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THE CONCEPT OF CONSTRUCTING SET-THEORETIC MODELS OF STRUCTURES OF INTELLIGENT MULTI-AXIS MECHATRONIC ROBOT MODULES

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Abstract. *The article discusses the features and areas of application of multi-axis electromagnetic mechatronic modules in modules of mechatronic and robotic systems that allow not only to increase productivity and improve the quality of manufactured products, but also by replacing heavy, monotonous and sometimes associated with a risk to human health, manual labor with a machine to release a person for creative constructive work. The generalized structure of a multi-axis mechatronic module is presented; multiple theoretical models of construction principles for the study of electromagnetic mechatronic modules of robots and robotic systems are constructed. In this case, the main attention is paid to the determination of the main and auxiliary sources of the magnetic field in such modules. An algorithm for the formation of equations for electromagnetic mechatronic modules is given on the example of an electromagnetic mechatronic module with linear motion, formed from electrical, magnetic and mechanical components interconnected with each other. The algorithm includes questions of constructing a structural model, the transition from a structural model to a structural-mode model, the choice of variables and connections between the electrical, magnetic and mechanical parts of the module, writing the equations of nodal parallel or contour sequential variables according to the structural-mode model, depending on the appropriateness of one or another method for specific components of the mechatronic module.*

Keywords: *Mechatronic module, robot, robotic system, sources of magnetic field, multiple theory model.*

1. Introduction

The intensification of work in the field of mechatronics and robotics, which is currently observed in the whole world, is due to both economic and social needs in the creation of new technology that allows not only to increase labor productivity and improve the quality of products, but also by replacing heavy, monotonous and sometimes associated with a risk to human health of manual labor by machine tools to release a person for creative constructive labor and are relevant [1].

2. Literature review

The considered multi-axis electromagnetic mechatronic linear motion module (MEMMLD) is characterized by simplicity and manufacturability of design, allows for direct, without information conversion, control from a computer or microprocessors, is convenient both for embedding directly into the design of a robotic system, and for maintenance and repair [2]. The module also has high reliability and low noise floor. From the point of view of functionality, it is characterized by a wide range of dynamic states with the provision of stop and reverse at points set within the working stroke, the ability to operate in discrete and continuous motion modes with the provision of artificial change in the price of a step, as well as an auto-synchronous motion mode with its inherent improved energy performance and high speed [2, 3].

3. Materials and methods

To obtain linear motion of the moving part (MP), electromagnetic mechatronic modules (EMM) are used with direct conversion of electrical energy into kinetic energy of linear motion of the MP and with the transformation of rotary motion into linear motion using mechanical gears (connecting rod - crank, cam, eccentric, etc. device).

The generalized structure of the EMM multi-axis actuators is shown in Fig. 1.

