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The Concept of Synthesis Hinged Mechanisms as a Part of Mechatronic Systems

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Abstract

In recent years, the increasing use acquires mechatronic devices to implement complex laws of motion of the executive bodies of the machinery. In this regard, there was a need for modification of the classical approaches to the mechanisms synthesis as subsystems of mechatronic systems. The new concept is based on the synthesis of mechanisms through a systematic approach that takes into account lot criteria of quality. The kinematic transfer functions in this case have a secondary importance. In the new concept of mechanisms synthesis with finite number degrees of freedom, the task of movements planning is one of the most important. No less important role has the control system of movement that is synthesized based on the selected variant of kinematic structure and the possibility of realization the law of motion of the executive body received as a result of solving the problem of movements planning. Systemic synthesis of mechanisms mechatronic systems advantageously carried out in parallel with executive bodies movements planning and with the synthesis of control systems.

Keywords: Mechatronics, System, Mechanism, Transfer function, Movements planning, Control system, Synthesis.

Introduction

Synthesis of mechanisms is one of the most important parts of the mechanisms theory. Its formation is rightly associated with the name of P.L. Chebyshev and his method of approximation theory of functions [1]. General synthesis methods have been developed in the writings of many scientists, but P.L. Chebyshev was one of the first scientists to successfully apply mathematical methods developed by him to solve synthesis problems of guides and transfer mechanisms [2].

Methods of synthesis are very diverse. Their development has allowed to create many new mechanisms with unique properties. Large list of scientific works in this area made by the end of the 50^{th} of the twentieth century is shown, for example, in [3]. Modern classical theory of synthesis has fundamental basis and is sufficiently developed, however, it is constantly being improved and in scientific and technical literature one can find many original works aimed at solving modern theoretical and applied problems.

The classical process of new mechanisms designing is usually divided into three main stages that can be performed, including, simultaneously. In the process of analysis are being used methods, that allow to evaluate the quality of the synthesis at each stage. At the initial stage of the mechanism design, structural synthesis problems are being solved. The result of such synthesis is the formation of mechanism structure that provides the required number of degrees of freedom and closed contours formed by links. In the process of structural synthesis, as a rule, are trying to minimize the number of links and eliminate the redundant connections. [4-7]. It should be noted that in order to perform one type functions formally can be chosen the set of mechanisms that in generally able to fulfill indicated conditions [8]. However, as experience shows, often from this set of mechanisms are being selected mechanisms that have a structure the effectiveness of which is confirmed by operation practice.

In the classical approach to the mechanisms design, the most important stage is kinematic (metric) synthesis. The generally accepted concept of kinematic synthesis of guides and transfer mechanisms is based on the determination of kinematic parameters that allow to implement necessary trajectory of a certain point or a position function of executive body for given movement law of an input link [2,3,9-14]. It is known that with this approach most synthesis problems do not have exact solutions, and some motion laws of output links can be realized only with great inaccuracy and only for multilink mechanisms, that reduces reliability. Finally, kinematic parameters determined through the optimal synthesis often prove constructively unsuitable.

After setting the metric parameters of the mechanism that satisfy structural and kinematic requirements, it is possible to solve the problems of dynamic synthesis, in process of which sizes of the links, their masses and moments of inertia are clarified, are solved problems balancing of mechanisms, are provided necessary motion smoothness, movements resistance, damping of oscillatory processes, noise levels reduction, etc. The problems of dynamic synthesis are extremely diverse and their solutions are often associated with the optimization of parameters in accordance with various quality criteria.

The synthesis of mechanisms represents a very complicated task in mathematical and technical points of view that is often performed by successive approximations using simultaneously methods of structural, kinematic and dynamic analysis. In practice, it requires significant resources and often no leads to finding necessary solutions. This is the motivation to search for new methods for solving problems of synthesis, including those using modern computational tools and information technologies.

Development and mass application in manufacturing of mechatronic technologies allows in many cases to abandon the classic concept of synthesis and to use alternative approaches for solving applied tasks. The new concept of synthesis, proposed in this paper, is based on systematic approach that allows to design mechanisms that are naturally embedded in certain technical system and satisfy its quality criteria.

Methods

Mechanisms as Subsystems of Mechatronic Systems

According to Finniston [15], the term "mechatronics" was introduced to describe technologies that emerged at the intersection of electrical engineering, mechanical engineering and software. Today it is a branch of science and technology, based on the synergetic interconnection of mechanics with electronic, electrical and computer components the objectives of which are to design, manufacture and operate qualitatively new technical systems, including machines that perform functional movements under the influence of intellectual control systems. One of objectives of mechatronics (but not the only) is the control of precise movements of elements of technical (mechatronic) systems [16].

The ability of mechatronic systems which includes an intelligent control subsystems, to self-organization allows in most cases to use mechanisms of the simplest structure [17]. Basically, the typical mechatronic modules, that already contain in its structure relatively simple mechanisms, are capable of performing many features that in traditional devices are available only to multilink mechanisms with developed structure. But the combination of mechanisms with mechatronic modules allows to solve a lot of new technical problems and promotes original design solutions and to the creation of unique technical systems, including having many degrees of freedom.

Using the terminology of system analysis according to which the system is a set of components that are in certain relation to each other, dependence and act as a single unit [18], a mechatronic system can be considered as a system that combines a set of mechanical, electronic and control devices that form a synergistic unity [19]. That is, the mechatronic system is an ordered set of dynamically interconnected subsystems, functioning of which in space and time is subject to a single goal. It is important to note that the synergistic association of subsystems in the mechatronic system leads to the acquisition of them of a new quality features that disappear after decomposition of the system. This is one of the most characteristic features of mechatronic systems, which distinguishes them from other, obtained by the mechanical unification of diverse subsystems [20]. Thus, it is arguable that mechanisms which included as subsystems in mechatronic systems have new qualitative properties with respect to the mechanisms working as part of the traditional technical systems. These properties are lost as soon as the mechanisms are considered as independently functioning units.

One of the main qualitative differences of mechanisms in mechatronic systems is that their structure has no decisive influence on the kinematics. Identical (even very complicated) laws of motion of the executive bodies can be obtained using many mechanisms with different structure. This, above all, explains the desire to use in mechatronic systems mechanisms of the simplest structure. In particular, this approach is most suitable for transfer mechanisms. It does not contradict to the classical approach [2], but allows to significantly expanding the set of evaluated variants when choosing the optimal solution.

Thus, the use of the mechanisms with a simple structure in the mechatronic systems can be considered as the rule. However, in practice there are exceptions (see, e.g., Timofeev [21]), which, in our opinion, cannot be attributed to optimal technical solutions.

