Dynamic correction in manipulator control systems based on intelligent linear motion mechatronic module

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Abstract. Robotic complexes and robotic manipulators are widely used in the management of various objects and processes of control systems; their performance is directly related to the execution element. Electromagnetic actuators of multi-function control systems are structurally created separately for each adjustment body and lead to system complexity. To solve these problems, improve the executive system's weight-gauge indicators, and simplify the structural schemes, implementing intelligent mechatronic modules that perform linear and rotational movements in space coordinates is one of the urgent tasks. In this article, dynamic correction in manipulator control systems built based on an intelligent linear motion mechatronic module is considered. In manipulator control systems, the use of intelligent mechatronic modules in dynamic correction for manual and semi-automatic control manipulation systems that do not have a feedback channel for forces and moments and the relevance of the handle movement and manipulation objects with such a selection of the forces and moments vector m developed by them was seen. The article presents mathematical models for calculating vector components based on the current values of the generalized coordinates of the manipulator, their speed and acceleration, and the selection of the vector of forces and moments m developed by the intelligent mechatronic modules of the manipulator.

1 Introduction

When the manipulator moves, if it is controlled in one way or another, forces arise due to this movement and, depending on the speed and acceleration of the relative movement of the joints, their masses, and moments of inertia. Determined by the first part of the dynamic equation $A^T(\tau + \tau_в) = B^{0T}(F_1^0|M_1^0)^T$ these forces change the direction specified by the operator of the CRT10 industrial robot manipulator handle movement; they occur during control and significantly affect the nature of the processes. Compensating the effect of these forces on the motion of the linear actuator based mechatronic module is called dynamic correction for the CRT10 robot manipulator. The problem of dynamic correction is especially relevant for manual and semi-automatic control manipulation systems that do not have a feedback channel for forces and moments. The intelligent mechatronic module,

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having information about the forces and moments of inertia that appear during movement, serves to correct the movement when the operator performs the same operations directly by hand or with a control device and for dynamic correction based on the speed and acceleration of the movement, their masses and moments of inertia [1,2]. This leads to a significant optimization of the execution time of operations and an increase in the quality of control when using CRT10 robot manipulators in industry.

2 Research Methodology

The problem of dynamic correction is also logical for binary systems. In such systems, the operator feels the inertial forces arising from the movement of the manipulator, in addition to the inertial forces arising from the movement of the manipulated object, and sometimes superior to the first one. This destroys the authenticity of the operator's work and increases his physical load [2, 3]. At the same time, the inertia properties of the manipulator (masses, moments of inertia of the links) are known in advance, and based on the results of mathematical models, it is possible to calculate the estimated forces resulting from its movement. The task of compensating these force control signals with appropriate corrections can be assigned to the control computer. From this point of view, we make it possible to formulate the problem of dynamic correction.

3 Analysis and results

This $B^{0T}[G^0 + F_v^0 + F_1^0 | M_v^0 + M_1^0]^T + \mu = 0$, the dynamics of the execution mechanism can be considered. To simplify ideas, let's assume that the external forces and moments are applied only to the last link (grip) of the manipulator, and the expression can be written as follows:

$$G^{0\prime} = [G_1 \vdots \cdots \vdots G_{N-1} \vdots 0]^t$$

$$F_I^{0\prime} = \left[F_{I_1} \vdots \cdots \vdots F_{I,N-1} \vdots 0\right]^t$$

$$M_I^{0\prime} = \left[M_{I_1} \vdots \cdots \vdots M_{I,N-1} \vdots 0\right]^t$$

$$[F_v \vdots M_v]^t = [F_{v\,N} \vdots M_{v\,N}]^t$$

$$[G^0 + G_I^0 \vdots M_I^0]^t = [G^{0\prime} + F_I^{0\prime} \vdots M_I^{0\prime}]^t$$

Now the mathematical equation $B^{0T}[G^0 + F_{\text{в}}^0 + F_1^0 | M_{\text{в}}^0 + M_1^0]^T + \mu = 0$ can be written as follows:

$$\mu + B^{0t}[G^0 + F_I^0 \vdots M_I^0]^{\text{ъ}t} + A^t[G_N + F_{IN} + F_v \vdots M_{IN} + M_v]^t = 0. \quad (1)$$

