Mechatronic Approaches for Functional Structural Synthesis of Mechanical Systems of Industrial Robots
Part II Functional Types of Kinematic Chains and Goal Motions

Vitan Galabov, Vencislav Slavkov, Gocho Slavov, Svetoslav Savchev

Emails: vgalabov@tu-sofia.bg office@spesima.eu s_savchev@abv.bg

Abstract: *The identified five types of kinematic chains (primary, parallel, secondary, additional and subsidiary), with different functionality, allow the the synthesis of structures of manipulators according to defined goal tasks and specific functional requirements for hybrid systems, in particular specialised industrial robots.*

Keywords: *Goal motions, kinematic chains, mechanisms, structural synthesis*

1. Introduction

In part I was laid out the objective of our entire study, namely the introduction of new methods for the structural synthesis of mechanisms in accordance with the development of the hybrid technical systems, and more particularly to specialized industrial robots. To achieve the target is required in this part II of the study to identify kinematic chains with different functionality [16] - the necessary basis for structural synthesis of manipulation mechanisms (path generator in part III and motion generator in part IV) according to defined goal tasks and specific functional requirements for hybrid systems, in particular for specialized industrial robots.

The advantages and disadvantages of universal and specialised industrial robots have long been established [9]. Specialized robots have both the advantages of universal and of specialised robots - they have the output of the special ones, they program as the universal ones, and are economically more advantageous than the latter.

In the specialized robotics part of the goal tasks of manipulation systems are solved by the synthesis of their structure in order to minimize the number of degrees of freedom required for the realization of the goal task. Generation of motion, trajectory or function using mechanism will be summarized conditionally with the term *passive kinematic control* [5]. This control is assigned to the specially formulated *control transfer mechanisms* [15] that solve the problem of generating the geometry of motion, separating it from the task of motion control in time, according to the so-called *first principle of mechatronics* for preliminary physical and functional separation (decoupling) of motion in space and time [21].

The formulation of basic interconnections between the set goal motion, and the tasks of active and passive kinematic control will facilitate the search for the most rational distribution of functions of mechanical and control system at an early stage of their design, which is the goal of our overall study. This facilitates the solving of priority tasks of the so-called mechatronic approach to design mechanisms in modern technology (see part I of this work). By solving these problems is continued the development and implementation of some ideas related to laying the groundwork for the design of mechatronic systems [19], [22], [20], [17].

2. Functional types kinematic chains

At the heart of the design of the mechanical systems lies the synthesis of their mechanisms. The majority of the scientific literature for structural synthesis of the mechanisms puts emphasis only on the tasks of counting pluralities of topological schemes of kinematic structures, which are not specific targets of the synthesis, and functional requirements for the mechanisms, as seen from the fundamental works on structural synthesis of Accyp [1, 2] and Gruebler [18], as well as articles [4], [3], [10] as well as the monographs of Кожевников [7] and [6].

By the generation of different sets of topological structures and the extraction of the non-isomorphic structures, it is apparent that the development of the structural synthesis of mechanisms is almost at a completed stage [13]. In other articles, such as the Chew et al. [11] is developed a conceptual structural synthesis, based on expert systems for certain types of mechanisms. Thereby some of the existing methods are imrpoved, without going beyond the frames of the topological synthesis.

The beginning of topological structural synthesis of the was initiated by Freudenstein et al. [14] and Crossley [12]. The functional and operational constraints of the graph theory do not allow the approaches, based on this theory, to implement structural constraints associated with important functional requirements, other than the degrees of freedom of the mechanisms. Therefore are pursued other non-traditional approaches to structural synthesis.

The existing algorithms and programs provide the designer with thousands of structures of mechanisms, but still did not give sufficient clear orientations for definitive choice [10]. Therefore, the designer, without precise argumentation and often without scientific approach selects the structure of the mechanism, which does not always lead to an optimal solution under certain conditions, even when optimsing the dimensions of the mechanism. Instead of using the heterogeneous and lengthy procedure for parallel synthesis (concurrent engineering approach to the synthesis - [23]) the troubled designer prefers to intuitively focus on a particular structure, although the risk of an unsuccessful choice.

New approaches are needed for structural synthesis, by which can be directly assigned a limited number of structures, that carry the potential for solving technical problems raised and to meet the specific requirements to the designed mechanical system. In this work these approaches have been developed on the idea of building mechanism structures by overlaying open kinematic chains with sequential topology and different functionality [16], forming closed loops of control transfer mechanisms [15]. These unbranched chains are primary building blocks for functional topological synthesis of the manipulation mechanisms . According to their main functionalities they can be distinguished as **primary** (prim), **parallel** (par), **secondary** (sec), **additional** (add) and **subsidiary** (sub).