Guides mechanisms of the mechatronic systems also can be considered from a systems perspective. Trajectories points of links in space are functions of coordinates and the possibility of their implementation using mechanisms with one degree of freedom is defined not only by the structure but also by the system of kinematic parameters, specified by systems of coupling equations. Typically, in traditional mechanical systems the mechanisms of multilink structure are used to implement complicated trajectories. However, considering them as subsystems of mechatronic systems, we can assume that for the realization of complex trajectories the most rational are sequential or parallel structures of mechanisms with a number of degrees of freedom more than one. Such approach, for example, is successfully used in robotics and in many respects is borrowed from the biological objects [22-25]. In particular, as we know, manipulators of industrial robots represent mechanical systems designed to reproduce movements similar to the movements of the human hand, the structure and other characteristics of which from different points of view can be considered optimal [26]. But the movements of hand are carried out under the influence of commands of the central nervous system and, therefore, human hand can be considered optimal only as a subsystem, which operates as part of biomechanical system (human), which, in its turn, interacts with the environment.

By linking with the help of space-time relations the point coordinates, belonging to one of the links of the mechanism with a finite number degrees of freedom, and given the ability to synchronize drives of the mechatronic system, we can to implement relatively complex trajectory of the point, deciding, so, the main synthesis task of guides mechanisms [2].

It should be noted that mechanical movements of executive bodies in developed mechatronic systems usually are nonlinear and to implement them by means of guides or transfer mechanisms we must have effective control systems. The most suitable for these purposes can be considered adaptive control systems [27,28]. An obligatory condition is the use of effective subsystems of obtaining information about the real process of functioning of the mechatronic system in general, its processing, interpretation and transfer to control programs. Modern control systems as a part of mechatronic systems for the most part can be attributed to the intelligent group [29]. They are based on algorithms of fuzzy logic [30,31], associative memory [29], neural, neuro-fuzzy networks [32,33], evolutionary (genetic) and other methods [34].

Control systems development for mechanisms that operates as subsystems of mechatronic systems is one of the most important tasks of mechatronics. Their possibilities determine the level of and complexity of solved tasks. New qualities of mechanisms as subsystems of mechatronic systems is largely determined by abilities of controlling subsystems solve the problems of speed control, dynamic decoupling of movements with compensation of mutual influence of degrees of freedom, eliminate errors of kinematic and dynamic parameters of links in dynamic models, compensate influence of friction in kinematic pairs, etc.

Formulation a New Concept of Mechanisms Synthesis

Despite the relatively short period of growth and development, mechatronics as a separate branch of science and technology has shown its advantages in solving practical engineering problems [20,35-37]. But until now discussions are taking place about its role and place in modern science and about concepts of synthesis of mechatronic systems in general and their elements in particular [38-40]. But the general opinion of most researchers reduces to the fact that the tasks of analysis and synthesis of mechatronic systems should be solved from positions of system approach, considering all subsystems included in them as a synergistic inseparable unity. At the same time, one should not neglect by problems of analysis and synthesis of subsystems decomposed mechatronic systems, bearing in mind that in this form they represent only one of the possible partial cases.

The proposed concept synthesis of guides and transfer mechanisms of mechatronic systems is based on the system approach. However, it does not contradict to the classical concepts, but on the contrary, includes it into itself. That is, the mechanisms, the synthesis of which is made on the basis of the traditional approach can be used in mechatronic systems, but they cannot be considered as an optimal.

As the conceptual frameworks of the synthesis, the following provisions are accepted:

1. In the synthesis of the mechanism structure the preference is given simplest mechanisms which output links are capable to perform movements of the required form.
2. At the stage of the metric synthesis are determined kinematic parameters that provide the necessary amplitude of movements or limits of the working space of executive bodies and domains of definition of the mechanism position functions, the problems of movements planning are solved. The main condition of synthesis it is a providing of continuity of kinematic transfer functions in the domains of definition (conditions of absence of singular configurations); an additional condition – providing domains of definition of kinematic transfer functions which must meet the requirements typical mechatronic modules.
3. At the initial stage of modeling, is performed the design process of basic units of mechanisms, are specified values of kinematic parameters, masses and moments of inertia of links, are determined types and sizes of drive modules.
4. At the stage of dynamic synthesis the necessary software and the concept of control system are developed. The structure of control system is generally determined by the type of mechatronic system as a whole. Design of mechanisms is changed depending on the degree of compliance with the necessary quality criteria. If necessary, in order to ensure adequacy of mathematical models of mechanisms, the parameters identification procedure is carried out.
5. At the final stage of synthesis is carried out modeling of mechatronic system as a whole, which work under the influence of control systems of mechatronic drives.

It is easy to notice, that bases of the proposed concept of mechanisms synthesis differ substantially from classic concept. The main difference is that the mechanisms that work in the mechatronic systems are considered as their subsystems are operating in conjunction with other subsystems under the influence of the environmental factors. Structures and transfer functions as own characteristics of mechanisms, that distinguish them from many other mechanisms, in this case are of secondary importance. In the new concept, the implementation of the required laws of motion of the executive bodies is mostly determined by capabilities of mechatronic drives, functioning under the influence of control system commands.

It should be noted, that the new concept does not imply the denial from classic. Moreover, it represents the development of the latter that became possible as a result of the development of drives, sensory, computing techniques, programming and technologies of synthesis of advanced control systems. The main provisions of the new concept do not regulate the sequence of actions, the implementation of which is necessary during the mechanisms synthesis, but determine their final result aimed at creating system, which capabilities are superior to the sum of capabilities of its constituent subsystems [41].

Results

Mechanisms of mechatronic systems. The examples of solving some synthesis problems

Motion planning of the planar manipulator of parallel structure. The method of arbitrary restrictions: It is considered that the manipulators of robots represent one of type of mechatronic systems [42]. In below example- it is a 7-link planar guides mechanism parallel structure (manipulator) with lower (rotational) kinematic pairs (Figure 1). It can be used in mechatronic devices, in which is required to provide accurate movements of reference point O in the working area of plane.

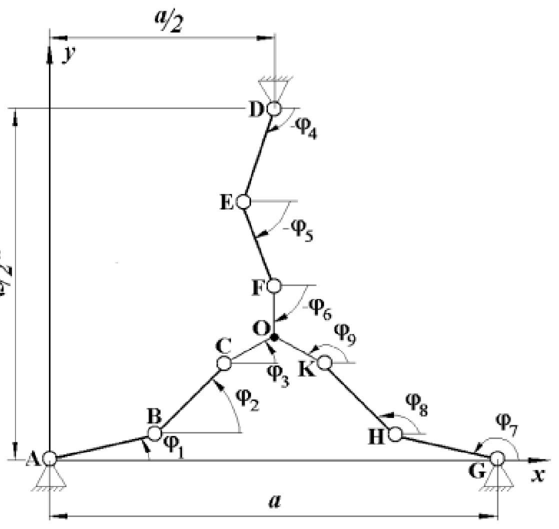

Figure 1: Schematic diagram of planar 7-link manipulator of parallel structure

Manipulator has 3 degrees of freedom and, therefore, a redundant mobility in plane. I.e., the required movements can be performed by any two of three engines, which provide independent movements of links 1, 4, 7. Such structure can be adopted at the initial stage of the synthesis in order to provide the required maneuverability.

