DEVELOPMENT OF AN INTELLIGENT CONTROL STRUCTURE FOR A MECHATRONIC MODULE DISPLAYING 3D GRAPHICS

Rakhimov T.O.,
Department of Mechatronics and Robotics, Faculty of Electronics and Automation, Tashkent State Technical University named after Islam Karimov,
Tashkent, Uzbekistan
E-mail: rahimov_timur@bk.ru

Fakhriddinov A.F.,
Department of Mechatronics and Robotics, Faculty of Electronics and Automation, Tashkent State Technical University named after Islam Karimov,
Tashkent, Uzbekistan
E-mail: faxriddinovazizbek042@gmail.com

Abstract. The article presents the development of an intelligent control structure for a mechatronic module designed to display 3D graphics. The main objective is to achieve high precision in controlling the module's spatial movements, identify its current state using sensor data, and ensure stable operation through feedback. In addition, mathematical models for synthesizing dynamic characteristics according to specified positioning coordinates are introduced. Based on these models, a motion control algorithm and an intelligent system structure ensuring coordinated movement of the executive elements are proposed. The approach provides accurate, reliable, and efficient movement control for the mechatronic module in practical 3D applications.

Keywords: 3D graphics display, mechatronic module, intelligent control structure, coordinate and position motion control, feedback, executive elements, sensor system, control algorithm.

Introduction.

The rapid development of digital technologies, computer graphics, and intelligent control systems today is driving a growing need for mechatronic systems capable of displaying 3D graphics on various surfaces with high precision, speed, and stability [1]. Of particular importance is the effective use of mechatronic modules in industry, education, medicine, architecture, robotics and interactive visualization, ensuring high-precision and efficient execution of movements when displaying 3D graphics in accordance with specified coordinates and positions [2]. Such systems require the development of a control system that ensures precise positioning of graphic objects, their movement along a given trajectory, and stable operation in various spatial positions. From this perspective, the development of an intelligent control structure aimed at continuous monitoring of the module's current state, error detection based on feedback, and their elimination is a pressing task [3,4]. In this area, many studies have been conducted that address issues of projection accuracy, calibration and control of individual executive elements, but a unified intelligent control structure for mechatronic modules displaying 3D graphics has not yet been developed [5,6]. At the same time, existing studies do not sufficiently cover the issues of closed-loop coordinate-position control, complex processing of sensor signals in real time, and coordination of movements of executive elements [7,8]. In addition, most of the proposed solutions have been tested only under limited conditions, while a generalized mathematical model adapted for use on various surfaces and under conditions of external dynamic influences has not yet been developed [9]. The approach proposed in the article pays special attention to the development of an intelligent control structure for a mechatronic module displaying 3D graphics, as well as ensuring high-precision control of its movements, determining the current state based on sensor data, coordinating the movements [10] of executive elements and stable operation based on feedback. In addition, mathematical models are proposed that ensure the formation of motion parameters in accordance with a given coordinate trajectory and positions, as well as intelligent control algorithms developed on their basis.

Research methodology.

Determining control actions for a mechatronic module displaying 3D graphics when it is brought to a given point in space at a given speed. Given initial and final coordinates, as well as the required speed of movement, the mechatronic module displaying 3D graphics can be brought to a given position by solving an inverse dynamics problem [3,11].

To implement the movement of a mechatronic module displaying 3D graphics along a given trajectory, it is necessary to first bring it to one of the points of this trajectory, ensuring that the direction of the linear velocity vector is tangent to it. Let's assume that the gripper initially has coordinates x_k, y_k, z_k, and its linear velocity is zero. We need to determine the control actions that ensure the movement of the mechatronic module displaying 3D graphics with a given velocity vector $\vec{u}_k$ in each of its positions, assuming stability and a damped transient process. The dynamics of a mechatronic module displaying 3D graphics with n degrees of freedom is described by the following differential equation:

$$\sum A_{ij}(q_j, c_j)\ddot{q}_i + B_j(q_j, \dot{q}_i) = Q_j \ (j = 1, \dots, n), \quad (1)$$

where $c_s (s = 1, \dots, m)$ are constant parameters of the mechanism [12]. Therefore, it is advisable to write and solve the problem of the motion of a mechatronic module displaying 3D graphics in vector form:

$$A(\bar{q})\bar{\ddot{q}} + \bar{B}(\bar{q}, \bar{\dot{q}}) = \bar{Q}, \quad (2)$$

where $A(\bar{q})$ is a matrix of size; $\bar{B}(\bar{q}, \bar{\dot{q}})$ is a vector of size $1 \times n$; $\bar{q}, \bar{\dot{q}}, \bar{\ddot{q}}$ are vectors of size $1 \times n$.