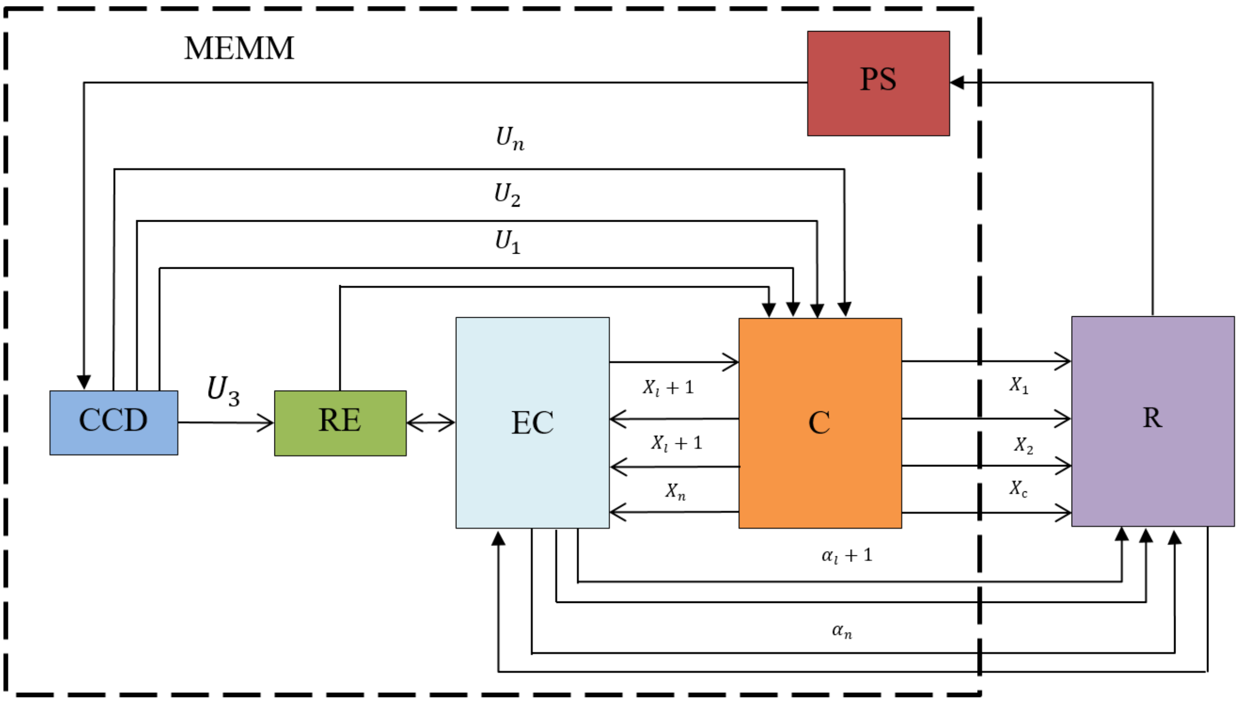

Fig. 1. Generalized block diagram of a multi-coordinate electromagnetic mechatronic module:

MEMM- multi-axis electromagnetic mechatronic module; CCD-computer control device; RE- reciprocating engine; EC-elements of conjugation; C-couplings; R-robot; PS-position sensor.

The principle of constructing multi-output EMM is based on the supply of reciprocating motion with several couplings, controlled by a separate computer control device.

The generalized block diagram of MEMMLD (Fig. 1) includes a computer control device (CCD), a reciprocating engine (RE), combined into groups of traction and fixing clutches (C), mechanical connected to RE, interface elements made in the form of non-magnetic rods flexible cables, converting organs associated with the robot's control devices, the computer control device is used to control the motor, working and fixing couplings in accordance with the relevant law [4].

RE can be performed on the basis of electromagnets, or pneumatic or hydraulic drives and serves to ensure the reciprocating movement of the working bodies of the robot. The separate traction fixing clutches are controlled from the control device and, through the interface elements, interacts with the regulating bodies. In this case, independent linear movements of the interface elements can be transmitted to the control bodies either directly or through intermediate rods using traction and fixing couplings, as well as controlled from the control device, or through converting bodies [4, 5].

The shape, size, position, principle of operation of couplings, depending on the nature and type of load, are performed differently.

The interface elements are used to transfer the movements of the traction couplings to the control elements of the control object and are different shafts, rods, flexible elements (cables), the shapes, sizes and materials of these units can be different (rigid, flexible, tubular, ferromagnetic, non-ferromagnetic, etc.).

The transforming organ is used to transform the linear movements of the conjugation elements into angular ones.

Various roller systems of drums, gears, pulleys, etc., can be used as converting bodies. since elements that are directly connected to the controls of the robot [6, 7, 8].

Clutches by the method of holding the object are mechanical, hydraulic, pneumatic, electromagnetic.

4. Results and Discussion

The method for obtaining several linear and angular motions is based on converting the reciprocating motions of two moving parts moving in the opposite direction into $n(n \geq 2)$ independent linear and angular movements of rods and cables by alternately turning on and off a group of $2n$ working and n fixing couplings, controlled separately for each independent movement from the control device. The functions of converting X to X_i, $i = \overline{1, n}$, are set by the laws of changing the signals of the control device $U_1, U_2, ... U_n$ in time [1, 8, 9].

As a result, the reciprocating movements of the RE are transformed into a set of linear $(X_1, X_2, ... X_e)$ or angular $(\alpha_{e+1}, \alpha_{e+2}, ... \alpha_n)$ movements, which are transmitted to the moving links by means of transmission mechanisms in particular to the degrees of mobility of a robot arm or a robotic system.

A characteristic feature of intelligent EMMs with direct conversion of electrical energy is the absence of mechanical transmissions, simplicity of design, high reliability and low cost. Determination of the full class of possible principles for constructing such EMM with linear motion can be achieved using the concept of a magnetic field source (FS), the definition of varieties of FS and functional dependencies of the FS on the geometric coordinates of the EMM [1, 8, 9, 10].