At the stage of the metric synthesis is necessary to determine the parameters of links providing the required dimensions and shape of the working area. This is the classic synthesis problem, which can be solved by any of the known methods. For example, in solving problems of this type the method of investigation of the parameters space distributed uniformly in a multidimensional cube, is effective [43,44].

The implementation of this method is quite bulky, so in this paper the metrical synthesis was not implemented and the dimensionless kinematic parameters of mechanism, in general, were chosen arbitrarily:

$l_{AB} = l_{BC} = l_{GH} = l_{HK} = l = 1; lCO = lKO = R = 1;\quad l_{CF} = l_{FK} = l_{KC};$

$$\varphi_9 = \frac{2\pi}{3} + \varphi_3,\ \ rad$$

At the same time were taken into account requirements for the size of the working space in the circle shape with the center at the point O of the link CFK.

In this example we consider one of the possible approaches to the problem of the manipulator motion planning.

Let required to determine the motion laws of mechatronic drives during movement of point O on a circle of radius $r = 0.3$ at the center of point $S\left(\frac{x_D}{2}, \frac{y_D}{2}\right)$.

When solving the motion planning task, a redundant mobility can be excluded by arbitrarily selecting one unknown value. As an example, let's take $\varphi_3 = 0\ \ rad$. Then, from the system of geometric constraint equations,

$$\begin{aligned}
&l\cos\varphi_1 + l\cos\varphi_2 + R\cos\varphi_3 - x = 0\\
&l\sin\varphi_1 + l\sin\varphi_2 + R\sin\varphi_3 - y = 0\\
&a + l\cos\varphi_7 + l\cos\varphi_8 - \frac{1}{2}R\cos\varphi_3 - \frac{\sqrt{3}}{2}R\sin\varphi_3 - x = \\
&l\sin\varphi_7 + l\sin\varphi_8 + \frac{\sqrt{3}}{2}R\cos\varphi_3 - \frac{1}{2}R\sin\varphi_3 - y = 0
\end{aligned} \qquad (1)$$

we receive $\varphi_1, \varphi_2, \varphi_7, \varphi_8$ as functions of coordinates (x, y) of the point O (Figure 2a). The set of mechanism configurations during point O movement on the circle is shown in Figure 2b.

Afterwards may be defined also and variables φ_4 and φ_5, however, to explain the meaning of the used approach, they are of no interest.

Obtained solution of the inverse problem of kinematics, in general, is not optimal, as one of the unknown has been chosen randomly. In this case one of drives (in the present case, the drive of the link DE) is not active. We can to assume, that the considered and similar structures of mechanisms are ineffective. However, in reality, the presence the redundant mobilities in mechatronic systems is often necessary for their flexibility, which in many cases is a significant advantage. In addition, the redundancy can be involved in the implementation of the necessary movements of executive bodies if they meet certain quality criteria.

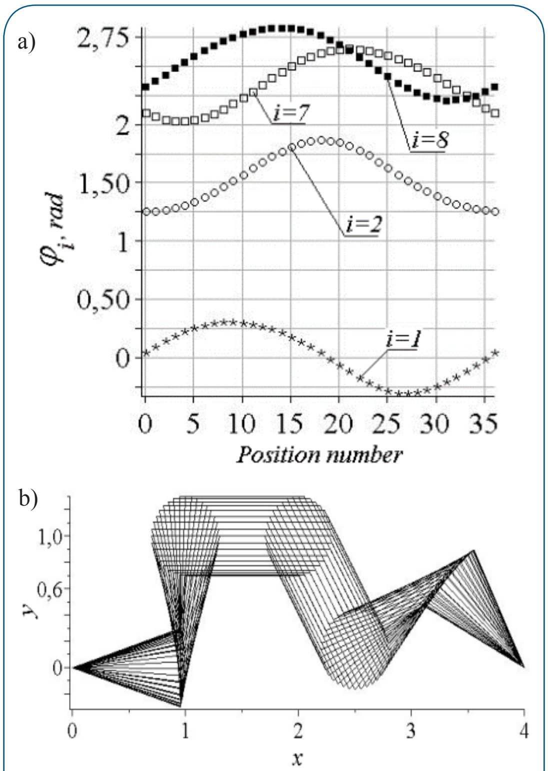

Figure 2: The point O movement on the circle of radius r with the center at the point S, subject to $\varphi_3 = 0\ \ rad$: a) graphs of functions $\varphi_i = f_i(k)$, $i = 1,2,7,8$; the set of the manipulator configurations (*DE* and *EF* links are conventionally not shown)

Motion planning of the planar manipulator of serial structure. The method of a configuration space optimization: As an example of motion planning of the executive body on the basis of optimization approach, let's consider planar 4-link anthropomorphic manipulator of serial structure (Figure 3).

Having accepted dimensionless parameters of links: l_{AB}=3, l_{BC} = 2, l_{CD} = 1, we write the system of geometric constraint equations:

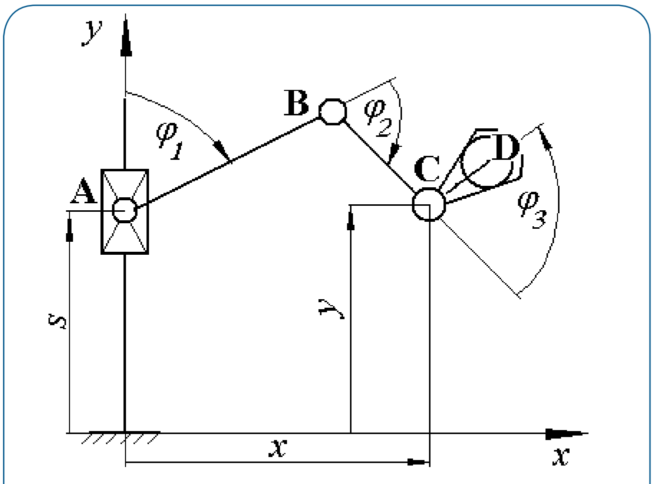

Figure 3: Schematic diagram of planar 4-link anthropomorphic manipulator of serial structure

