected to the base 0, and one new intermediary binary link 6, with which the number of the degrees of freedom is reduced to two. This structure does not allow only one of the two adjustable-speed motors to be mounted on the frame. This opportunity allows for the next subgroup.

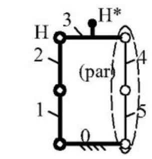
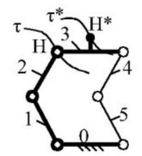
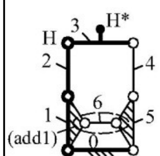
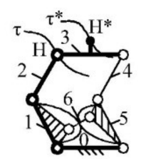
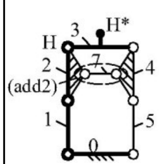
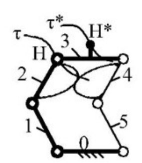
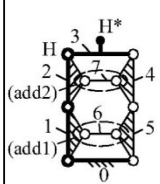
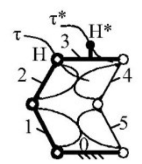
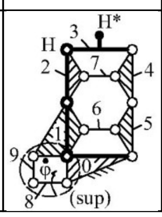
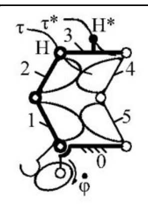
Subgroup A3. One additional kinematic (add2) is formed by the links 2 and 4, connected to the output link 3, and one new intermediary binary link 7. The number of the degrees of freedom remain two. The advantage of the structure

A3 in comparison to *A2* is the opportunity both mftors to be mounted on the frame.

Group B. The structure of this subgroup can be observed as a combination of the subgroups *A2* and *A3,* attained after netering two additional kinematic chains (add1 and add2). An eight-bar manipulation mechanism is obtained one degrees of freedom and respectively one adjustable-speed motor, which can appropriately be mounted on the frame.

Group C. The structure of this group can be formed by the previous subgroup *A3* after inputting the subsidiary kinematic chain (sub), which with two binary linus 8 and 9 connects kinematically the base link 0 with link 1. A four-bar topological structure of an subsidiary motion-generator mechanism with input velocity (5) is formed.

Table 2

N	Components of the goal motion	Topologic structures	Necessary input paramenters	Dependencies in the related movements	Sample motion-generator mechanisms
A				N/A	
				- - - - - - - - -	
				- - - - - - - - -	
B				- - - - - - - - - - - - - - - - - -	
C				- - - - - - - - - - - - - - - - - - - - - - - - - - -	

3. Conclusion

In Part I of this study is justified the necessity for new approaches to structural synthesis of mechanical systems. In Part II are identified five types of kinematic chains with different functionalities, as well as there are formulated goal tasks and functional requirements for manipulation mechanisms, consistent with the control of industrial robots. On this basis, in Part III are introduced two mechatronic approaches for functional structural synthesis of mechanical systems of industrial robots, where the main manipulation mechanism is path generator.

Similarly in that of Part IV both mechatronic approaches are developed and oriented towards more complex manipulation mechanisms – motion generators. These approaches make it possible to directly identify a limited number of potential opportunities to solve technical problems raised and to meet the specific requirements of designing mechanisms primarily of specialised robots.

Emphasis is placed on the tasks of passive control of the manipulation systems associated with the specialised robotics. These problems are solved by functional synthesis of their structure and dimensions at minimum number of degrees of freedom, required for the realization of the goal task.

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