Mechatronic Approaches for Functional Structural Synthesis of Mechanical Systems of Industrial Robots
Part I In Regard with the Necessity of New Approaches for Designing Mechanical Systems

Vitan Galabov, Vencislav Slavkov, Gocho Slavov, Svetoslav Savchev

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

Abstract: *In this part I of the research is specified the necessity of new approaches for structural synthesis of mechanical systems, to directly identify a limited number of structures that carry a potential for solving technical problems raised and to meet the specific requirements for the design of mechanical systems, mainly for specialised robots.*

Keywords: *Structural synthesis, manipulation mechanisms, specialised robots*

1. Introduction

Depending on the level of specialization in industrial robots are divided into three groups [8]: multi-purpose or **universal** - intended for various main and auxiliary operations, **specialised** - designed to perform identical operations for service of process machinery [5], [1], [10] **special** - designed for a particular operation or to service a particular machine [29].

The executing mechanisms of universal industrial robots usually have an open kinematic chain with 5 or 6 degrees of freedom. Their relatively simple structure and flexible programming are at the expense of a complex structure and setting of the control system [13].

The executing mechanisms of specialised industrial robots usually have closed-open kinematic chain with 3 or 4 degrees of freedom [20], [11]. Their structure includes at least one closed-loop control mechanism, generating part of the goal motion, which simplifies the structure and setup of the control system, but requires structural and dimensional synthesis of the mechanism according to set conditions [6].

The executing mechanisms of special industrial robots are generally composed of one or two modules [33] or have a closed kinematic chain of a control mechanism with 1 degree of freedom [29]. The control system is maximally simplified at the expense of a complicated synthesis of control mechanism with variable transmission rate [4].

In Universal Robotics the control tasks of manipulators are placed upon their design and construction. With the purchase of a suitable universal robot can be solved tasks, related to the technological and (or) support operations. In most cases, the mechanisms are controlled by an open kinematic chain with a open topology, with having sufficient, but in some cases excessive number of degrees of freedom (redundant robots). It is relied on the intelligent system for active control of the implementation of the task [12].

The specialised and special robotics part of the control tasks of manipulation systems are solved by synthesis of their structure and dimensions for minimum degrees of freedom, required for the realisation of the goal task. The generation of movement (moving) trajectory or function using a mechanism will be summarised conditionally with the term *passive kinematic control* [5]. This control is assigned to the specially designed control transfer mechanisms [19] that solve the problem of generating the geometry of motion, separating it from the task of controlling the motion with time. In many cases, the manipulation or control systems are unnecessarily complicated, if you relied only on the possibility of either a passive or active control.

The aim of our study is the overall input of new approaches for the structural synthesis of mechanisms consistent with the development of the hybrid systems, and more particularly of the specialised industrial robots. To achieve this goal it is necessary to identify kinematic chains with different functionality (Part II), and on this basis to formulate basic interrelationships between specified coal motion and tasks of the active and passive kinematic control to reach the most rational distribution of the functions of mechanical and control system at an early stage of the design of path-generator mechanisms (part III) and motion-generator mechanisms (part IV), forming the structure of the mechanical systems of specialised robots.

A specific purpose of Part I of this study is to reveal the need for new approaches to structural synthesis of mechanical systems, through which directly can be identified a limited number of structures that carry a potential for solving technical problems raised, and to meet the specific requirements for the design of mechanical systems, mainly specialised robots. This is followed by a justification of the target necessity.

2. Development of the structural synthesis

At the core of the design of the mechanical systems lies the synthesis of their mechanisms. The majority of the scientific literature for the structural synthesis of the mechanisms is directed

only towards the task of counting multitudes of topological schemes of kinematic structures
that do not account for the type of kinematic pairs, the specific purposes of the synthesis, and the functional requirements for the mechanisms. This is demonstrated by the fundamental works on structural synthesis of Accyp [2, 3] and Gruebler [23], by dozens of other publications, as well as the monographs Кожевников [7] and Galabov [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 [17]. This does not mean that work in the field of topological structural synthesis is completed. On the contrary, in articles such as the Tischler et al. [33], after a brief review of the existing methods for generating structures and detection of isomorphism are given a more rational possibilities to generate a complete list of structures, including a significantly lower number of isomorphic structures. In other articles, such as the Chew et al. [15] 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 whit graphs of the was initiated by Freudenstein et al. [18] and Crossley [16]. 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 [9]. 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 - [31]) the troubled designer prefers to intuitively focus on a particular structure, although the risk of an unsuccessful choice.