$$3\cos\varphi_1 + 2\cos(\varphi_1+\varphi_2) + \cos(\varphi_1+\varphi_2+\varphi_3) - y = 0$$
$$s + 3\sin\varphi_1 + 2\sin(\varphi_1+\varphi_2) + \sin(\varphi_1+\varphi_2+\varphi_3) - x = 0, \quad (2)$$

which, by excluding unknown (e.g., using the Buhberher algorithm [45]) can be reduced to one equation:

$$U(s,\cos\varphi_1,\cos\varphi_3) = 16 - 32\cos\varphi_3 + 16\cos^2\varphi_3 + 48\cos\varphi_1\cos\varphi_3 y - 48\cos\varphi_1\cos\varphi_3 s + 16\cos\varphi_3 xy - 8\cos\varphi_3 s^2 + 8s^2 - 16sy - 28x^2 + 8y^2 - 8\cos\varphi_3 y^2 - 48\cos\varphi_1 s - 48\cos\varphi_1 y - 8\cos\varphi_3 x^2 - 36\cos\varphi_1 s^2 y - 72\cos^2\varphi_1 sy + 36\cos\varphi_1 sy^2 + 12\cos\varphi_1 s^3 + 36\cos^2\varphi_1 s^2 - 4s^3 y + 6x^2y^2 + 2s^2x^2 + 12\cos\varphi_1 sx^2 + 36\cos^2\varphi_1 y^2 + 36\cos^2\varphi_1 x^2 + s^4 + 2x^2y^2 - 4sy^3 - 12\cos\varphi_1 y^3 + y^4 + x^4 - 4sx^2y - 12\cos\varphi_1 x^2 y = 0. \quad (3)$$

The only solution of equation (3) is possible when the desired variables are defined by additional terms or they meet certain quality criteria. For example, it can be assumed, that movement of the links of the anthropomorphic manipulator should satisfy to the criterion of minimal discomfort which is reasonable with biomechanical point of view [46,47]:

$$K = \frac{1}{G}\sum_{i=1}^{n}\left(\gamma_i q_i^{norm} + G\times QU_i + G\times QL_i\right) \Rightarrow \min \quad (4)$$

Where qi, q_{Ni}, q_{Ui}, q_{Li} - i[th]- generalized coordinate, its neutral, maximum and minimum values, respectively;

$q_i^{narm} = \dfrac{q_i - q_{Ni}}{q_{Ui} - q_{Li}}$; γ_i and G - weight coefficients;

$$QU_i = \left\{0.5\sin\left[\frac{5.0(q_{Ui}-q_i)}{q_{Ui}-q_{Li}} + \frac{\pi}{2}\right] + 1\right\}^{100};$$

$$QL_i = \left\{0.5\sin\left[\frac{5.0(q_i-q_{Li})}{q_{Ui}-q_{Li}} + \frac{\pi}{2}\right] + 1\right\}^{100}$$

Let's introduce following designations of the variables: $q_1 = s$, $q_2 = \cos\varphi_1 = c1$, $q_3 = \cos\varphi_3 = c3$ and set the desired limits of their changes:

$s^{\min} \le s \le s^{\max}$; $c1^{\min} \le c1 \le c1^{\max}$; $c3^{\min} \le c3 \le c3^{\max}$. (5)

In addition, to be able further to formalize the process of exclusion of variables, let's decompose the criterion (4) in a Taylor series in powers q_i in neighborhoods q_i^{norm}, $i = 1,2,3$. As a result we obtain a certain polynomial K^* that with increasing degree of q_i will seek to K.

The objective function of optimization problem can be written as follows:

$F(s,c1,c3,\lambda) = K^*(s,c1,c3) - \lambda U(s,c1,c3)$, (6)

where λ - Lagrange multiplier; $c1 \equiv \cos\varphi_1$; $c3 \equiv \cos\varphi_3$.

The necessary conditions of the extremum of function (6) are as follows:

$\dfrac{\partial F}{\partial s} = 0; \dfrac{\partial F}{\partial c1} = 0; \dfrac{\partial F}{\partial c3} = 0; \dfrac{\partial F}{\partial \lambda} = 0$. (7)

Excluding, for example, by the method of resultants [48] the variables $\lambda, c1, s$ of equations (7), we obtain a polynomial equation

$g(c3) = 0$, (8)

which solution $c3(x,y)$ for each pair (x,y) can be obtained by one of numerical methods, for example, as it is presented in [49]. Others unknown in the system (7) are defined substantially easier.

In graphic form the solution of the inverse kinematics problem of the manipulator during motion of base point D on the circle of radius $r = 0.8$ with center at the point $S(3.0,2.0)$ chosen for illustration, are shown in Figure 4a. Set of the manipulator configurations that meet the requirements of this example is shown in Figure 4b.

a)

b)

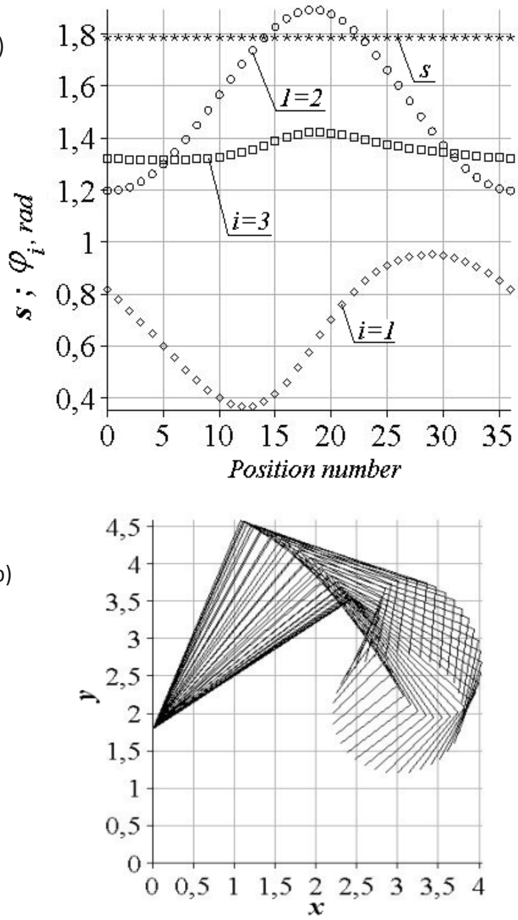

Figure 4: Point D motion on the circle of radius $r = 0.8$ centered at the point $S(3.0,2.0)$: a) graphs of functions $\varphi_i = f_i(k)$, $i = 1,2,3$ and $s = f_4(k)$; the set of the manipulator configurations

The presented examples illustrate only partial problems of mechanisms synthesis that work in the mechatronic systems. During their solution it is often necessary to use different (in character) quality criteria which at the stage of the metric synthesis can have dynamic content, and vice versa. Hence, the distribution of synthesis process on stages in the new concept is conditional. The most appropriate should be considered the parallel performance of all necessary stages between which there are cross relationships, are established to ensure the unity of the synthesis process.