Considering the manipulator's holder as an $N-$link with the object of manipulation as information, the components G_N, F_{IN}, M_{IN}, as well as the external force vector and $\mathfrak{I}_v = [F_v \vdots M_v]^t$, components are completely unknown. $B^{0t}[G^0 + F_I^0 \vdots M_I^0]'^t$ vector components can be calculated depending on the current values of the manipulator's generalized coordinates, speed, and acceleration.
We choose a vector of $\mu-$form:

$$\mu = A^t F + \mu_k, \quad (2)$$

where $F = [F \vdots M]^t -$ is the vector of control forces and moments defined by the operator or computer, $\mu_k -$ is a vector of corrective forces and moments consisting of sum

$$\mu_k = \mu_c + \mu_d$$

where $\mu_c = -B_1^{0'} G^{0'} -$ the vector of signals entered to correct the static moments due to the weight of the manipulator links and $\mu_d = -B^{0t}[F_I^0 \vdots M_I^0]'^t -$ dynamic correction vector [4,5].
The formula of $\mu_d -$ vector to the generalized coordinates of the manipulator q and their derivatives is $\left[\frac{F_I^0}{M_I^0}\right] = -\left[\frac{mB_1^0}{I^0 B_2^0}\right]\ddot{q} - \left[\frac{mD_1^0}{\Omega^0 I^0 B_2^0 + mD_2^0}\right]\dot{q} = -\mathfrak{F}B^0\ddot{q} - C^0\dot{q}$, where $\mathfrak{J} = \left[\frac{m \vdots 0}{0 \vdots I^0}\right]$, $C^0 = C^0(q,\dot{q}) = \left[\frac{mD_1^0}{\Omega^0 I^0 B_2^0 + mD_2^0}\right]$ depends on:

$$\mu_d = B^{0t}\mathfrak{T}'B^0\ddot{q} + B^{0t}C^0\dot{q} = A'(q)\ddot{q} - B'(q,\dot{q})\dot{q},$$

$$\mathfrak{T}' = \left[\frac{m \vdots 0}{0 \vdots I^0}\right], \qquad m' = diag[m_1 \dots m_{N-1} 0],$$

$$I^{0'} = diag[\tau_1 I_1^{(1c)} \tau_1^t \vdots \cdots \vdots \tau_{N-1} I_{N-1}^{(N-1c)} \tau_{N-1}^t \vdots 0],$$

$$A'(q) = B^{0t}\mathfrak{T}'B^0, \qquad B'(q,\dot{q}) = -B^{0t}C^0.$$

If the matrix A is intact, then with this selection of the vector μ of forces and moments developed by the intelligent mechatronic module of the manipulator, the movement of the handle and the object of manipulation obey the equation of motion of a free rigid body under the influence of control and external forces, i.e.

$$[G_N + F_{IN} + F_v + F \vdots M_{IN} + M_v + M]^t = 0. \qquad (3)$$

The introduction of $\mu_d -$ dynamic correction significantly simplifies the task of controlling the manipulator. Thus, when controlled by a force vector, assuming that there are no external forces G_N, $F_v -$ and moments M_v the direction of movement of the object of manipulation corresponds to the direction of the generalized control force $\mathfrak{J}$.
Incorporating such corrections with positional and velocity control reduces the dynamic interaction of degrees of freedom. In particular, if the inertial characteristics of the $N -$link are known and its $\mu_d = A(q)\ddot{q} - B(q,\dot{q})\dot{q}$, as stated above, the dynamics of the manipulator control system is described by the mathematical equations of a separate intelligent mechatronic module $-iIi^t p^2 q - W_2(p)pq + W_1(p)(g - -q) + B^{0t}[G^0 + F_v^0 \vdots M_v^0]^t = 0$. In addition to significantly simplifying the calculation procedure of the control system, it allows for improving the quality indicators of the system operation. It increases the speed, the characteristics of transition processes, and the quality of control [6,7]. A more effective way to perform dynamic correction is to formalize the vector of corrective forces and moments μ_k by measuring the forces and moments that hold the manipulator in its links. Sensors are used to measure the forces and moments developed by the intelligent mechatronic module of the manipulator in its connections [4,7,8]. In most cases, information about forces and moments can be obtained by measuring other physical quantities. Thus, the torque developed by an intelligent mechatronic module based on an electromagnetic linear motor is proportional to the direct current flowing through its armature winding [8,9]. Two approaches are commonly used to measure forces and moments when an object is being gripped by a manipulator (from the side of the load). The first of them is to install force and torque sensors on the wrist of the manipulator, that is, to