How can the difficulties be avoided? Primarily the duration of the designing of the mechanical system must be shortened, without a negative impact on the final product, which most often is an innovative project. Largest reserves in this respect can be found in the first stage of the design of mechanisms - in their synthesis. New approaches are needed for structural synthesis, by which can be directly defined a limited number of structures that carry a potential to solve the given technical problem and fulfill the specific requirements of the designed mechanical system.

3. Mechatronic approach for structural synthesis of the mechanisms

In modern technical devices ever closer are intertwined the problems of mechanics and electronics of "kinematic" and "electronic" intelligence [26], [28], [32]. The symbiosis of mechanics and electronics leads to a rational and cost-effective technical solutions for various devices. It has arisen the so-called mechatronic approach to the design of mechanisms and manipulators (Mechatronic Design of Mechanisms and Manipulators). This is an approach that gives appropriate integrated mix of the mechanics, electronics, and software implemented during design, testing, and production of products and systems to obtain optimal under certain conditions, technical solution [14].

The separability of the function "mechanical motion" in terms of geometry and time was announced by Konstantinov [27] as the ***first basic principle of mechatronics*** for *decoupling (division) of the motions in space and in time*. According to this principle, the task of planning the goal function "mechanical moton" is separated a purely geometric part of the overall control task of the mechanical system in space and in time. The mechanisms with a closed structure naturally generate the function "geometry of the motion" in the form of *curves of the motion and transfer functions,* which are independent of the *time* parameter but are determined solely by the structure and the dimensions of their kinematic schemes. When applying input kinematic parameters (speed and acceleration) *the motion curves* are transformed into *trajectories* and the *transfer functions* are converted into *kinematic functions* because they are now dependent on the parameter *time*. The synthesis of mechanisms solves the geometric part of the task of control of closed kinematic chains [4].

The mechanisms with closed structures have certain advantages over those with open structures ceteris paribus:

- a lower number of degrees of freedom and respectively controllable motors;
- ease of control, since the geometry of complex motions is achieved by the mechanism;
- stabilisation of the mechanical system and the ability to export drive modules on the frame, which lightens the mobile links;
- trouble-free motion of the end effector, with higher speeds and accelerations on a defined path with improved accuracy and reduced vibrations at the moment of placement.

In order to achieve an increase in the functionality of the mechanical systems, there are combined the qualities of the open and closed kinematic chains, which allows to obtain a wide variety of paths in an extended work area. There are obtained mixed open-closed kinematic chains, typical for various specialised robots, including those produced by the Bulgarian-German company SPESIMA.

Two groups of factors require changes in the approaches to synthesis of mechanisms. The first is associated with the objects of synthesis. Constant is the desire to optimise the internal state and the external interaction between different to their physical nature systems, - ie. *hybrid systems*. The second group of factors is related to the theoretical apparatus for the synthesis of mechanical systems. Through this

apparatus must be drawn mechanical mathematical models related to specific requirements for the engineered systems and their optimal adaptation.

At home and abroad there has been put a great effort into the theoretical and practical terms for the creation of so-called *intelligent machines*. As a first stage in the their development may be adopted the creation of so-called *hybrid machines* [22], to which can be attributed the specialised robots. Typically, these are devices with two or three degrees of freedom, wherein a corresponding number of servomotors are controlled in such a way, that the output end effector generate programmable non-uniform motion.

The mechatronic approach for synthesis of mechanisms is developing as a completely new approach to the design of hybrid technical systems. This approach to synthesis is still in its genesis stage of development, but is likely to be a realistic and particularly promising direction for the design of hybrid systems. Numerous problems of mechatronics are partially solved or awaiting a solution. In the synthesis of mechanisms for mechatronic devices, such as the specialised robots priority tasks, without claiming completeness, are:

1. ***Transformation of the primary target in the specified task assignment*** for synthesis of the hybrid system made when drafting the plan for its overall design.

2. ***Preliminary physical and functional decoupling (split) of the target task in space and in time.*** This is necessary for the synthesis of an optimal structure for a mechanical system which can realise the geometric component of the target motion.