Synthesis criteria elements of mechatronic systems is usually are realized on the basis of a set of quality criteria that can have controversial character. In this case, in order to maximize formalize the synthesis process it is appropriate to use one of the methods of systematic research of parameters space, for example, Sobol-Statnikov method [43]. Its effectiveness is determined by capabilities of computer facilities, reliability and speed of algorithms for calculating the values of objective functions. In this connection, special importance is got by the problem of choice methods for solving of nonlinear equation systems of large dimension.

Implementation of the New Concept at the Synthesis of the Real Mechatronic Device

A synthesis subsystems of mechatronic system to simulate wear hip joint endoprostheses: For simulation wear of spherical heads hip joint endoprostheses, testbench based on mechatronic modules Festo was developed in accordance with the requirements of ISO/DIS 14242-1 (Figure 5) [50]. Later, after modification of the receiving devices of tested objects, testbench was adapted for fatigue tests transpedicular fixation systems of spine according to ISO/DIS 18192-1 [51]. When testbench creating as an integral system were used principles of the concept of mechanisms synthesis formulated above.

Figure 5: General view of the testbench for simulation wear of spherical heads hip joint endoprostheses

The mechanical system of the testbench is designed to implement rotational movements FE, AA and IOR[1] of the tested object

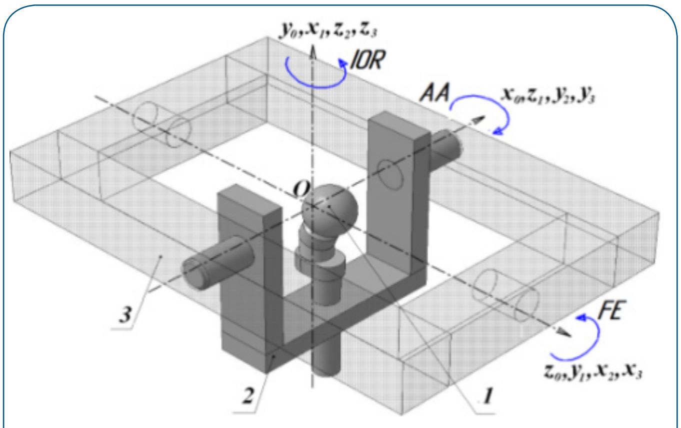

Figure 6: The absolute and local coordinate systems associated with rotating links of the mechanical system: 1 - head of a test specimen; 2 - U-shaped bracket; 3 - carriage

1 with respect to a certain point O fixed relatively to the base (Figure 6). Additionally the mechanical system includes a device for creating the load applied to the test specimen. Thus every

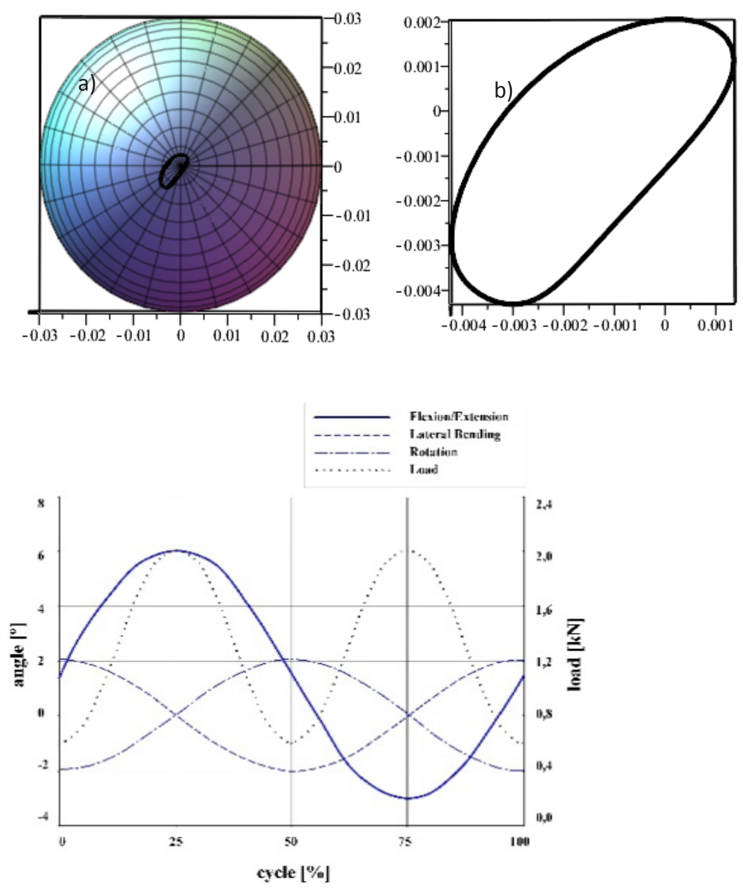

Figure 7: The trajectory of the pole head of tested endoprosthesis (a) corresponding to laws changing of generalized coordinates of the mechanical system according to ISO/DIS 18192-1 (b)

1 FE: flexion/extension - rotation by an angle φ that provides human step during walking;
AA: abduction/adduction - rotation by an angle ψ that provides thigh swinging in the transverse plane; IOR: inward/ outward rotation - rotation by an angle θ that provides thigh rotation around the vertical axis.

point on the sphere surface, center of which is at the point O, moves along a certain trajectory (Figure 7a) that is defined by its radius and laws of specified rotations: $FE = \varphi(t)$, $AA = \psi(t)$, $IOR = \vartheta(t)$ (Figure 7b).

At the initial stage of the synthesis was performed the analysis multiple variants of the mechanical system structure. As a result the mechanical system with series-parallel structure was selected: with serial arrangement drives of rotational movements and parallel functioning loading device. It is clear that the operation of the device having such a structure is possible only if the synchronization of drives can be ensured.

At the second stage synthesis as executive mechanisms of mechanical system were chosen simplest slider-rocker mechanisms (except that IOR movements are reproduced directly). Their metrical synthesis was carried out taking into account required amplitudes of rotational motions output links at given displacements of input links.

Stages of the metric and dynamic synthesis of mechanisms were performed in parallel with their computer modeling. As a result, were chosen typical mechatronic modules and were created 3D-models of mechanism that satisfy given kinematic and dynamic conditions. To drive the load device and the rotation mechanism of the carriage (EF) were selected electromechanical axes EGC-185-100-TB-KF-50H-GK-ZUB-2MY2X, and for the rotation mechanism of U-shaped bracket (AA) - the electromechanical axis EGC- 120-50-TB-KF-50H-GK-ZUB-2MY2X; for direct reproduction of motion IOR uses a stepper motor EMMS-ST-87-M-SEB with an internal reducer. As an example, Figure 8 shows the kinematic scheme and 3D-model of the loading mechanism of mechanical system.