connect its handle with the front flange link of the kinematic chain (Fig. 1).

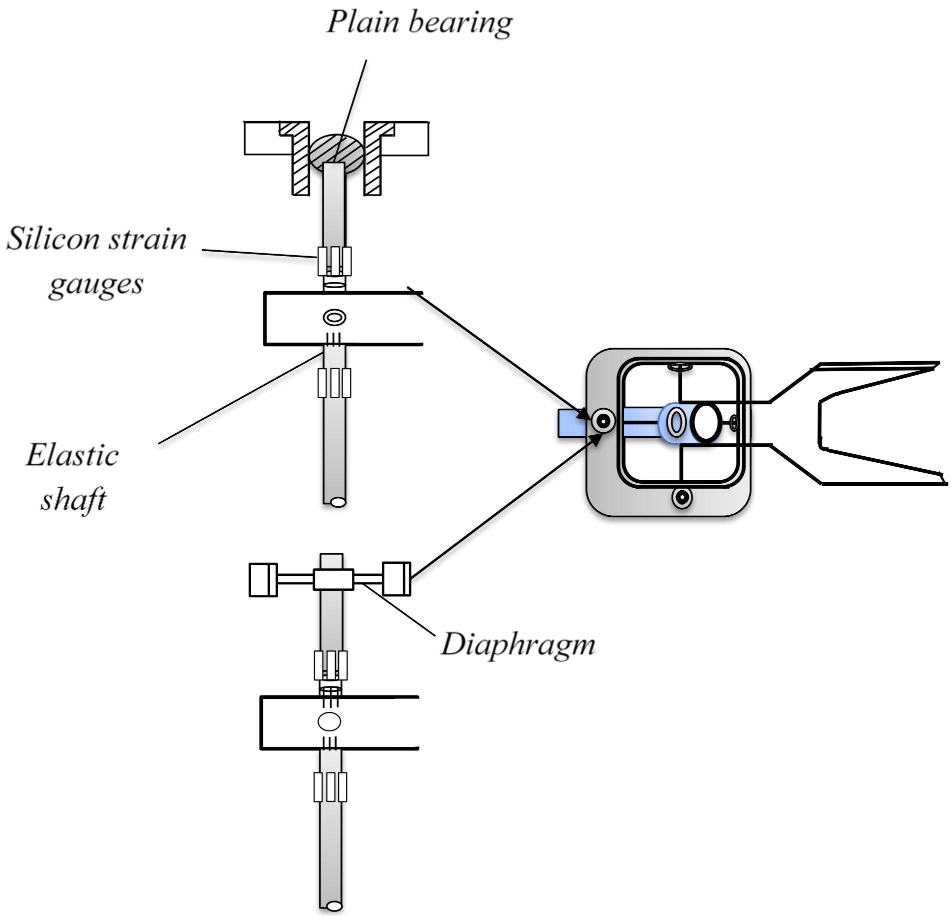

Fig. 1. Force and torque sensors in "flexible wrist" design.