3. ***Preliminary expert distinction in terms of the features and relative share of the components of the mechanics and electronics.*** This share depends on the actual degree of programmability, required in the implementation of targeted motion, taking into account the reliability of the building blocks of the device, and a number of economic factors.

4. ***Coordination of the type and location of the mechanical system according to the type and volume of regional working space, which sets the goal motion.*** From the multitude of kinematically complete kinematic chains in the process of synthesis is led to a limited number of competitive options, which completely or partially provide independent (decoupled) position control, which is of significant practical importance.

5. ***Determination of the optimum number of degrees of freedom of the mechanical system.*** Limiting their number can be achieved with the introduction of additional connections between units of the kinematic chains.

6. ***Multivariate structural synthesis and analysis of a set of possible solutions.*** This task is directly related to the problem of optimal placement of the active (propulsive) kinematic pairs in the boundaries of the whole mechanical system.

7. ***Choosing a rational method for dimensional synthesis*** and its implementation so that the tasks to generate the geometric components of the goal motion to be realised by the mechanical system.

8. ***Selection of rational methods of force analysis, dynamic, elasto-dynamic synthesis and analysis of the mechanical system***. This task is achieved by gradually taking into account the currently formulated priority tasks and is related to the constructive development of the synthesised kinematic schemes.

By solving these problems is continued the development and implementation of some ideas, related to laying the groundwork for the design of mechatronic systems [24], [25], [21].

4. Findings and conclusions

From the review in this study and the current status of the theory of structural synthesis of mechanisms can be made a number of findings and conclusions:

1. The structural synthesis of mechanisms fits poorly into the general theory of control of mechanical systems. The tasks for the synthesis of the mechanisms must be considered as the geometric part of the task management of the mechanical systems.

- The question of optimal, under certain conditions, distribution of functions for kinematic and microprocessor control the motoins of the mechanical system remains open. This issue is essentially related to the number of degrees of freedom and structure of the mechanisms.
- The role of the mechanisms in the hybrid systems is not sufficiently clarified, thus the levels of mobility and structure of the mechanisms are unjustifiably determined (mostly closed and with the robots - open) incl. the type of the kinematic pairs.
- The structural syntehsis is observed as a problem almost isolated from the process of the overall design of the mechanical systems (specifically their dimensional synthesis) and from the conteporary possibilities for the control of their motion

2. At the current stage the structural synthesis is highly developed in terms of structural formation of lever mechanisms with rotating kinematic pairs (so-called topological synthesis) and weakly associated with the functional requirements of the mechanisms and the basic tasks of their metric synthesis, which reduces the aggregation of the methods for structural synthesis.

- The structural synthesis is carried out on the basis of closed kinematic chains, with the exception of the approach of Accyp [3]. The synthesis of mechanical systems with closed-open and open kinematic chains is scantily represented and is developing one-sidedly, mostly for the needs of the universal robotics.
- Many approaches to structural synthesis developed on the basis of the graph theory, are not applicable in the general case, mainly due to lack of necessary and sufficient conditions for the application of these approaches.
- The choice of the type of mechanism is currently insufficiently determinated and thus, even in the most accurate metric synthesis rarely leads to optimal solution under certain conditions.

From the established findings and conclusions is derived the objective of this study in the following three parts, namely to introduce new

approaches for structural synthesis of a wide range of applicability, which would facilitate and accelerate the design of modern technical systems. These approaches should to the maximum extent be adapted to the requirements posed by "the symbiosis" of mechanics, electronics and software for the controlt of goal motions in order to obtain optimal solutions with given conditions.

The study is also oriented indirectly at objectives related to problems for development of specialised computer programs, as well as possible applications of contemporary technologies in intelligent design of manipulation mechanisms in specialised robotics [30].

5. Conclusion

In Part I of this study is justified the need for new approaches to structural synthesis of mechanical systems, through which can directly be identified a limited number of structures that carry a potential for solving technical problems raised to meet the specific requirements for the design of mechanical systems, primarily for specialised robots.

In the next three parts of the study will be identified kinematic chains with different functionality (Part II), and on this basis will be defined key relationships between specified goal motions and tasks of the active and passive kinematic control to reach the most rational distribution of the functions of the mechanical and control systems at an early stage of the design of path-genrator mechanisms (part III) and motion-genrator mechanisms (part IV), developing the structures of the mechanical systems of specialised robots.

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