The relationship between the generalized coordinates q_i and the Cartesian coordinates of the displayed 3D object can also be represented in vector form:

$$\bar{X} = \bar{F}(\bar{q}), \quad (3)$$

where $\vec{X} = [x, y, z]^T$; $\vec{F}_{(q)}$ – vector size $1 \times n$.

Expression (3) is determined by the features of the structural diagram of the mechatronic module designed to display 3D graphics [13]. Differentiating expression (2) twice with respect to time, we obtain:

$$\bar{\dot{x}} = J(\bar{q})\bar{\dot{q}}, \quad (4)$$

$$\bar{\ddot{X}} = J(\bar{q})\bar{\ddot{q}} + \bar{p}(\bar{q}, \bar{\dot{q}}), \quad (5)$$

where $J(\bar{q})$ – Jacobian matrix, which has the form:

$$J(\bar{q}) = \left[\frac{\partial F(\bar{q})}{\partial \bar{q}}\right],$$

$\bar{p}(\bar{q}, \bar{\dot{q}})$ – vector size $1 \times n$.

To ensure a smooth increase in speed when moving a mechatronic module displaying 3D graphics to a given point, the following speed change law must be applied:

$$\dot{\bar{x}} = \Phi(t)(\bar{v}_0 - \bar{v}_k) - \bar{v}_0, \quad (6)$$

where $\Phi(t)$ is a matrix of the form

$$\Phi(t) = \exp At,$$

For the system to be stable, all eigenvalues of the matrix must have a negative part [4,14]. We write the solution to the differential equation (5) as:

$$\bar{X}(t) = A^{-1}[I - \Phi(t)](\bar{v}_k - \bar{v}_0) + \bar{v}_k t + \bar{x}_0. \quad (7)$$

Since at the initial moment of time the velocity vector of the mechatronic module displaying 3D graphics is zero, we obtain:

$$\bar{x}(t) = A^{-1}[I - \Phi(t)]\bar{v}_k + \bar{v}_k t + x_0. \quad (8)$$

Using expression (8), we determine the parameters of the matrix A from the condition of achieving a given speed $\bar{v}_k$ at a given point $\bar{x}_k$.To do this, we substitute the value of the position vector of the mechatronic module displaying 3D graphics at point M_k into expression (8), and obtain:

$$\bar{X}_k(t) = A^{-1}[I - \Phi(t_k)]\bar{v}_k + \bar{v}_k t_k + \bar{x}_0. \quad (9)$$

Taking into account the simultaneous formation of all projections of the velocity vector [6,14] of the mechatronic module displaying 3D graphics, as well as the properties of the exponential function, we can write:

$$t_k I = 3A^{-1}. \quad (10)$$

$$A = \alpha I. \quad (11)$$

Therefore, the problem is reduced to finding the coefficients α. To find them, we write from (9) and (11):

$$\bar{x}_k = \bar{v}_k t_k + \bar{x}_0. \quad (12)$$

However, these conditions will only be valid in the case of ideal motion processing. However, during normal system operation, disturbances may be introduced that will cause the gripper to move along a displaced trajectory and, as a result, develop the required speed not at the given point $\bar{x}_k$, but at some other point in space [15]. To eliminate this undesirable phenomenon, we require that the deviation from $\bar{x}(t)$ be a decreasing function of the form:

$$\bar{X}(t) - (\bar{x}_0 - \bar{v}_k t + A^{-1}[I - \Phi(t)]\bar{v}_k) = \sum_{i=1}^{2} \exp\, B_i t \bar{c}_i. \qquad (13)$$

Expression (13) is the solution of a homogeneous vector differential equation of the second order of the form:

$$\Delta\ddot{x} = K_1 \Delta\dot{x} + K_2 \Delta x. \qquad (14)$$

Here $K_1 = B_1 + B_2$, $K_2 = -B_1 B_2$, where B_1 and B_2 − are matrices all of whose eigenvalues are negative or have negative real parts [16]. This ensures the stability of the mechatronic module displaying 3D graphics in the vicinity of the programmed coordinates. Furthermore, the following notations are introduced:

$$\Delta\ddot{\bar{x}} = \ddot{\bar{x}}(t) - A\Phi(t)\bar{v}_k;$$

$$\Delta\dot{\bar{x}} = \dot{\bar{x}}(t) - \big(I + \Phi(t)\big)\bar{v}_k; \qquad (15)$$

$$\Delta\bar{x} = \bar{x}(t) - [\bar{x}_0 + It - A^{-1}(\Phi(t) - I)]\bar{v}_k$$

Taking into account expression (14), the formula for acceleration can be represented as follows:

$$\ddot{\bar{X}}(t) = K_1 \Delta\dot{\bar{x}} + K_2 \Delta\bar{x} + A\Phi(t)\bar{v}_k. \qquad (16)$$

Further, if we organize the motion of the mechatronic module displaying 3D graphics so that acceleration varies according to law (16), then the task will be accomplished.