If the axis of the initial coordinate system e_i, $i = 1,\ 2{,}3$ are connected with the sensor, R is the radius vector connecting the origin of the coordinate system with the center of mass of the $N-$th link (Fig. 2), the sensor is used to measure the force vectors F^* allows and is defined by the moment ratio M^*

$$[F^* \vdots M^*]^t = A_d^t[F_v + F_{IN} + G_N \vdots M_{IN} + M_v]^t \qquad (4)$$

Where

$$A_d = \left[\frac{e_1}{0} \vdots \frac{e_2}{0} \vdots \frac{e_3}{0} \vdots \frac{\lambda(e_1)R}{e_1} \vdots \frac{\lambda(e_2)R}{e_1} \vdots \frac{\lambda(e_3)R}{e_1}\right]$$

The second method is to use contact force torque sensors located in the jaws of the manipulator handle. If $F_i -$, is the force measured by the $l-$th sensor, the results of the radius-vector measurement $l = 1, \dots, M, R_{0l} -$ acting from the mass center of the manipulated object to the $l-$th sensor (Fig. 3) can be written as follows:

$$\left.\begin{aligned} F^* = \sum_{l=1}^{M} F_l = G_0 + F_{I0} + F_v, \\ M^* = \sum_{l=1}^{M} \lambda\,(R_{0l}) F_l + M_v = M_{I0} + M_v. \end{aligned}\right\} \qquad (5)$$

Here the values of G_0, F_{I0}, M_{I0} differ from G_N, F_{IN}, M_{IN} in that, they actually belong to the object of manipulation.

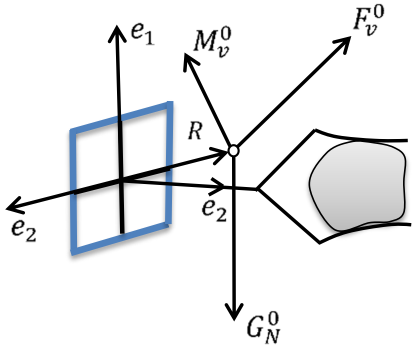

Fig. 2. Scheme of strain gauge sensor in measurement of forces and moments.

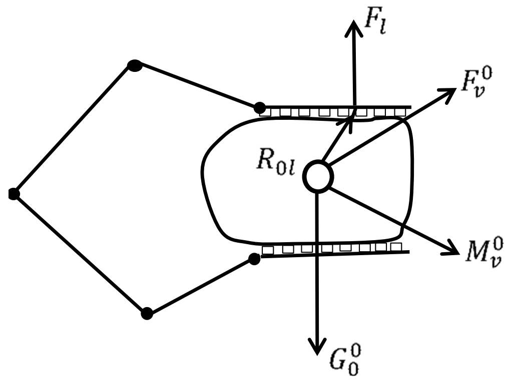

Fig. 3. Scheme of application of contact sensors in measurement of forces and moments.

Measurements μ^* of forces and moments in the links of the manipulator are determined according to equation (1):

$$\mu^* = -B^{0t}[G^0 + F_I^0 \vdots M_I^0]'^t - A^t[G_N + F_{IN} + F_v \vdots M_{IN} + M_v]^t \qquad (6)$$

comparing equations (4) and (6), we get the following expression

$$\mu_k = \mu^* + A^t(A_d^t)^{-1}[F^* \vdots M^*]^t \qquad (7)$$

if $[F^* \vdots M^*]^t$ vector is determined by the formula (4).

Thus, the vector of corrective forces and moments can be calculated from the determined values of μ^* and $[F^* \vdots M^*]^t$.

In the second case, that is, according to formulas (1) and (5), when changing the forces and moments acting on the handle, first of all, dynamic equations should be slightly changed [6,7]. We consider the $(N+1)$ −th link of the load manipulator is to be stationary concerning N.

Assuming that the matrices $\tilde{B}^{0t}$ and $\tilde{A}^t$ are obtained for such a mechanism, we can determine the vector μ^* from the following equation.

$$\mu^* = -\tilde{B}^{0t}[G^0 + F_I^0 \vdots M_I^0]'^t - \tilde{A}^t[G_0 + F_{I0} + F_v \vdots M_{I0} + M_v]^t, \qquad (8)$$

