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## MATHEMATICAL MODELS OF MULTI-COORDINATE ELECTROMECHATRONIC SYSTEMS OF INTELLECTUAL ROBOTS

H. N. Nazarov

*Tashkent state technical university named after Islom Karimov, nazarov\_hayriddin@bk.ru*

R. O. Temurbek

*Teacher in 'Telecommunication Engineering' department of Urgench branch of Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, rahimov\_timur@bk.ru*

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**MATHEMATICAL MODELS OF MULTI-COORDINATE  
ELECTROMECHATRONIC SYSTEMS OF INTELLECTUAL ROBOTS**

**Nazarov Hayriddin Nuriddinovich  
Doctor of Philosophy of Mechatronics and  
Robotics Department, Tashkent state technical  
university named after Islom Karimov  
E-mail: [nazarov\\_hayriddin@bk.ru](mailto:nazarov_hayriddin@bk.ru)**

**Temurbek Rakhimov Omonboyevich  
Teacher in 'Telecommunication Engineering'  
department of Urgench branch of Tashkent  
University of Information Technologies named  
after Muhammad al-Khwarizmi  
E-mail: [rahimov\\_timur@bk.ru](mailto:rahimov_timur@bk.ru)**

**Abstract:** In the article mathematic description of mechatronic module in intelligent robots and robotic systems are observed. To display the structure of mechatronic modules, which consist of interrelated different electrical, magnetic and



mechatron components, mathematic models by the help of multiplication theory based on relations and visualising lines and points are designed. Analytical explanation of mechatronic models in intelligent robots is provided.

**Keywords:** robotic systems, mechatronic models, mathematic models, intelligent robots.

**Аннотация:** В статье приведено математическое описание мехатронного модуля в интеллектуальных роботах и роботизированных системах. Для отображения структуры мехатронных модулей, которые состоят из различных взаимосвязанных электрических, магнитных и мехатронных компонентов, с помощью теории умножения, основанной на отношениях и визуализации линий и точек, разработаны математические модели. Дано аналитическое объяснение мехатронной модели в интеллектуальных роботах.

**Ключевые слова:** Робототехнических системы, мехатронные модели, математические модели, интеллектуальные роботы.

**Аннотация:** Maqolada intellektual robot va robototexnik tizimlarida mexatronik modulning matematik ta'rifi keltirilgan. Mexatronik modullarning strukturasini bir-biriga bog'liq bo'lgan turli xil elektr, magnit va mexatron komponentlardan tashkil etish uchun o'zaro tahlillarga asoslangan multipleksiya nazariyasi yordamida va matematik chiziqlarni va nuqtalarni ko'rsatish orqali matematik modellar ishlab chiqilgan. Intellektual robotlarda mexatronik modelni analitik tahlil qilish ko'rib chiqilgan.

**Калит so'zlar:** robototexnik tizimlar, mexatronik modellar, matematik modellar, intellektual robotlar.

### **Introduction**

The mathematical description of multicoordinate mechatronic modules (MMM) is the most important stage of the theoretical analysis and synthesis of modules of intelligent robots and robotic systems. At present, the absence of models suitable for a detailed description of the structures of such systems precludes the possibility of automating the design of specific structures.



An element of MMM can be identified with a system that has the properties of material reproducibility and repeatability; therefore, it is naturally possible to define a formal theory of MMM and its model in the language of set theory, as is customary in systems theory.

### Literature Review

To display the structures of MMM, consisting of interconnected heterogeneous electrical, magnetic and mechanical components, in the work there are set-theoretic models operating with the following concepts: relations, mappings, unified relation, lines and points:

$$S = \langle L, P, R_L, \pi, R_{L\pi} \rangle,$$

$$S^{-1} = \langle P, L, R_L, \pi, R_{\pi L} \rangle,$$

where  $L, P$  - many lines and points;  $R_L$  - equivalence relation given in the set  $L$ ;  $\pi$  - combined relation given in the set  $P$ ;  $R_{L\pi}$  - mapping of the set  $L$  in the set  $\pi$ .

Combined relations in the work are called the combination of binary and ternary relations.