The primary kinematic chain (Fig. 1, scheme 1 - **prim**) is the shortest (in number of units) circuit only with inferior kinematic couples, which connects the end effector (actuator) with the stand. Most universal robots only have a primary circuit, with each pair of the kinematic chain is active (driven).

The parallel kinematic chain (Fig. 1, scheme 2 - **par**) is structurally identical to the primary chain. If there are several parallel chains, then one of them can be considered primary if it contains only lower kinematic pairs. These chains typically create variability of the kinematic configurations of mechanisms and better conditions for their stability, accuracy and balance.

The secondary kinematic chain (Fig. 1, scheme 3 - **sec**) connects two nonadjacent links of a primary or parallel chain. It is possible that secondary kinematic chain connects two nonadjacent links of another secondary chain (Fig.2).

The additional kinematic chain (Fig. 1, scheme 4 - **add**) connects two nonadjacent links from different kinematic chains (prim, par, sec). Their introduction in the structures is dictated primarily by the need to reduce the degrees of freedom of the mechanism by establishing kinematics dependence on the motions of links by two different chains (mostly links associated with the base - Fig. 2b, links 1 and 3).

Subsidiary kinematic chain (Fig. 1, a 5 - sub) connects via two intermediate units two other adjacent units of primary, secondary or parallel kinematic chain. Typically is formed a four unit topological structure of a mechanism, via which is set the necessary input motion, which if involves downtime, leads to downtime in the subsequent units of the mechanism. Such circuits typically have manipulation mechanisms built into the structures of special robots or machines powered directly by motors without control.

The secondary and additional kinematic chains are usually involved in creation of closed loops of the so called control transfer mechanisms, to which relative bases are movable units.

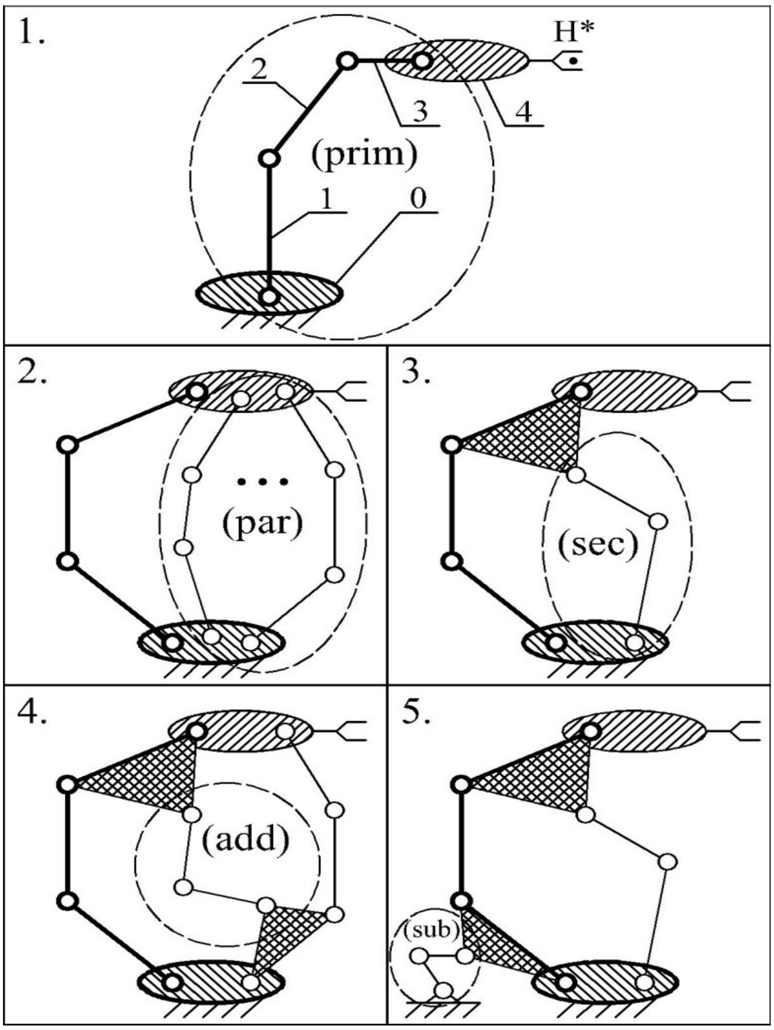

Fig.1. Functional types kinematic chains

The most simple, in terms of structure, are the manipulation mechanisms only with primary chain of the universal robots. The connected kinematic chains normally form closed loops and lower the degrees of freedom and thereby the number of motors, as is the case with the specialized robots. Each attached chain by definition also includes the links, which it connects from one or two other chains. These units are common for associated with them kinematic chains. In this way emerge ternary, quaternary, etc. links