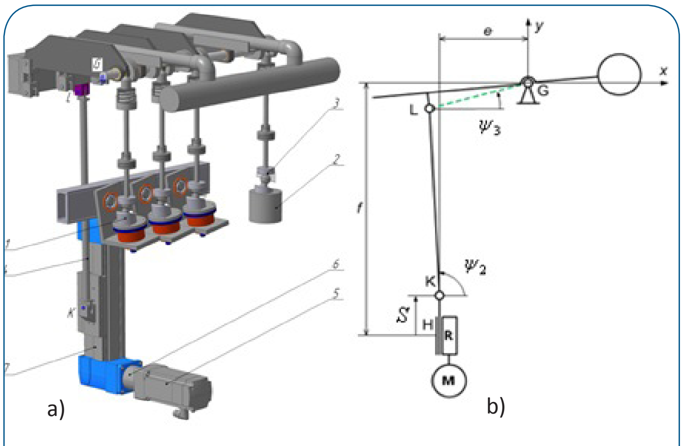

Figure 8: The loading mechanism of mechanical system: a) 3D-model; b) the kinematic scheme

Calculations showed that unlike drives that implement rotations of AA and IOR, rotation drive of the carriage (FE) should provide more essential driving forces. This is explained, firstly, by the big moment of inertia of the carriage ($JCar > 7{,}0\ kg.\ m^2$), considering units and counterweights installed on it, and, secondly, more big amplitude of movements which regulated by the ISO standards ($\Delta\varphi_{Car} \approx 45^\circ$). Therefore, to ensure the carriage movements accuracy in accordance with the necessary laws, it is necessary to use the adaptive control system.Schematic diagram of three-modular control system of the testbench is shown in Figure 9.

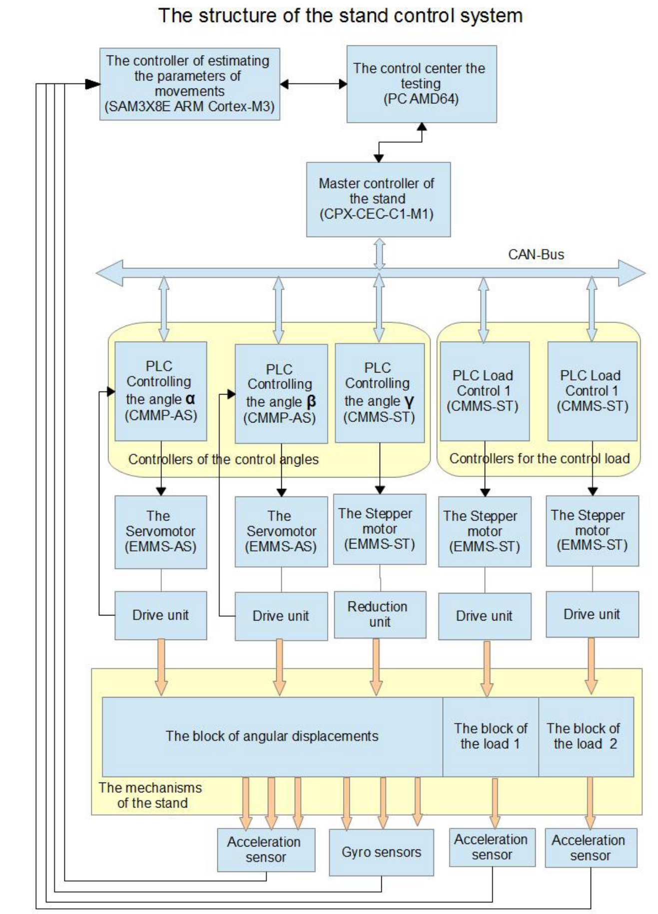

Figure 9: Schematic diagram of three modular control system of the testbench

It is based on means of computer technologies and includes in its structure the following types of devices: personal computer with architecture PC (AMD64); programmable industrial controller with the software CoDeSys 2.3 and SoftMotion, that supports PLCOpen; program-logic controllers of Festo; controller with architecture ARM Cortex-M3.

The testbench control module is designed for testing process control, the test progress planning, for programming and configuration of all computer modules. The base of control module is a personal computer under the operating system Windows 7 Pro. The software includes following components: CoDeSys 2.3 - Industrial computers programming system; FCT - Software Standard Tool for Configuring and Commissioning Electrical Drives by Festo; Program of accumulation, storage and searching of test results, are based on database management systems; Program of statistical analysis and visual representation of the data, are based on Rstudio IDE (R-tools).

Motion control module built on the basis of industrial controllers of Festo, provides movement of tested objects on the given trajectory and supplies the required load. It consists of the following controllers: Terminal CPX-CEC-C1-M1; Two program-logic controllers CMMP-AS of servomotors; Three program-logic controllers CMMS-ST of stepper motors.

The terminal is a 32-bit program-logic controller designed to control by controllers of drives through CAN-Bus. This controller is programmed according to the standard IEC 61131-3 and supports SoftMotion PLCOpen. Its main tasks – to provide synchronous movements. Programming and program settings are carried out through the testbench control module in the environment CoDeSys. PLC of the drives serve as slave devices and perform commands of CPX terminal according to protocol CANOpen. The initial setup of controllers is carried out through the control module in the environment FCT.

The movement parameter estimation module is built on 32-bit microcontroller based on SAM3X8E ARM Cortex-M3 from Atmel. The controller is designed for the independent calculation of parameters of motion of tested objects according to information received from micro sensors of linear accelerations and angular velocities. As sensors, 3DOF accelerometers MMA7361 (Sparkfun Electronics) and gyroscopes ITG 3205 (InvenSense Inc.) are used.

Software is created out in the environment Arduino IDE 1.5 (Rei VILO). It is processing data from sensors using recursive algorithms for parameter estimation using the Kalman filters. Processed data comes from the estimation module to the testbench control module where they are synchronized with the data about coordinates from the motion control module. Subsequently these data are used to evaluate the results of control.

Discussion

In the new concept of synthesis mechanisms working as a part of the mechatronic system, there is no need for providing certain constructive kinematic transfer functions. But such mechanisms should provide the required movement type, size and shape of the work area. The most effective in such cases are the mechanisms with several degrees of freedom. If they have the redundant degrees of freedom, then for the implementation of unambiguous movements is necessary take into account different criteria of quality, allowing to eliminate the kinematic redundancy. Criterial synthesis methods of mechanisms with redundant mobility developed in sufficient detail and, therefore, in this article are not considered.