In such EMM systems, the workflow is based on the interaction of magnetic fluxes generated by various components of the system. In the general case, the set of main parts can be divided into two systems of sets of magnetic field sources, depending on the function performed. We will call one of these systems a set of main sources of a magnetic field (MSF), and the other - a set of auxiliary sources of a magnetic field (ASF). In this case, by the main source of the field we mean a source, the energy of which is directly converted into a convertible useful mechanical or electrical energy. An auxiliary source of a field is understood as a source, the energy of which is not directly converted into a convertible useful mechanical or electrical energy.

Usually, the sources of the magnetic field are a winding with a current (CW), a permanent magnet (M), a ferromagnetic core (C), a shield (S) and their various combinations [1, 3, 10, 11].

The complete set of magnetic field sources is a system of three disjoint sets:

$$U = \{A, \overline{A}, B\}, \tag{1}$$

where $A -$ is a set of independent sources of a magnetic field;

$\overline{A} -$ a set of dependent magnetic field sources;

$B\ -$ a set of combined sources of magnetic field.

In this case, an independent source of a magnetic field is understood as a source, the field of which is created by the current of an independent voltage source. $A = \{\{C\}\}$, i.e.

$A\ -$ one-element set, the only element of which is the winding with current $\{C\}$.

By a dependent source of a magnetic field, we mean a source, the field of which is created by a macro or microcurrent that depends on other magnetic fields.

$$\overline{A} = \{M, C, S, MS, MC, CS, MCS\} \quad (2)$$

The elements of the set $\overline{A}$ are a permanent magnet (M), a ferromagnetic core (C), a screen (S), a permanent magnet - a ferromagnetic core (MC), a ferromagnetic core-screen (CS) and a permanent magnet - a ferromagnetic core - screen (MCS).

The elements of the set $\{\overline{B}\}$ are possible combinations of independent and dependent field sources, such as a winding - a permanent magnet (WM), a winding - permanent magnet - screen (WS), a winding - a screen (WS), a winding - a permanent magnet - screen (WMS) and winding - permanent magnet - ferromagnetic core - screen ($WMCS$). The elements of the set $\{\overline{B}\}$ are possible combinations of independent and dependent field sources, such as a winding - a permanent magnet (WM), a winding - a ferromagnetic core (WC), a winding - a screen (WS), a winding - a permanent magnet - shield (WMS) and winding - permanent magnet - ferromagnetic core - shield ($WMCS$). Their various combinations (Fig. 1) [4, 9,].

$$B = \{WM, WC, WS, WMC, WCS, WMS, WMCS\}, \quad (3)$$

From these sources of magnetic field, the elements of the set of MSS are: $\{W\}, \{WM, \{WC\}, \{WS\}, WMC\}, \{WMS\}, \{WCS\}, \{WMCS\}$; an ASS :$\{W\}$, $\{\mathrm{M}\}$, $\{\mathrm{C}\}, \{S\}, \{\mathrm{MC}\}, \{\mathrm{C}S\}, \{\mathrm{M}S\}, \{W\mathrm{M}\}, \{W\mathrm{C}\}, \{WS\}, \{W\mathrm{MC}\}, \{W\mathrm{M}S\}, \{W\mathrm{C}S\}$, $\{\mathrm{MC}S\}$, $\{W\mathrm{MC}S\}$. Various combinations of elements of the sets of MSS and ASS give one or another principles for creating EMM. For example, the combination $W\mathrm{C} - \mathrm{C}$, $WC \in \{MSS\}$ and $C \in \{ASS\}$ and is known in the literature as an electromagnetic system; combination of $W - M, W \in \{MSS\}$ and $M \in \{ASS\} -$ magnetoelectric system; combination of $W - W, W \in \{MSS\}, W \in \{ASS\} -$ electrodynamic system: combination of $WC - WC, WC \in \{MSS\}, WC \in \{ASS\} -$ ferrodynamic system; combination $WC - S, WC \in \{MSS\}$ and $S \in \{ASS\} -$ induction system, etc.,[1, 10, 11].

These listed systems are only a part of the full set of possible options for constructing an EMM with rectilinear motion, determined by the above method.

To study the electromagnetic modules of linear motion of robotic systems, it is necessary to form the equations of such modules. According to the structural - regime model of the electromagnetic system, one can write equations, some of which will be independent, determined by the adopted tree (forest). Usually, MEMMLD is characterized by a large number of variables and therefore the choice of the shortest path to the goal plays an important role. We will take this into account in further considerations. In order to formalize the process of transforming the original systems of equations and, therefore, to eliminate errors in the derivation of equations, we will use the methods of nodal parallel and contour sequential variables in the canonical coordinate system.

