THE CONCEPT OF THE MATHEMATICAL DESCRIPTION OF THE MULTI-COORDINATE MECHATRONIC MODULE OF THE ROBOT

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Abstract—The article deals with the concept of mathematical description of multi-coordinate mechatronic modules of robots. The main results of the work are a generalized structure of a multi-coordinate mechatronic module of motion, a kinematic diagram of an electromagnetic multi-coordinate mechatronic module with three independent coordinate linear and angular movements is proposed, consisting of four electromagnets, controlled couplings designed to transmit the reciprocating motion of the moving parts of electromagnets to the output rods and a cable, which are associated with the links of work and bringing them into linear and angular motion. A simulation model of the functioning of the multi-coordinate mechatronic movement module in the MATLAB system has been developed. A mathematical description of the mechatronic module is given, which includes a description of the engine, a description of a mechanical transmission and a control device. An important aspect of the study is the use of a multi-coordinate mechatronic movement module in robots, which allows obtaining several linear and angular coordinates in one module at the output, which reduces the weight and dimensions of the robot and thereby improves its dynamic characteristics. There are no constructive solutions for a similar purpose in the literature. The proposed concept of the mathematical description of the multi-coordinate mechatronic module is original, which are oriented to display their structural and operational features.

Keywords— manipulator, mechatronic module, movements, multi-coordinate module, robots, position module.

I INTRODUCTION

A feature of the modern stage of development of electromagnetic multi-axis mechatronic modules (EMMMs) of robotic systems is the intellectualization of the processes for controlling their functional movements. The main attention is paid to the development of a fundamentally new generation of multi-coordinate modules, in which the integration of three components is carried out - electromechanical, electronic and computer and it is possible to obtain multiple coordinates of the module. The technical implementation of intelligent motion EMMMs has been made possible thanks to the rapid development in recent years of microprocessor systems focused on motion control tasks [1, 2].

II LITERATURE REVIEW

To date, measures are being taken to effectively organize technological processes and emission control systems in the Republic of Uzbekistan. Leading scientific centers and universities of the world, including Bergen Laboratories Ins, University of Michigan General Electric (USA), Sony and Tokyo Technology INSTITUTE, Tashkent State Technical University named after Islam Karimov (Uzbekistan), carry out research on topical issues of developing mechatronic systems and their mathematical models [1]. Increased demand for intelligent automatic control systems requires the use of multi-coordinate mechatronic systems, where initial information is incomplete or inaccurate, a priori focus on working in uncertain environments, the use of non-traditional approaches to management, the use of completely new technologies and artificial intelligence[3].

III MATERIALS AND METHODS

Electromagnetic multi-coordinate mechatronic motion modules make it possible to obtain many linear and angular motions at the output. Continuous improvement of production technologies leads to a stable decrease in the cost of hardware, which has made them by now cost-effective for the practical implementation of EMMM [3, 4].

The generalized structure of the EMMM system of automatic control is shown in Figure 1. The computer control device (CCU) based on the input information coming...
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Fig. 1: The generalized structure of a multi-coordinate motion module

from the upper control level and through the feedback circuits from the sensors; issues control electric signals to the multi-axis actuator modules in time. In power converters, power amplification of these signals and their modulation occur. Then, the executive modules generate the corresponding efforts (forces and moments) for the links of the robot, which as a result provides the targeted movement of the final link of the work - its working body.

To interface the elements, special interface devices I1, I2, I3, I4, I5, I6, I7 are introduced into the system.

Let us look at examples of interlock interfaces that are most often found in computer-controlled robots that are widely used in automated production. Interface I1 is a set of network hardware and software tools for interfacing computer control devices with a computer network, or a human-robot interface, if the control goal of the mechatronic system is set directly by the human operator. Modern human-machine interfaces are implemented in the form of remote controls and handles for remote control (for example, for programming industrial robots by the teaching method) of touch display devices for displaying information in virtual reality systems [3, 4, 5].

The I2 interface usually consists of a digital-to-analog converter and an amplifying-converting device and serves to generate control electric voltages for the executive modules.

The I3 interface is, as a rule, mechanical transmissions connecting the executive modules with the links of the robot. Structurally, such transmissions usually include gearboxes, couplings, flexible couplings, brakes, etc.

The I4 interface at the UCF input, if sensors with an analog output signal are used in the mechatronic module, is based on analog-to-digital converters.

The interfaces of the sensors I5, I6 and I7, depending on the physical nature of the input variables of the state of the system, can be divided into electrical and mechanical. Mechanical devices include connecting devices for module feedback sensors (photo pulse, code revolvers, etc.), torque and tactile sensors, as well as other sensing tools and information about the movement of modules, robot links. It should be noted that the connection of all elements with a computer control device involves not only hardware pairing, but also appropriate software for organizing real-time data exchange [4, 5].