One of the important steps of mechanisms synthesis is the stage of solving the problem of motion planning. Thus, as shown above, various approaches may be used. It is clear that the inclusion of a variety of quality criteria will lead to different solutions of the problem of motion planning.

One of the significant advantages of mechatronic systems is the possibility of their quick reconfiguration and using in different workflows. So, the stand discussed above as the example, originally was designed to simulate wear of total hip endoprostheses, and can be easily modified to be used for certified testing of intervertebral disc endoprostheses, transpedicular spinal fixation systems, spherical friction couples of vehicles suspensions, etc. At this, the special importance acquires accuracy of movements, which may be realized by the advanced control system.

In the testbench for simulation wear of spherical heads hip joint endoprostheses the test object control can be carried out by setting various laws of motions output elements of electromechanical axes or forces they create. The program, by means of which is carried out setting of the necessary laws of motions, is made in the control module using CAM Package of SoftMotion Editor. This procedure is performed by the operator in graphical mode for drives motions all degrees of freedom of the testbench. After entering, the information is automatically digitized and recorded in tabular form in the terminal CPX-CEC-C1-M1. Figure 10 shows the window of GUI CAM of the SoftMotion Editor in

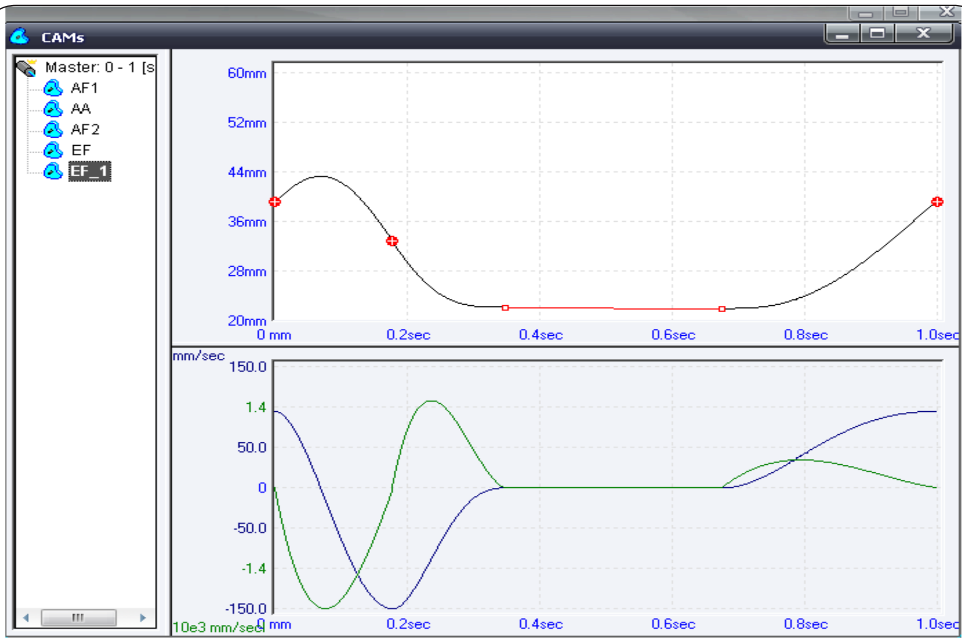

Figure10: GUI CAM of the Soft Motion Editor in CoDeSys

CoDeSys, in which given by the desired law of motion. In this example it is the law of motion of the carriage with delay in one of the end positions.

Figure 11 shows the dynamics of implementation of the given motion law under the influence of the testbench control system. It is easy to see that under given conditions the actual law of motion of the slider of electromechanical axis (red curve) almost coincides with the necessary one (blue curve).

Analysis of test results has shown that the control system of testbench allows to realize many complex laws of motion within the capabilities of drive mechatronic modules used in given mechatronic system. As an example, in Figure 13 is shown the dynamic of the movement process of the slider of electromechanical axis by law with a constant speed (in a certain region).

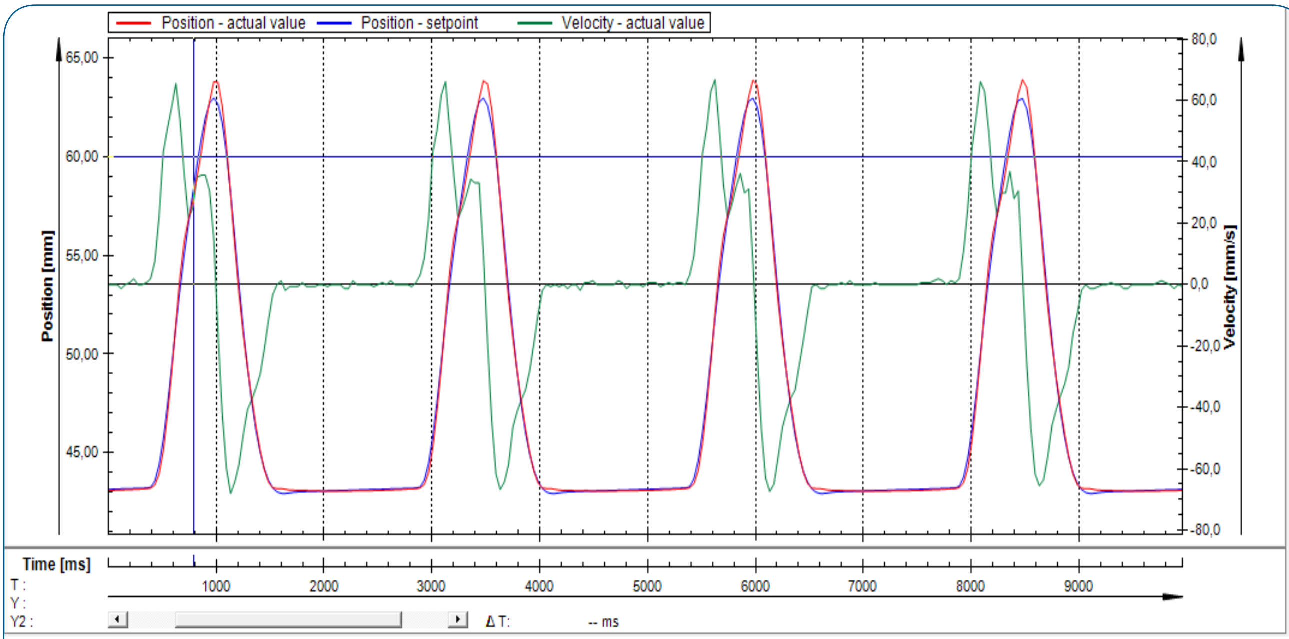

Figure11: The dynamics of the slider movement electromechanical axis in drive of carriage rotation (FE) during the implementation of the motion law with delay