$S, S^{-1}$  models are transformed into other forms depending on the properties of the relations  $R_L, \pi$  of  $LR_L\pi$  mappings and the goals of the problem:

$$S_1 = \langle L, P, \mathcal{L}, P, \Gamma \rangle;$$

$$S^{-1} = \langle P, L, P, \mathcal{L}, \Gamma^{-1} \rangle;$$

$$T = \langle L, P, P, C, \Gamma \rangle;$$

$$T^{-1} = \langle P, L, P, C^{-1}, \Gamma^{-1} \rangle;$$

where  $\mathcal{L}, P$  - families of classes of lines and points, respectively,

$$L_i \in L, P_j \in P \text{ для } i = 1, n, \quad j = 1, m;$$

$C$  - family of properties.  $C^{-1}$  - reverse family of properties;  $C_i$  - many properties,

$$C_i = \left\{ \left\{ C_{iki}^j \right\} \right\}, k = \overline{1, l_{ki}}, j = \overline{1, P_{ki}};$$

$C_{iki}^j$  - many private properties,

$$C_{iki}^j = C_{iki}^0 \cap P_i;$$



$C_{iki}^0$  - original line property  $l_{iki}$ .

$\Gamma, \Gamma^{-1}$  - structural and inverse structural sets, respectively;

$$\Gamma = \{\Gamma_i\}, i = \overline{1, l}; \Gamma_i - \text{structural class}$$

$$\Gamma_i = \{\Gamma_{iri}\}, k = \overline{1, l},$$

$$\Gamma_{iri} - \text{structural element}; \Gamma_{iri} = \frac{\{c_{iki}\}}{l_{iki}}, j = \overline{1, P_{ki}}.$$

Three pairs of forms of models (S, S-1, S, S-1, T, T-1) are equivalent in the semantic content of the information presented by them about the system element and differ from each other only in the ways of representation. When operating with models, the interchangeability of components becomes important, which determines the possibility of excluding from consideration certain components of a model at various stages of its use. The latter becomes possible if the necessary part of information about the deleted components of the model is saved in the remaining ones. In models S, S1, T information about the set L is completely contained in the sets PL, RL $\pi$ ,  $\Gamma$ ,  $\xi$ ; information about the set of P- in the sets  $\pi$  R $\pi$ L, G-1, P; information about RL is contained entirely in the sets  $\xi$ ,  $\Gamma$ , and partly in sets C. Information on RL $\pi$  is partially contained in the sets  $\Gamma$  and C. This is shown in Table 1 by graphs whose vertices indicate the amount of information about the components inscribed at the vertices. Solid arcs indicate the complete inclusion of information about a component located at the beginning of the arc. Dotted arcs indicate partial inclusion of information. From Table 1 it can be seen that the exclusion of the component G from the model S1, the components RL $\pi$  from the model of type T is impossible, since in this case the remaining parts of the models lose connectivity.

Table 1

№	Types of models	Model graphs
1	<p style="text-align: center;">S</p> <p style="text-align: center;"><math>\langle K, P, R_L, \Pi, R_{LII} \rangle</math></p>	
2	<p style="text-align: center;"><math>S_I</math></p> <p style="text-align: center;"><math>\langle L, P, \xi, P, L \rangle</math></p>	
3	<p style="text-align: center;">T</p> <p style="text-align: center;"><math>\langle L, P, \xi, C, L \rangle</math></p>	

### Research Methodology

Comparison of models shows a great flexibility of the type T model, which keeps the remaining parts connected even if the component T is removed with the largest amount (number of incoming arcs) of information, which is impossible in other models. This property of the model allows, in the intermediate calculations, to temporarily exclude some of its components and easily transform the structural set  $\Gamma$ , the family of the line  $\xi$  or the family of properties C by removing one of the floors in the expression of the structural element. Based on these considerations, in the work of the model T and T-1 taken as the basis and called structural models.

Analysis of the models showed that all information about the components  $L, \xi, C$  (components  $P, P, C-1$ ) of the structural model  $T$  (models  $T-1$ ) is completely contained in the structural set  $G$  (structural inverse set  $G-1$ ). This allows us to uniquely find the expression of the components  $L, \xi, C$  ( $P, P, C-1$ ) of the structural model by the expression of the structural (reverse structural) set and reduce the task of representing the structural model to the representation of the structural set.

**Definition** The partition of the linear (point) property corresponding to the partition of  $\xi$  (partition of  $P$ ) is called the colored linear (point) property. Structural sets  $\Gamma$  can be linearly colored ( $\Gamma\Delta$ ), point-colored  $\Gamma_T$  and linearly point-colored ( $\Gamma\Delta T$ ) depending on the partitions  $\xi$  and  $P$ . Linearly - pointwise (LT) colored MMM structural sets have the form:

$$\Gamma^{\Delta T} = \{\Gamma_{\Xi}^{\Delta T}, \Gamma_M^{\Delta T}, \Gamma_{MX}^{\Delta T}, \Gamma_{B3}^{\Delta T}\}$$