IV RESULTS

There are three areas of intellectualization EMMM:

- development of integrated interfaces connecting the control controller with a top-level computer, a single hardware-software control complex (interface II);
- creation of intelligent power control modules by integrating control controllers and power converters (I2 interface);
- development of intelligent sensors of mechatronic modules, which, in addition to the usual measuring functions, carry out computer processing and signal conversion using flexible programs (I3 interface).

The principle of constructing multi-axis mechatronic modules of linear motion is based on supplying the moving part (armature) of the electromagnet with several gripping organs, which are controlled separately.

An EMMM includes a control device, a block of electromagnets and permanent magnets, gripping organs (other-
wise, controlled couplings), and fastening and coupling elements. Electromagnets are used to convert the input electrical signals into mechanical movements of the reciprocating action, and the gripping organs and interface elements to transmit movement to the organs of movement of the robotic system. Anchors are moving parts of electromagnets. The number of gripping organs corresponds to the number of moving links of the robot.

**Fig. 2:** Three-coordinate EMMM design.

The reciprocating movement at the output of the electromagnet is converted into a set of linear and angular movements of the organs of movement of the robot, coupled by the gripping and (or) coupling organs.

The developed EMMM design with three outputs is shown in Fig. 2. and includes four of the same type of power electromagnet 1, 2, 3 and 4 armored type, anchors 16, 17, 18, 19 of which form two movable parts. Three pairs of electromagnetic couplings 7, 8, 10, 12, 11, 13 are rigidly mounted to the moving parts with the help of strips 5, 6, covering two flexible rods 14, 15 made in the form of a closed loop (not shown in the drawing) and one rigid rod 9.

By setting various control laws for electromagnetic couplings 7, 8, 10, 12, 13, it is possible to obtain independent laws of movement of the rods 9, 14, 15, namely, translational step movements.

The principle of operation of electromagnetic couplings is analogous to that described in [1] and consists in providing rigid coupling of the rods to the moving parts of the EMMM when they are turned on, i.e. when applying constant voltage to their windings. Electromagnetic couplings perform the functions of mechanical keys transmitting the reciprocating movements of moving parts to the rods, the switching on and off of which provide the conversion of the reciprocating movements into translational movements [5, 6, 7]. Does an EMMM contain four of the same type of power electro-
magnet? 1, 3, 4, working synchronously in pairs, i.e. at one moment in time, extreme electromagnets 1, 4 are working, at another moment in time, middle electromagnets 2, 3.

The designs of electromagnetic couplings are also of the same type and, to reduce their time from working, the windings are controlled from forcing pulses [6, 7]. The direction of the coordinate movements depends on the law of change of the control signals received from the computer control device.

V Discussions

In manipulators of industrial robots, the use of a multi-coordinate mechatronic motion module (MMMD) is effective because allows you to get several linear and angular coordinates at the output. In Figure 3. The typical scheme of the multi-coordinate mechatronic module for the movement of robotic arms is given:

MMMD - multi-coordinate mechatronic motion module, movement transfer and conversion mechanism, PS, SS - position and speed sensors, CD, CD1, CD2 - control device and its two parts.

A simulation model of MMMD has been developed in the MATLAB system. And is shown in Fig. 4. The obtained simulation results reflect the output characteristic of the multi-coordinate mechatronic module (Fig. 5).

Along with general position feedback, there is speed feedback in the circuit, which plays the role of corrective flexible feedback and often serves to control the speed. The speed sensor is often placed at the output of the module in front of the mechanism. The control device can be continuous, pulse or digital. According to the control algorithm that determines the nature of the movement at the output of the mechatronic modules, there are distinguished cyclic, positional and contour ones:

- cyclic mechatronic module is a mechatronic module with relay control, which performs one-step movement with a stop at the mechanical stop;
- the position module is a mechatronic module with discrete point-to-point control, that is, it performs step-by-step movement with a stop after each next step;
Fig. 6: Structural diagram of a manipulator with a mechatronic module.

- the contour module is a continuous mechatronic tracking module that ensures the development of a continuous input master signal \( q_3 \), i.e., the equality \( q \cong q_3 \).

In accordance with the dynamics equation of the mechanical system of the manipulator, the mathematical description of the system of the mechatronic module of the manipulator should be a dependence

\[
Q_g = A_n(U_n) \tag{1}
\]

where \( Q_g \) is the vector of the driving forces (moments) at the output of the mechatronic module of the manipulator of dimension \( n \), which sets in motion its degree of mobility; \( A_n \) is the operator of the mechatronic module system; \( U_n \) is the vector of control actions at the input of the mechatronic module [8, 9].

As for the displacements \( q \) at the output of the mechatronic module, since the latter are connected by a common mechanical system of the manipulator, these movements are not independent variables, and to find them it is necessary to solve together a system of equations describing the mechanical system from the mechatronic module.