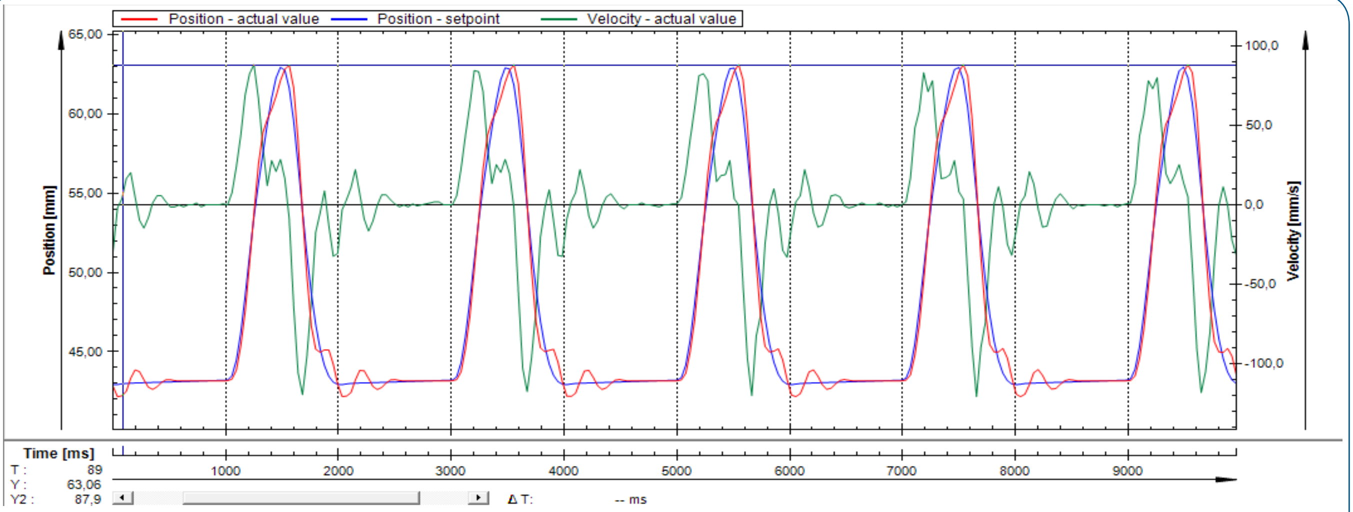

Figure 12: The dynamics of the slider movement electromechanical axis in drive of carriage rotation (FE) with strongly pronounced overregulation at appreciable increase in speed

However, it should be noted that drive control system is able to accurately track the given laws of motion only within certain limited parameters of electromechanical axis. For example, at the speed increasing (which requires more power), the differences in the given and realized motion laws become noticeable (Figure 12).

Conclusion

The development of mechatronics as a science determines necessity to develop not only new synthesis methods of mechatronic system elements, but also the formation of innovative approaches to the synthesis, taking into account the synergistic

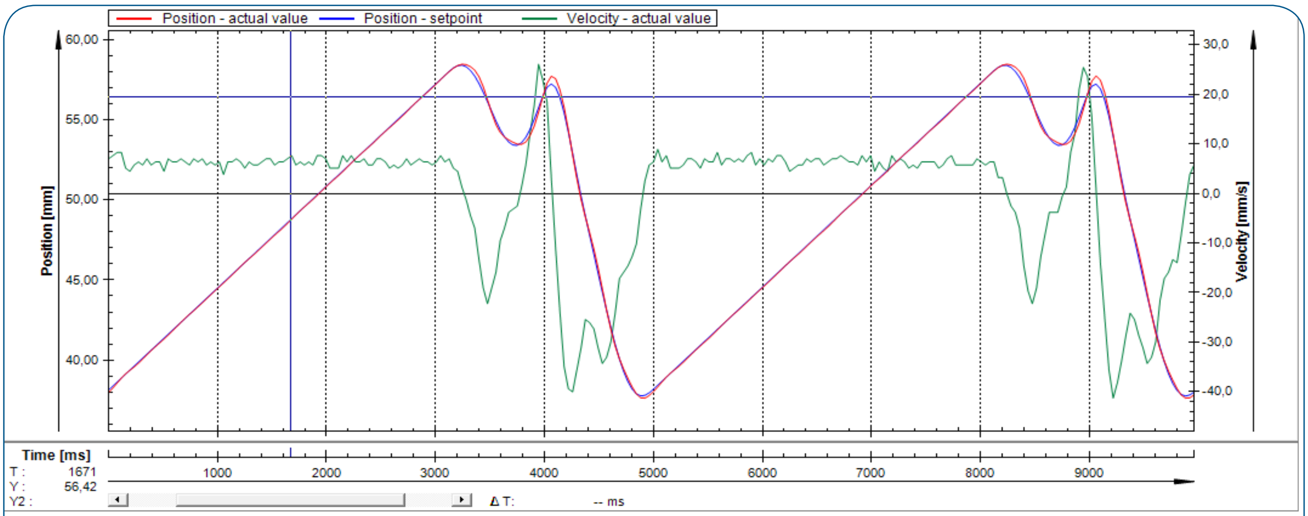

Figure 13: The dynamic of the movement process of the slider of electromechanical axis by law with a constant speed

relationships of all system elements. Synthesis process should be seen as a system of relations between necessary stages, including (in the general case): formulation of the problem, multicriteria synthesis of structure elements, design, manufacture, assembly, installation, operation, repair and disposal of objects.

Referring to mechanisms of mechatronic systems, it can be argued, that the concept of synthesis should also be based on the system approach with features, typical to classical synthesis. For example, in the provisions formulated by us it was proposed to use mechanisms of simplest structures that can carry out the necessary movements. It was also noted that the kinematic transfer functions such mechanisms in this case have secondary importance. However, the development of synthesis methods of mechatronic systems mechanisms, obviously, will lead to the change of this approach. For example, mechanisms with a simple structure represent particular interest, when their kinematic transfer functions provide the least impact on the quality of transition processes for different laws of motion of executive bodies. Many alternative ways can be offered to solve trajectories planning problems of executive bodies, which in turn will affect the algorithms and element base of control systems. Fundamentally the situation could change also in case of the creation of qualitatively new driving modules.

Formulated bases of the new concept of synthesis over a long period of time have been used in practice of synthesis of some specialized technical devices (such as robotic manipulation systems). However, to the present time its general theoretical framework and methods are not yet developed. In this work the authors attempted to formulate the problem and show that on the basis of the proposed concept can be successfully resolved the problems of synthesis of modern mechatronic systems that meet the standards of modern technology.

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