A LOAD ADAPTIVE CONTROL SYSTEM OF MANIPULATOR ROBOT'S DRIVE

АДАПТИВНАЯ К НАГРУЗКЕ СИСТЕМА УПРАВЛЕНИЯ ПРИВОДОМ МАНИПУЛЯЦИОННОГО РОБОТА

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Abstract: *The control dynamics for the electric drive of manipulation robot (MR) link is considered. Joint-drives in mobility degrees of MR experience the variable loads caused by changes of a spatial configuration of MR in the course of motion, mass and dimensions of the moved payloads, etc. Changes of load can happen over a wide range and cause the essential deterioration in dynamic properties (speed, damping, etc.) of the system of automatic control (SAC) of drive. With the aim to stabilize the desired dynamic properties the algorithm of drive control is proposed which is adaptive to changes of load. The unknown parameters of drive load, necessary to form the adaptive control algorithm, are identified in observing device (OD). The work algorithm of OD to identify the unknown parameters of drive load is proposed. For the proposed control and work of OD algorithms the structural scheme of drive control is construction. The simulation results on computer are proved that in considered SAC of drive the stabilization of desired dynamic properties are ensured.*
***KEYWORDS**: MANIPULATOR ROBOT, DRIVE OF JOINT, LOAD ADAPTIVE CONTROL SYSTEM, OBSERVING DEVICE*

1. Introduction

Spatial movements of the end-effector of the multi-joint manipulator robot (MR) are carried out by operations of its joint-drives [1]. Joint-drives of the MR experience the variable mechanical loads caused by changes of a spatial configuration of MR in the course of motion, mass and dimensions of the moved payloads and also technology factors, etc. [2]. Variable load of each drive is characterized by changes of a moment of inertia and an external moment of the mechanical load. The moment of inertia is the parameter (coefficient of the differential equation) and the external moment of load is the external disturbing signal of the system of automatic control (SAC) of the drive [3]. Changes of these variables of load can happen over a wide range and cause the essential deterioration in the dynamic properties (speed, damping, etc.) of the SAC of drive. There is a problem of creation in each joint of MR of a load adaptive SAC of drive which dynamic properties do not depend on changes of load. Therefore, it is necessary to define and use the variable parameters of load of drive for the stabilization of desirable dynamic properties of the SAC of drive. If MR moves unknown payloads, then these variables of load will be not only changing, but also unknown. Both the unknown and changing parameters of load necessary to form a load adaptive control algorithm of SAC it identifies (defines, estimates) by means of the observing devices (OD) [4].

2. Preconditions for resolving the problem

Thus for stabilization of desirable dynamic properties of SAC of joint-drive of MR is to make a load adaptive control system with the OD of identification of unknown parameters of load. The OD of identification of parameters of load it makes for the "mechanical" part of the drive which is described by the equation of the moments on a shaft of the direct current (dc) electric motor [2]:

(1) $$Js\omega_m = M_m - M,$$

where J is the moment of inertia;
M is the external moment of load;
ω_m is the speed of rotation of the shaft of motor;
$s = d/dt$ is the differentiation operator;
M_m is the moment of motor.

The moment of the dc motor is formed according to a formula:

(2) $$M_m = k_m i_a ,$$

where k_m is the motor's torque constant;
i_a is the armature current.

In [5] based on the main provisions of the theory of observing devices [4] the algorithm of work of OD of identification of unknown value of moment of inertia of load of dc electric motor is proposed in following form:

(3) $$d\left(k_m/\hat{J}\right)/dt = \delta_1 i_a k_s(\omega_m - \widehat{\omega}_m),$$
$$d\widehat{\omega}_m/dt = \left(k_m/\hat{J}\right)i_a + \lambda_1 k_s(\omega_m - \widehat{\omega}_m),$$

where $\hat{J}$ is the estimation of value of moment of inertia J identified in the OD;
$\widehat{\omega}_m$ is the estimation of the speed of rotation of the shaft of motor ω_m received in the OD;
k_s is the transfer coefficient of sensor of angular speed of a shaft of the motor;
δ_1, λ_1 are the constant coefficients.

However in this OD described by the equations (3) the influence of the external moment M of load of the motor isn't considered, while it can cause the instability work of OD. Therefore in [6] by analogy with a "mechanical" part (1) of the dc motor the algorithm of work of OD of identification of moment of inertia of load is proposed in following form:

(4) $$d\left(1/\hat{J}\right)/dt = \delta_1(k_m i_a - M)k_s(\omega_m - \widehat{\omega}_m),$$
$$d\widehat{\omega}_m/dt = \left(1/\hat{J}\right)(k_m i_a - M) + \lambda_1 k_s(\omega_m - \widehat{\omega}_m).$$

In expressions (4) it is supposed that the external moment M of load of the motor is measured by the sensor of moment and its value is known. However a measurement of the external moment M is difficult to realize and it isn't always possible, therefore it is required to develop the OD in which both the moment of inertia J and the external moment M of load are identified in common.