The mathematical description of the engine of a separate drive with angular displacement (rotating) has the form

\[
\begin{aligned}
J_g \omega_g &= M_g - M_L \\
(T_g p + 1) M_k &= f(U, \omega_k)
\end{aligned} \tag{2}
\]

Here \( J_g \) is the moment of inertia; \( M_L \) - load moment on the motor shaft; \( M_k \) - the driving moment developed by the engine; \( \omega_k \) - angular velocity, \( T_g \) is the time constant of the chain connecting \( M_g \) with control action \( U_n \); \( f(u_n, \omega_k) \) static characteristic of the engine.

In a linear approximation, the last dependence:

\[
f(u_n, \omega_k) = k_u u_n - k_\omega \omega_k. \tag{3}
\]

For an electric motor, \( T_g \) is the electromagnetic time constant, which can usually be neglected, compared to the time constant determined by \( J_g \).

In view of (3), system (2) is reduced to the equation:

\[
(T_g' p^2 + T_g' p + 1) \omega_k = ku_n - \frac{T_g + 1}{k_\omega} M \tag{4}
\]

Where \( T_g' = \frac{J_g}{k_\omega}, \ k = \frac{k_u}{k_\omega} \) At \( T_g = 0 \), equation (4) takes the form

\[
(T_g' p + 1) \omega_k = ku_n - \frac{1}{k_\omega} M \tag{5}
\]

The mathematical description of the mechatronic module as a whole includes, in addition to the description of the engine, a description of the mechanical output gear (for example, a gearbox) and a control device. In accordance with the drive circuit, the algorithm implemented by its control device is PD control. PID control algorithms are also used.

When studying the dynamics of manipulators “in large”, it is necessary to take into account the nonlinearity of the static characteristics of the engine — saturation in \( u_n \) and \( \omega_g \), which limit the speed of the mechatronic module [9, 10, 11].

In general, the mathematical description includes the considered dependencies:
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Fig. 7: Imitation model scheme of a mechatronic modular manipulator

\[
\begin{align*}
  x &= f(q) \\
  q &= A_m(Q_g, Q_b) \\
  Q_g &= A_n(u_n)
\end{align*}
\]  

(6)

Here \( A_m \) and \( A_n \) are the operators of the mechanical system and the mechatronic module system of the manipulator, and \( u_n \) is the vector of control actions at the input of the mechatronic module. If we use the dynamics equation of the manipulator (1) and linearize the equation of the drive (the circuit of which is shown in Fig. 6), we obtain a description of the manipulator with such industrial robot modules:

\[
\begin{align*}
  A(q) p^2 + b(pq, q) + c(q) &= Q_g - Q_B \\
  Q_g &= W_{n2}(p) u_n - J_g p^2 q \\
  u_n &= W_{n1}(p) (q - q_3) - W_{n3}(p) pq
\end{align*}
\]  

(7)

Here \( u_n \) is the vector of control actions at the input of the mechatronic module; \( W_{n2}(p) \) the transfer matrix of the module, connecting the vectors \( Q_g \) and \( u_n \); \( W_{n1}(p) \), \( W_{n3}(p) \) - transfer matrices of sequential and parallel correction links; \( J_g \) is the diagonal matrix of the moments of inertia of the motors reduced to the output of the q module.

The computer model MMM is presented in (Fig. 7.), and the results of modeling are presented in Fig. 8.

At low speeds (approximately less than 0.5 m/s), when the dynamic mutual influence of the modulus is small, this mutual influence on acceleration and velocity can be neglected, i.e., off-diagonal elements of the matrix \( A(q) \) and mixed products of velocities in the expression \( b(pq, q) \). In this case, the left side of equation (8) takes the form

\[
\begin{align*}
  [J_g + J_e(q)] p^2 q + b(pq, q) + c(q)
\end{align*}
\]  

(8)
Here, \( b(pq, q) = \sum_{i=1}^{n} b_{ij}(q) (pq_{i})^{2} \), does not contain the terms \( b_{ij}(q) q_{i} q_{j} \). \( J_{e}(q) = \text{diag}(J_{1e}, J_{2e}, \ldots, J_{ne}) \) is the diagonal matrix of effective moments of inertia with respect to \( q_{i} \) of the \( i \)th and all subsequent links \([i+1], \ldots, n\], which can be determined by the formula

\[
J_{e} = \frac{dQ_{g}}{dq_{i}}
\]

i.e., based on the equation of dynamics of the mechanical system of the manipulator when replacing \( A(q) \) with \( J_{e}(q) \). Accordingly, this expression can be represented as follows:

\[
J_{e}(q) \left( \frac{dq_{i}}{dQ_{g}} \right)^{-1} = A^{-1}(q) i^{-1}
\]

VI Conclusion

This article discusses the concept of building structural-mode models of multi-coordinate mechatron modules of intellectual robots. The proposed concept of the mathematical description of the multi-coordinate mechatron module of the robot allows us to study the structural and operational features of robots operating in different coordinate systems. The above MMMM allows you to get on the basis of a single module located on the basis of the robot many step, independent linear and angular movements of the links of the robot and has wide functionality, small weight and size indicators and improved performance.

References

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