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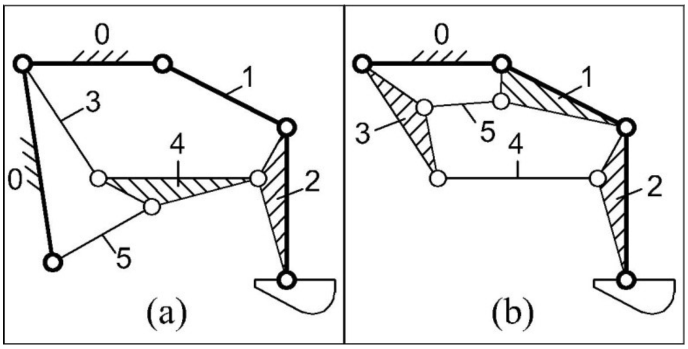

Fig. 2. Functional types kinematic chains of die casting dosing robots of the firms: (a) Toshiba and Advance: primary – units 0, 1, 2; two secondary – units 0, 3, 4, 2 и 0, 5, 4 ;
(b) The Bulgarian-German firm SPESIMA (FEEDMAT 1): primary – units 0, 1, 2;
secondary – units 0, 3, 4, 2 and additional - 1, 5, 3

The number and character of the functional requirements may be different, because it depends on the concrete task assigned when designing. Eleven examples of functional requirements and their corresponding function types of kinematic chains are given in Table 1. The signs "+" and "-" denote conditionally the functional suitability and functional inadequacy of the five types kinematic chains to satisfy the requirements.

Table 1.

Functional requirements	**Functional types kinematic chains**				
	(prim)	**(par)**	**(sec)**	**(add)**	**(sub)**
1. *minimising* the number of the links and the number of kinematic pairs	+	-	-	-	-
2. *minimising* the work space of the mechanism	+	-	-	-	-
3. *maximising* the work space of the end effector	+	-	-	-	-
4. *multivariance* of the kinematic configurations of the mechanism	+	+	+	-	-
5. *minimising* the number of kinematic pairs, in which the end effector is present	+	-	+	+	-
6. *optimising* the number and the order of the active kinematic pairs	-	+	+	+	-
7. *minimising* the structural errors of the mechanism	-	+	+	+	-
8. *optimising* the actuation via changes in the order of the active pairs	-	-	+	+	+
9. *stability* of the mechanism	-	+	+	+	-
10. *balancing* of the mechanism	-	+	+	-	+
11. *decoupling* of the actuation of the end effector	+	+	+	-	-

3. Goal motions

The goal motion can generally be represented by three components – trajectory τ of the characteristic point H of the end effector (working instrument or gripper), its speed V_H and the angular speed ω_{ef} of the effector. This decoupled representation of motion is appropriate for speciali robots, as they usually generate unchanging trajectory τ of the

Each component is fits into the summarised concept image or function (f), which is derived from set theory and belongs (О) to a set (F) - an area of continuous functions [8]. A function (f) by definition $(::=)$ can be replaced (var) or not replaced (invar) with another function. The field (F) may be defined by condition or defined by the means of characteristic point H with variable speed V_H and with a dependent or independent angular velocity ω_{ef} of the effector.

one or more related fields $(A, B, ...)$, for example f ::=О var F Ь $(A, B, ...)$.

In this formulation the kinematic components of goal motion of the end effector, respectively the main tasks for structural synthesis of manipulation systems of industrial robots and for synthesis of their active and (or) passive kinematic control can be formally divided into eight groups:

group №	1 (A)	2 (B)	3	4	5	6	7	8 (C)
τ	var	invar	var	var	var	invar	invar	invar
V_H	var	var	invar	var	invar	var	invar	invar
ω_{ef}	var	var	var	invar	invar	invar	var	invar

The most common and typical for the universal robots is task № 1, where the functions of the velocities are independent $(V_H / \omega_{ef} ::= \mathrm{var})$, so that the minimum number of moving links, degrees of freedom, and required independent input parameters of their open kinematic chain are 3. With the specialized robots these functions are generally dependent $(V_H / \omega_{ef} ::= \mathrm{invar})$ due to the introduction to the primary kinematic chain of another or other functional types of kinematic chains.

4. Conclusion

In Part I of this study is justified the necessity for new approaches to structural synthesis of mechanical systems. In this Part II are identified five types of kinematic chains (primary parallel, secondary, additional and subsidiary) with different functionalities, which provides for the creation of structures of manipulation mechanisms according to defined goal tasks and specific functional requirements for hybrid systems in particularly specialized industrial robots. In the next two parts of the research topic will be introduced mechatronic approaches to functional structural synthesis of the mechanical systems of industrial robots, where the main manipulation mechanism is path generator (part III) or motion generator (part IV).

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