By solving expressions (2) and (3) together, we find the control vector:

$$\bar{Q} = D(\bar{q})J^{-1}(\bar{q})(K_1\Delta\dot{\bar{x}} + K_2\Delta\bar{x}) - \bar{p}(\bar{q},\dot{\bar{q}}) - \bar{H}(\bar{q},\dot{\bar{q}}). \qquad (17)$$

Expression (17) for the control vector $\bar{Q}$ is a nonlinear vector function of time, generalized coordinates, and velocities. This expression ensures that the mechatronic module, displaying 3D graphics, is directed to a given point in space with the required velocity vector, and also guarantees the required motion characteristics in terms of position and velocity [17].

Thus, the spatial movement of the mechatronic module displaying 3D graphics can be implemented automatically based on a single control command after setting the required position and movement parameters.

Analysis and results.

An orientation mechanism with two translational and one rotary motion ensures spatial orientation of the mechatronic module displaying 3D graphics. The module's orientation is achieved through the coordinated movement of links using a spherical mechanism, shown in Figure 1. The functional relationship between the spatial orientation angles of the mechatronic module, designed to display 3D graphics, φ_1 and φ_2, and the movements in the linear drives S_1 and S_2 is determined by the following relationships:

$$S_1^2 = b_1 + h + a_1 - 2b_1 a_1 \cos\varphi_2 - b_1\, h\cos\varphi_1 \sin\varphi_2; \qquad (18)$$

$$S_2^2 = b_2^2 + a_2^2 - 2b_2 a_2 \cos\varphi_1 - 2b_2 h \sin\varphi_1, \qquad (19)$$

where $h, b_i, a_i (i = 1,2)$ represent constant design and geometric parameters of the orientation mechanism, and $S_i (i = 1,2)$ are the linear movements of the executive elements of the mechatronic module.

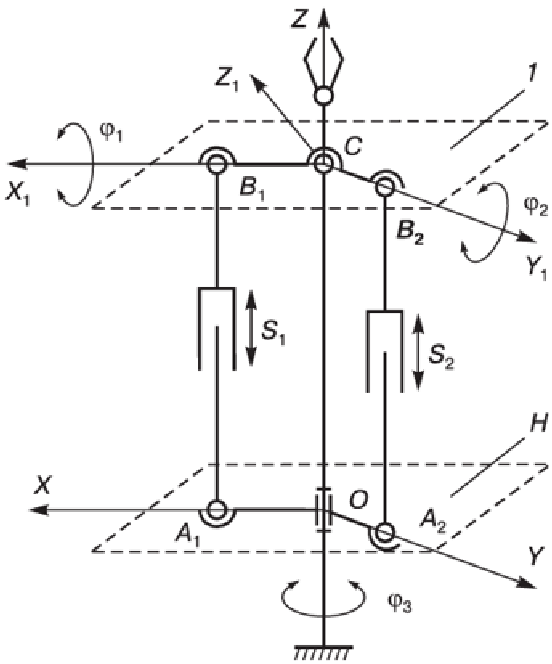

Fig. 1. Kinematic diagram of the spatial movement of a mechatronic module displaying 3D graphics.

For given values of angles φ_1 and φ_2, the displacements of the linear executive elements are determined from expressions (18) and (19). Rotation around the Z-axis by angle φ_3 is implemented independently. The control algorithm for the orienting motion of the mechatronic module displaying 3D graphics is shown in Figure 2, where S_x, S_y are the angular signals from the module's position sensors, and S_1, S_2 are the converted values of the current angular position of the module [18].

The complexity of implementing spatial movements in a mechatronic module displaying 3D graphics stems from the need for high-precision control of the linear movements of the executive elements.

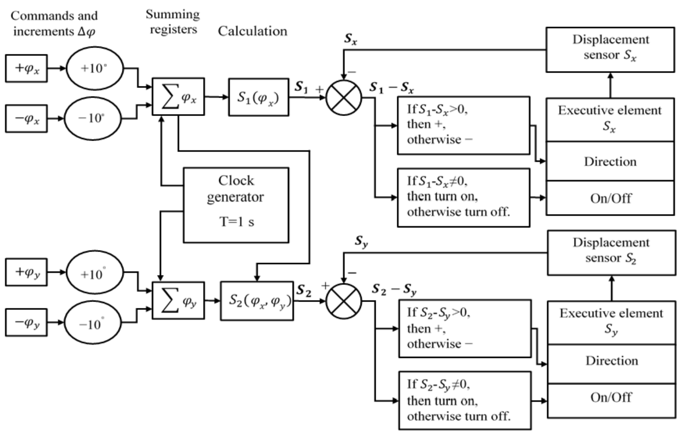

Fig. 2. Algorithm for controlling the spatial directions of movement of a mechatronic module displaying 3D graphics.