3. Resolving the problem

Let's consider the equations of the drive of rotation of a link of MR being the control object (CO) and consisting of the amplifier of power, the dc electric motor and the mechanical transfer (reducer) with the variable mechanical load [3].

The equation for an electric circuit of the dc motor is:

(5) $$u_a = (1 + \tau_a s)R_a i_a + e_m,$$

where u_a is the armature voltage;
τ_a, R_a are the time's constant and the resistance of armature;
e_m is the motor's back-emf.

The equation of the motor's back-emf is given by:

(6) $$e_m = k_\omega \omega_m,$$

where k_ω is the motor's back-emf constant.
The equation of the amplifier of power of the drive is:

(7) $$(1+\tau s)u_a = ku,$$

where k, τ are the coefficient of amplification and the time's constant of the amplifier of power;

u is the input voltage of the amplifier of power of the drive.

We will notice that in the equation (1) in relation to MR link drive the quantities J and M mean the following:

$J = J(\vec{q}, \vec{\xi})$ is the moment of inertia of a load of the drive changing in dependence on a $\vec{q}$ vector of generalized coordinates and a $\vec{\xi}$ vector of parameters of MR and its payload (geometrical, weight-inertial parameters, etc.) [2] - it is the unknown parameter of a CO;

$M = M(\vec{q}, \dot{\vec{q}}, \vec{\xi}) = M_e(\vec{q}, \dot{\vec{q}}, \vec{\xi})/i$ is the counted to a shaft of motor the external moment of the drive load which changes are caused by mutual influence of movements on degrees of mobility of MR, moments from the gravity of links and a payload of MR, etc. [2] – it is the external disturbing signal for a CO;

M_e is the external moment of load of the drive;

i is the gear ratio of the coupling from the motor to the MR link.

In expression (1) J and M quantities are variables and characterize the variable mechanical load of the drive of a link of MR.

There are following kinematic ratios of the drive:

(8) $$\omega = \omega_m / i\ ,\ \varphi = \varphi_m / i\ ,$$

where ω is the angular speed of an output shaft of the drive;

φ_m, φ are respectively the angular positions on a shaft of the motor and an output shaft of the drive.

Solving in common the equations (1), (2), (5)-(8) and neglecting the lag effect of the electric circuit since $\tau = \tau_a = 0$ we will receive the following equation of the drive (of the CO):

(9) $$Js\omega_m + k_m k_\omega R_a^{-1}\omega_m = k_m k R_a^{-1} u - M,$$

where u is the control signal of CO.

The block diagram of the electric drive, i.e. CO, made on the equations (1), (2), (5)-(8) at $\tau = \tau_a = 0$, is submitted in Fig. 1.

In expression (9) the changes of J and M quantities will worsen dynamic properties of the SAC of the drive. Therefore for compensation of influence of variables of load to dynamical properties of the SAC of the drive, we choose a control algorithm of the drive, being adaptive to changes of the moment of inertia J and the external moment M of load of the drive [7]:

(10) $$u = u(\varphi, \omega_m, \hat{J}, \widehat{M}) = (k_p k_1(\varphi^* - \varphi) - -k_s k_2 \omega_m)\hat{J} + k_s k_3 \omega_m + k_4 \widehat{M},$$

where φ^*, φ are respectively the demand and the actual angular positions of an output shaft of the drive;

k_p, k_s are respectively the transfer coefficients of sensors of angular position of a shaft of the drive and angular speed of a shaft of the motor;

$k_3 = k_\omega/(k_s k)$, $k_4 = R_a/(k_m k)$ - the constant parameters;

$\hat{J}$ and $\widehat{M}$ are the estimations of J and M quantities of the load received in the OD of identification of these quantities.

In expression (10) the k_1, k_2 constant parameters are selected with the accounting of values of k_m, k_ω, R_a, k, k_p and k_s parameters so, that at $J = J_0 = const$ and $M = 0$, set in models of the drive (9), the desirable transition process of the SAC at $\varphi^*(t) = 1(t)$ will have the set duration T, s and the set overshoot $\sigma = 0$, % [8]:

$$k_1 = 9iR_a/(kk_m k_p T^2), \qquad k_2 = 6R_a/(kk_m k_s T).$$

In our case for clear proof the desirable transition process is chosen aperiodic (monotonous) (Fig. 2, the curve 3). Setting various values of the moment of inertia J and the external moment M of load in model of the drive (9) with the not adaptive to a load control algorithm when in expression (10) $\hat{J} = J_0 = const$ and $\widehat{M} = 0$ it is possible to see that to increase in the values of J and M there is a deterioration in characteristics of transitional functions $h(t) = \varphi(t)$ (duration, overshoot and steady-state error increase) - in the Fig. 2, the curves 1 and 2. In this regard there is a problem of stabilization of desirable dynamic properties of the SAC of the drive with the variable mechanical load. The solution of this task is carried out due to development of the self-adjusted control system of the drive, adaptive to changes of the moment of inertia J and the external moment M of load which uncertain values are estimated in the identification OD which also is adaptive to changes of the specified quantities of drive's load.