Let us consider an algorithm for the formation of equations using the example of an electromagnetic mechatronic module with rectilinear motion, formed from electrical, magnetic and mechanical components interdependent with each other.

The first step in solving the problem is to build a structural model.

The second step is the transition from a structural model to a structural - regime model formulated in accordance with the rules. The obtained structural - regime model of MEMMLD is given in [1, 4, 10].

In this case, it is necessary to make a choice of variables and connections between electrical, magnetic and mechanical circuits.

The choice of variables and the indicated connections between them determines the type of the MEMMLD equations. In this case, MEMMLD, there are the following relationships between the variables of dissimilar circuits:

$$U \subset F, \phi \subset I, \phi \subset f, X \subset \delta,\ Z_{mYa}, X \subset Y_E;$$

$$I \subset F, \qquad U \subset \phi.$$

The third step consists in writing the equations of nodal parallel or contour sequential variables according to the structural-mode model, depending on the expediency of one method or another for specific components of the MEMMLD electrical, magnetic and mechanical circuits.

In this case, for the MEMMLD electrical circuit, we use the method of nodal parallel variables, and for magnetic and mechanical circuits, the method of contour sequential variables in matrix form, and at the same time we obtain an expanded matrix in the canonical coordinate system. This matrix will be composed of electrical, magnetic, mechanical and interconnection submatrices [1, 10, 11].

To derive the matrix equations of the nodal parallel variables of the MEMMLD electrical circuit, we will compose a structural matrix.

$$\prod = \begin{Vmatrix} 0 & -1 & -1 & 0 & 0 \\ 0 & 0 & +1 & +1 & +1 \\ +1 & 0 & 0 & -1 & 0 \end{Vmatrix} \tag{4}$$

Let us write down the product of the conductivity matrix Y_B and the transposed structural matrix $\prod^t$.

$$Y_B * \Pi^t = \begin{Vmatrix} y_{26} & 0 & 0 & 0 & 0 \\ 0 & y_{27} & 0 & 0 & 0 \\ 0 & 0 & y_{24} & 0 & 0 \\ 0 & 0 & 0 & y_{25} & 0 \end{Vmatrix} * \begin{Vmatrix} 0 & 0 & +1 \\ -1 & 0 & 0 \\ -1 & +1 & + \\ 0 & +1 & -1 \\ 0 & +1 & 0 \end{Vmatrix} =$$

$$\begin{Vmatrix} 0 & 0 & y_{26} \\ -y_{27} & 0 & 0 \\ -y_{24} & y_{24} & 0 \\ 0 & y_{25} & -y_{25} \end{Vmatrix} \tag{5}$$

Therefore, the conductivity matrix,

$$\text{У}_\text{у} = \Pi \text{У}_\text{у} \Pi^t = \begin{Vmatrix} 0 & -1 & -1 & 0 & 0 \\ 0 & 0 & +1 & +1 & +1 \\ -1 & 0 & 0 & -1 & 0 \end{Vmatrix} \cdot \begin{Vmatrix} 0 & 0 & y_{26} \\ -y_{27} & 0 & 0 \\ -y_{24} & y_{24} & 0 \\ 0 & y_{25} & -y_{25} \end{Vmatrix} =$$

$$\begin{Vmatrix} y_{27} + y_{24} & -y_{24} & 0 \\ -y_{24} & y_{24} + y_{25} & -y_{25} \\ 0 & -y_{25} & y_{26} + y_{25} \end{Vmatrix} \tag{6}$$

taking into account the interconnections of the circuits

$$\text{У}_\text{у} = \begin{Vmatrix} \text{У}_{27}(x) + \text{У}_{24} & -\text{У}_{24} & 0 \\ -\text{У}_{24} & \text{У}_{24} + \text{У}_{25} & -\text{У}_{25} \\ 0 & -\text{У}_{25} & \text{У}_{26}(x) + \text{У}_{25} \end{Vmatrix} \tag{7}$$

For the magnetic circuit, we determine the contour magnetic resistance matrix. Let's compose a contour matrix for this chain:

$$\text{y}_{\text{y}} = \begin{Vmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{Vmatrix} \tag{8}$$