where,  $\Gamma_{\Xi}^{\Delta T}, \Gamma_M^{\Delta T}, \Gamma_{MX}^{\Delta T}$  - colored structures of the electrical, magnetic, and mechanical subsystems, respectively;  $\Gamma_{B3}^{\Delta T}$  - colored structural sets of the relationship subsystem, which are represented as

$$\Gamma_{\Xi}^{\Delta T} = \{\Gamma_{\Xi 1}^{\Delta T}, \dots, \Gamma_{\Xi 2}^{\Delta T}, \dots, \Gamma_{\Xi K}^{\Delta T} \dots \Gamma_{\Xi C}^{\Delta T}\}$$

$$\Gamma_M^{\Delta T} = \{\Gamma_{M1}^{\Delta T}, \Gamma_{M2}^{\Delta T}, \dots, \Gamma_{MK}^{\Delta T}, \dots, \Gamma_{MC}^{\Delta T}\}$$

$$\Gamma_{MX}^{\Delta T} = \{\Gamma_{MX1}^{\Delta T}, \dots, \Gamma_{MX2}^{\Delta T}, \dots, \Gamma_{MXK}^{\Delta T} \dots \Gamma_{MXL}^{\Delta T}\}$$

$$\Gamma_{B3}^{\Delta T} = \{\Gamma_{B31}^{\Delta T}, \Gamma_{B32}^{\Delta T} \dots \Gamma_{B3K}^{\Delta T}, \dots, \Gamma_{B3c}^{\Delta T}\}$$

$\Gamma_{\Xi K}^{\Delta T}, \Gamma_{MK}^{\Delta T}, \Gamma_{MXK}^{\Delta T}$  - colored structural elements of the electrical, magnetic and mechanical subsystems, respectively;

$\Gamma_{B3K}^{\Delta T}$  - the painted structural element of the relationship subsystem is represented as

$$\Gamma_{\Xi K}^{\Delta T} = \frac{C_{\Xi K}}{\ell_{\Xi K}}, \quad \Gamma_{MK}^{\Delta T} = \frac{C_{MK}}{\ell_{MK}}, \quad \Gamma_{MXK}^{\Delta T} = \frac{C_{MXK}}{\ell_{MXK}}, \quad \Gamma_{B3K}^{\Delta T} = \frac{C_{B3K}}{\ell_{B3K}}$$

Here  $C_{\Xi K}, C_{MK}, C_{MXK}$  - a family of properties of the electrical, magnetic, and mechanical subsystems, respectively.  $C_{B3K}$  - family of properties of the relationship subsystem.

$$C_{\text{ЭК}} = \{C_{\text{ЭК}}^1, \dots, C_{\text{ЭК}}^2 \dots C_{\text{ЭК}}^j \dots C_{\text{ЭК}}^{P_{\text{ЭК}}}\}$$

$$C_{\text{МК}} = \{C_{\text{МК}}^1, \dots, C_{\text{МК}}^2 \dots C_{\text{МК}}^j \dots C_{\text{МК}}^{P_{\text{МК}}}\}$$

$$C_{\text{МХК}} = \{C_{\text{МХК}}^1, \dots, C_{\text{МХК}}^2 \dots C_{\text{МХК}}^j \dots C_{\text{МХК}}^{P_{\text{ЭК}}}\}$$

$$C_{l3k} = \{C_{l3k}^1 \dots C_{l3k}^2 \dots C_{l3k}^j \dots C_{l3k}^{P_{l3k}}\}$$

In them  $C_{\text{ЭК}}^j, C_{\text{МК}}^j, C_{\text{МХК}}^j$ - family of particular properties of the electrical, magnetic, and mechanical subsystems, respectively;  $C_{l3k}^j$  - family of private properties of the relationship subsystem:

$$C_{\text{ЭК}}^j = \{P_{\text{ЭК}j}^1, \dots, P_{\text{ЭК}j}^2 \dots P_{\text{ЭК}j}^l, \dots, P_{\text{ЭК}j}^{P_{\text{ЭК}j}}\}$$

$$C_{\text{МК}}^j = \{P_{\text{МК}j}^1, \dots, P_{\text{МК}j}^2 \dots P_{\text{МК}j}^l, \dots, P_{\text{МК}j}^{P_{\text{ЭК}j}}\}$$

$$C_{\text{МХК}}^j = \{P_{\text{МХК}j}^1, \dots, P_{\text{МХК}j}^2 \dots P_{\text{МХК}j}^l, \dots, P_{\text{МХК}j}^{P_{\text{ЭК}j}}\}$$

$$C_{l3k}^j = \{P_{l3kj}^1, P_{l3kj}^2, \dots, P_{l3kj}^l, \dots, P_{l3kj}^{P_{\text{МХК}j}}\}$$