Therefore, it is advisable to determine the module's current spatial position based on signals received from sensors. This article proposes a system for controlling the directions of movement of a mechatronic module displaying 3D graphics (Fig. 3), ensuring precise and reliable rotation at deflection angles φ_1 and φ_2 when projecting 3D graphics onto surfaces. Furthermore, in this system, the current state of the moving links is determined by parameters $S_1$and S_2, recorded by displacement sensors. Thus, the control task consists of generating appropriate control signals for the executive elements, taking into account their current state. The movements are realized by the executive elements of the mechatronic system, and the control signals are generated depending on the sign of the error at the angles φ_1 and φ_2.

When the set angle values are reached, the pulse generator stops supplying the control voltage. This activates the feedback loops, ensuring continued system operation. The required angular values are generated in the corresponding functional control unit. The kinematic diagram shown in Figure 1 and the algorithm shown in Figure 2 are based on a single principle and are designed to provide coordinated control of the spatial motion of the mechatronic module. Rotation of the movable link in the required direction is determined by the sign of the deviation of the specified angle γ_1 from the current position. With a positive deviation, a control signal is sent to the executive element, ensuring that the module is brought to the specified position; with a negative deviation, movement is realized in the opposite direction [11,19]. Thus, the control system is a complex of tracking systems, including displacement sensors, comparison units, amplification devices, and executive elements. When controlling the motion of the mechatronic module, software guidance signals are generated in the control unit and transmitted via the control panel. The system's structural structure is a set of interconnected kinematic transmissions and executive elements. In some cases, spatial movements are implemented based on predefined programs, while the functional control structure ensures the coordinated operation of individual executive elements.

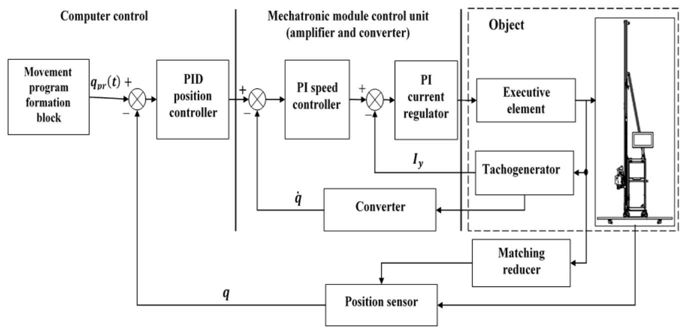

Fig. 3. Structural diagram of the functional control of the mechatronic module displaying 3D graphics.

The primary advantage of this control system is its ability to ensure the module's precise final spatial position in accordance with a specified trajectory. The control process is based on the laws of change in generalized coordinates and measurement information received from sensors [8,20].The control system consists of a control computer, a programmable motion generation unit, and a pulse generator. The programmable control unit includes a voltage source, modulators, pulse sweeps, and algorithm encoders. A keyboard is used as an input device, enabling position selection, with preset points stored in memory as control sequences. The mechatronic module can move at various rotation speeds. At each section of the trajectory, vector quantities change proportionally to time, while the trajectory shape is selected in accordance with the current state of the control channel. Furthermore, the controller's tuning system ensures the required trajectory accuracy depending on the operating mode of the executive elements. Thus, the mechatronic module control system is a software-based coordinate-tracking system, the effectiveness of which is ensured by position sensors and feedback loops.

Conclusion.

This article focuses on the development of an intelligent control structure for a mechatronic module displaying 3D graphics. The primary goal is to create an intelligent control system that ensures highly accurate and timely execution of mechatronic module movements in accordance with specified coordinates and positions. Mathematical models have been developed that enable the synthesis of the dynamic characteristics of a mechatronic module displaying 3D graphics in accordance with a specified coordinate trajectory and positions. Based on these models, an algorithm for controlling the mechatronic module's movement along a specified coordinate trajectory and positions has been developed, as well as the structure of an intelligent control system that ensures the coordinated operation of the executive elements. In this control system, when executing the mechatronic module's movements in accordance with specified coordinates and positions, control signals are generated based on the deflection angles φ_1 and φ_2, the state parameters S_1 and S_2, and signals from the sensors. Furthermore, this system ensures precise, reliable, and responsive movement of the mechatronic module, effective control of its spatial position, and stability of its motion parameters. The research results serve as the primary software and information tool for mechatronic modules used to display 3D graphics on various surfaces. Furthermore, increasing the intelligence of mechatronic modules displaying 3D graphics, as well as the stable synthesis of their dynamic characteristics, enables energy savings of 5–7%.

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