Next, we find the product of the resistance matrix of the branches and the transported contour matrix

$$Z_B * \Gamma^t = \begin{Vmatrix} Z_{29} & & & & & & & \\ & Z_{30} & & & & & & \\ & & Z_{31} & & & & & \\ & & & Z_{32} & & & & \\ & & & & Z_{33} & & & \\ & & & & & Z_{34} & & \\ & & & & & & Z_{35} & \\ & & & & & & & Z_{36} \end{Vmatrix} \cdot \begin{Vmatrix} 1 & 0 \\ 1 & 0 \\ 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 1 \\ 0 & 1 \\ 0 & 1 \end{Vmatrix} =$$

$$\begin{Vmatrix} Z_{29} & 0 \\ Z_{30} & 0 \\ Z_{31} & 0 \\ Z_{32} & 0 \\ 0 & Z_{33} \\ 0 & Z_{34} \\ 0 & Z_{35} \\ 0 & Z_{36} \end{Vmatrix} \tag{9}$$

Determine the matrix of contour magnetic resistances

$$Z_k = \Gamma * Z_{\text{в}} * \Gamma^t = \begin{Vmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{Vmatrix} \cdot \begin{Vmatrix} Z_{29} & 0 \\ Z_{30} & 0 \\ Z_{31} & 0 \\ Z_{32} & 0 \\ 0 & Z_{33} \\ 0 & Z_{34} \\ 0 & Z_{35} \\ 0 & Z_{36} \end{Vmatrix} =$$

$$\begin{Vmatrix} Z_{29} + Z_{30} + Z_{31} + Z_{32} & 0 \\ 0 & Z_{33} + Z_{34} + Z_{35} + Z_{36} \end{Vmatrix} \tag{10}$$

taking into account the interconnections of the circuits

$$Z_k = \begin{Vmatrix} Z_{29} + Z_{30}(x) + Z_{31}(x) + Z_{32}(x) & 0 \\ 0 & Z_{33} + Z_{34}(x) + Z_{35}(x) + Z_{36}(x) \end{Vmatrix} \tag{11}$$

Similarly, we determine the matrix equation for a mechanical chain and compose an expanded matrix in the canonical coordinate system, taking into account all interrelationships in the MEMMLD, which has the form (Table 1) [9, 10].

Table 1: Matrix in the canonical coordinate system

	J	f	x	U_1	U_2	U_3	φ_1	φ_2	
		-1					$K'_{f\varphi}$	$K''_{f\varphi}$	**f**
		1	$K_{38} + K_{39}$						**x**
				$Y_{27}(x) + Y_{24}$	$-Y_{24}$		$K'_{T\varphi}$		U_1
H=	-1			$-Y_{24}$	$Y_{24} + Y_{25}$	$-Y_{25}$	$-K'_{T\varphi}$	$K''_{T\varphi}$	U_2
					$-Y_{25}$	$Y_{26}(x) + Y_{25}$		$K''_{T\varphi}$	U_3
				K'_{MH}	$-K'_{MH}$		$Z_{29} + Z_{30}(x) + Z_{31}(x) + Z_{32}(x)$		φ_1
					K'_{MH}	$-K''_{MH}$		$Z_{33} + Z_{34}(x) + Z_{35}(x) + Z_{36}(x)$	φ_2

Matrix N consists of matrices of nodal electrical conductivities $Y_E$and magnetic contour resistances Z_M, matrices $К_{m\phi}, К_{mn}, К_{mx}, К_f$f and the vector K_T − a point image of the current source (Table 2).

Table 2. Nodal admittance matrix

	J	$\vec{f}$	$\vec{x}$	$\vec{U}$	$\vec{\varphi}$	
		K_f				$\vec{f}$
			K_{MX}			$\vec{x}$
$H =$	K_T			Y_E	$K_{T\varphi}$	$\vec{U}$
				K_{MX}	Z_M	$\vec{\varphi}$

5. Conclusions

The electromagnetic mechatronic modules considered in the article are distinguished by the direct conversion of electrical energy into mechanical energy, the absence of mechanical transmissions, simplicity of design, high reliability and low cost. The definition of a complete class of possible principles for constructing such MEMMLD was achieved using the concept of a magnetic field source, determining the varieties of field sources and their functional dependences on geometric coordinates, identifying the features and areas of application of multi-axis mechatronic modules in mechatronic and robotic systems. A generalized structure of a multi-coordinate electromagnetic module with a variety of linear and angular motions has been developed, set-theoretical models of the structures of electromagnetic mechatronic modules of robots and robotic systems have been constructed, an algorithm for forming equations is considered using the example of MEMMLD, formed from electrical, magnetic and mechanical components interdependent with each other. The above MEMMLD equations allow one to study various modes and processes in such modules of robotic systems.

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