Table 2

<p style="writing-mode: vertical-rl; transform: rotate(180deg);">Mechatronic module</p>	<p style="text-align: center;">1</p>	
<p style="writing-mode: vertical-rl; transform: rotate(180deg);">Topological image</p>	<p style="text-align: center;">2</p>	



Analytical description	3	$\left[ \frac{1/4 / D18}{24}, \frac{1/2 / D17}{25}, \frac{2/3}{26}, \frac{3/4}{27}, \frac{1/8}{28} \right];$ $\left[ \frac{8/5 / D19}{29}, \frac{5/6}{30}, \frac{6/1}{31}, \frac{1/8}{32}, \frac{9/10 / D20}{33}, \frac{10/11}{34}, \frac{12/9}{36}, \frac{11/12}{35}, \frac{1/11 / D21}{37} \right];$ $\left[ \frac{16/13 / D22}{38}, \frac{13/14}{39}, \frac{14/15 / D23}{40}, \frac{15/16}{41} \right];$ $\left[ \frac{D18 / D20}{42}, \frac{D17 / D19}{43}, \frac{D20 / D22}{44}, \frac{D19 / D22}{45}, \frac{D21 / D23}{46}, \frac{D18 / D22}{47}, \frac{D17 / D22}{48} \right].$
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Here  $P_{\exists K j}^l, P_{MK j}^l, P_{MXK j}^l$ - colored sets of points of the electrical, magnetic and mechanical subsystems, respectively;

$P_{l3kj}^l$  -  $\Lambda T$  colored set of interconnection subsystem points:

$$P_{\exists K j}^l = \{P_{\exists 1}, P_{\exists 2}, \dots, P_{\exists n}, \dots, P_{[\exists P]}\}$$

$$P_{MK j}^l = \{P_{M1}, P_{M2}, \dots, P_{Mn}, \dots, P_{[MP]}\}$$

$$P_{MXK j}^l = \{P_{MX1}, \dots, P_{MX2}, \dots, P_{MXn}, \dots, P_{[MXP]}\}$$

$$P_{l3kj}^l = \{P_{B31}, \dots, P_{B32}, \dots, P_{B3n}, \dots, P_{[B3p]}\}$$

$$P_{\exists K j}^f = \{P_{\exists 1}, P_{\exists 2}, \dots, P_{\exists n}, \dots, P_{[\exists p]}\},$$

$$P_{MK j}^f = \{P_{M1}, P_{M2}, \dots, P_{Mn}, \dots, P_{[mp]}\},$$

$$P_{MXK j}^f = \{P_{MX1}, P_{MX2}, \dots, P_{MXn}, \dots, P_{[m xp]}\},$$

$$P_{l3j}^f = \{P_{B31}, P_{B32}, \dots, P_{B3n}, \dots, P_{[B3p]}\}.$$

In them  $P_{\exists n}, P_{Mn}, P_{MXn}$  points of electrical, magnetic and mechanical - subsystems, respectively;  $P_{B3n}$ - interconnection subsystem point;  $l_{\exists K}, l_{MK}, l_{MXK}$  - lines of electrical, magnetic and mechanical subsystems, respectively;  $l_{B3K}$  - interconnection subsystem line.

Table 2 shows the LD structural sets of a particular mechatronic module [3], which are compiled according to its topological image. In this case, the topological image of MMM is constructed using the abstract concepts of "line" and "dot".

In contrast to the usual ways of displaying MMM graphs of schemes (for example, pole graphs) [4], which do not allow to indicate the entire topology of



interconnections, the latter are described in terms by graphs with two- and three-dimensional points. The MMM graph (Table 2) contains mentally divided four subgraphs: electrical, magnetic, mechanical, and interconnections. Winding on the magnetic core in the MMM column corresponds to the line (25) connecting one-dimensional points (1 and 2)., At the same time. (No. 1-4) - points of the electrical subsystem; (№5-12) - points of the magnetic subsystem; (# 12-16) - points of the mechanical subsystem; (№17-18) - interconnection points (two-dimensional) of the electrical subsystem; (№ 19-21) - points of interrelations of the magnetic subsystem; (№22-23) - interconnection points of the mechanical subsystem; (№24-28), (№29-36), (№37-41) - lines of the electrical, magnetic, mechanical subsystem; (№42-48) - interconnection subsystem lines.

### **Conclusion**

The set-theoretic description of the structures of multi-axis mechatronic modules of intelligent robots and robotic systems allows displaying structures from interconnected physical heterogeneous systems and determining the set of possible structures of modules.

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