Where

$$[G^0 + F_I^0 \vdots M_I^0]^t = [(G_1 + F_{I0})^t \vdots \cdots \vdots (G_I + F_{IN})^t \vdots 0 \vdots M_{I1}^t \vdots \cdots \vdots M_{IN}^t \vdots 0]^t.$$

based on mathematical equations (5) and (8), we get the following

$$\mu_k = \mu^* + \tilde{A}^t[F^* : M^*]^t. \quad (9)$$

By choosing the vector μ_k −in such a way and without violating the matrix $\tilde{A}$, we get an object of manipulation as a free rigid body under the influence of external forces and control force $\mathfrak{F}$:

$$[G_0 + F_{I0} + F_v]^t + F[M_{I0} + M_v + M]^t = 0.$$

The structural scheme of the manipulator control system, which allows dynamic correction of the vector of control forces according to mathematical equations (4) and (7), is shown in Fig. 4.

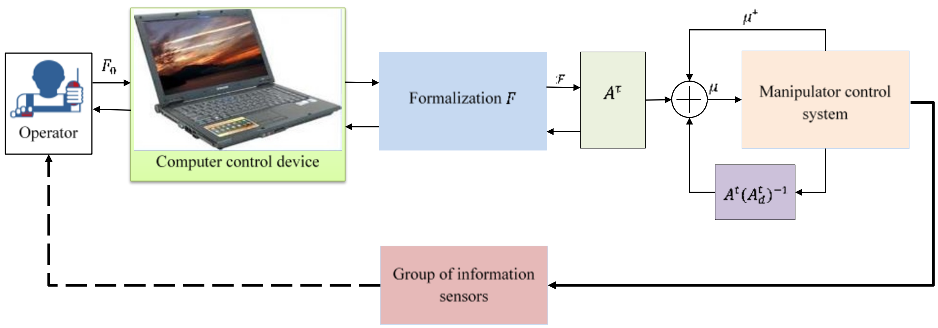

Fig. 4. Structural scheme of manipulator control system depends on force vector with dynamic correction.

μ^* is correction provided by F^* − forces and allows controlling the control object according to equations (3). In particular, if there are no external forces and moments, $M = 0$, then the system ensures the fulfillment of the condition $M_{IN} = 0$, that is, stabilization of the angular positions (or angular velocities) of the manipulated object is achieved when moving under the influence of a controlled force [9-11]. Otherwise, we get $G_N^* + F_{IN} = 0$ at $F = 0$, that is, stabilization of the position of the object's center of mass (or its speed of movement) is ensured when controlling its rotation using the M − vector.
The question of how much the efficiency of the control system increases as a result of correction depends on the energy efficiency and capabilities of the linear motion intelligent mechatronic module, which is the executive element of the manipulator, as well as the accuracy of measuring the vectors $\mu^*, [F^* : M^*]^t$. Theoretical and practical research is required to solve these issues. Using sensors mounted on the manipulator handle to determine the developed force and moment allows for improving the manipulator control systems. These forces and moments can be reproduced in the actuator by developing its degrees of freedom, forces, and moments

$$\mu_0 = kA^t(A_d^t)^{-1}[F^* : M^*]^t \qquad k = const$$

if said measurements are made according to equation (4), or

$$\mu_0 = kA^t[F^* : M^*]^t$$

if equation (5) is true. In this case, the operator does not feel inertial forces and moments due to the mass of the manipulator. Of course, such an organization of force feedback is possible only if the dynamic compensation described above is introduced. In other words, the task of correcting the manipulator's movement dynamics is assigned to the computer [12, 13]. The operator controls the movement of the manipulated object and senses the same forces and moments that occur when working directly with the controlled object. This increases the reliability and quality of the operator's work and makes it easier. In the manual and semi-automatic control systems of the manipulator, the shortcomings of the system (for example, complete compensation of the dynamics of the manipulator, lack of compensation for the movement of unknown external forces) are performed (compensated) by the human operator. In particular, it refers to the influence of external forces, which can occur due to many previously unknown reasons [14, 15]. In this case, it is necessary to correct the unknown external forces and moments, i.e., the correcting forces and moments vector μ_k should be selected according to the following formula

$$\mu_k = \mu_c + \mu_d + \mu_v, \qquad (10)$$

where $\mu_v = -A^t[F^* \vdots M^*]^t$ is the component of the vector μ_k introduced to compensate for the effects of unknown external forces and moments. To obtain information about the vector $[F^* \vdots M^*]^t$ by measuring the forces and moments F^*, M^*, acting on the handle of the manipulator, the vectors of inertia forces and moments of the manipulator object F_{I0}, M_{I0} moments (4) or (5) moments F_{IN}, $M_{IN} -$ should be calculated using the equations. For this, of course, it is necessary to have information about the object's mass to be manipulated, the tensor of inertia and the location of its center of mass, and the main axes of inertia relative to the manipulator handle [11, 15, 16]. They correspond to the desired movement without external forces and moments. The deviation of the movement due to these forces and moments occurring in the real situation is estimated by the results of the measurement of the forces and moments $[F^* \vdots M^*]^t$ acting on the handle of the manipulator. From equation (4), we get the following expressions:

$$\mu_v = -A^t(A_d^t)^{-1}\{[F^* \vdots M^*]^t - [F_{IN} + G_N \vdots M_{IN}]^t\} \qquad (11)$$

and from equation (5), we find the unknown external forces:

$$\mu_v = -\tilde{A}^t\{[F^* \vdots M^*]^t - [F_{I0} + G_0 \vdots M_{I0}]^t. \qquad (12)$$

As can be seen from the equations (7), (9), there is no need to determine the generalized forces $[F^* \vdots M^*]^t$ when using measurements of forces and moments μ^* at each degree of freedom because in the two cases under consideration

$$\mu_k = \mu^* + A^t(A_d^t)^{-1}[F_{IN} + G_N \vdots M_{IN}]^t$$

and

$$\mu_k = \mu^* + \tilde{A}^t[F_{I0} + G_0 \vdots M_{I0}]^t$$

we can calculate the vector of corrective forces and moments μ_k.
In cases where the dynamic characteristics of the manipulated object manipulator are mainly determined by the manipulated object, it is possible to implement without determining the force vector μ^* and using the above expression (10) to determine the following corrective force vector $\mu_d = 0$:

$$\mu_k = -\,B_1^{0t}G'^{0} + \mu_v \qquad (13)$$

where μ_v is determined by equations (11) or (12).

It should be noted that the definition of the vector functions F_{I0}, M_{I0}, corresponds to the movement along the selected trajectory without external forces and moments, for which the calculation of the necessary control force $\mathfrak{F}$ is considered sufficient.

From this equation follows:

$$\mathfrak{F} + [F_{I0} + G_0 \vdots M_{I0}]^t = 0$$

The manipulator can be considered as a system of linear constraints on the μ forces and moments developed by the intelligent mechatronic modules, such as the above equation:

$$\tilde{A}^t \mu + [F_{I0} + G_0 \vdots M_{I0}]^t = 0 \quad (14)$$

in general, the system of constraints can be vaguely defined.

Using one or another indicator of quality improvement, it may be required to optimize the system of constraints (14). If it is expressed in a linear form, the problem can be effectively solved by linear programming methods [8,14,16]. After finding the generalized forces $\mu_p(t)$, through the software, the control that ensures the independence of the movement from external forces can be found according to the following mathematical expression:

$$\mu(t) = \mu_p(t) + \mu_k(t)$$

where $\mu_k(t)$ is determined by formulas (7) and (9) or (13).

4 Conclusions

The article considered the correction of the manipulated object with positional and speed control based on the dynamic characteristics of the object manipulator using mathematical models. This makes it possible to improve manipulator control systems by using sensors to determine force and moment, considering dynamic changes when changing the forces and moments acting on the manipulator handle. These forces and moments serve to obtain information about the degrees of freedom of the moving device, the mass of the manipulated object, the tensor of inertia and the location of its center of mass, and the main axes of inertia relative to the handle of the manipulator. In addition, the deviation of the movement due to these forces and moments that occur in the real situation allows for the correction of the forces and moments affecting the handle of the manipulator and the formalization of the vector of forces and moments μ_k by measuring the forces and moments that hold the manipulator in its links, which is a more effective way of performing dynamic correction.

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