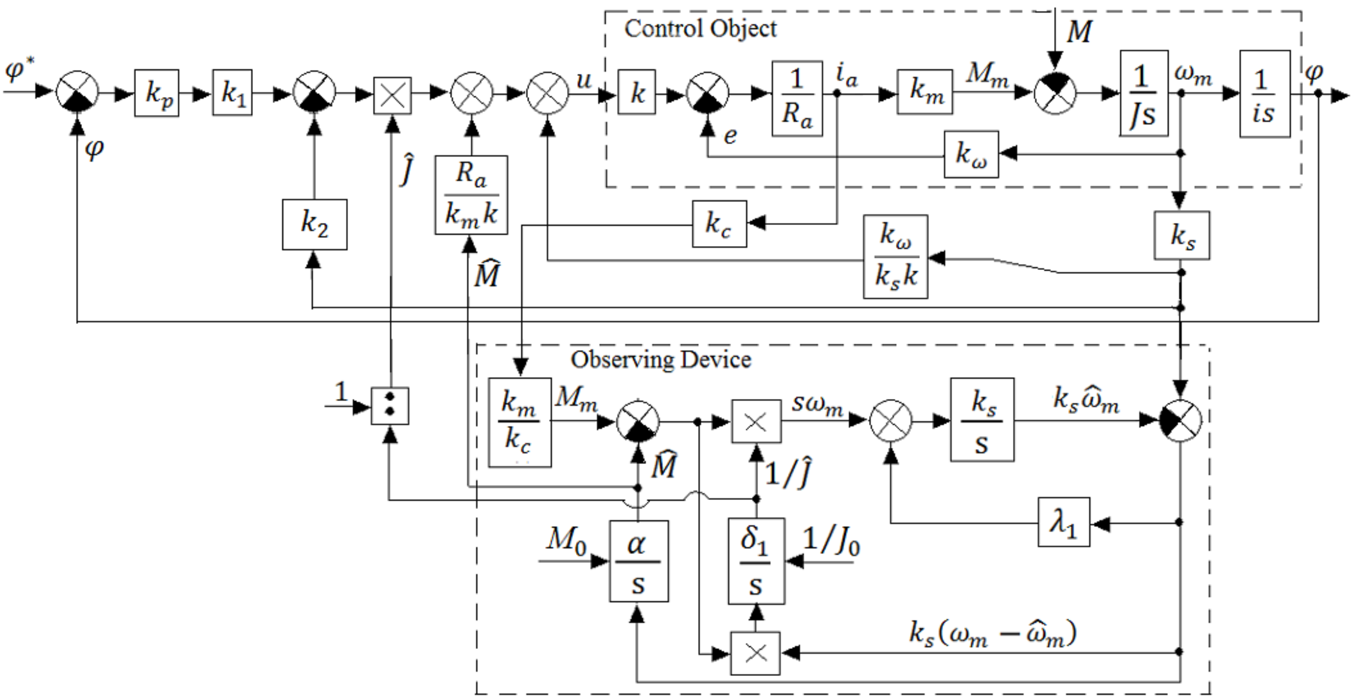

Fig.1 - Block diagram of the load adaptive system of automatic control of drive

For receiving of $\hat{J}$, $\hat{M}$ estimations, the algorithm of operation of the OD of identification of the moment of inertia J and the external moment M of load has the following form [8, 9]:

(11) $$d(1/\hat{J})/dt = \delta_1 \left(M_m - \hat{M}\right) k_s (\omega_m - \hat{\omega}_m),$$

$$d\hat{\omega}_m/dt = (1/\hat{J})\left(M_m - \hat{M}\right) + \lambda_1 k_s (\omega_m - \hat{\omega}_m),$$

$$d\hat{M}/dt = -\alpha k_s (\omega_m - \hat{\omega}_m)$$

with the initial conditions:

$$\hat{\omega}_m(0) = 0,\ \hat{J}^{-1}(0) = J_0^{-1},\ \ \hat{M}(0) = 0,$$

where J_0 is the average value from the possible range of changes of moment of inertia J.

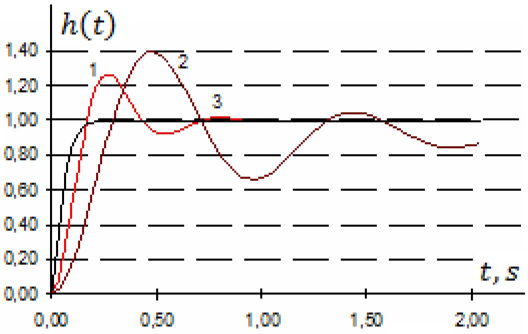

Fig.2 – The graphs of $h(t)$ transition functions
1 – SAC without OD at J =7 kg*m^2 and M =10 N*m;
2 – SAC without OD at J =25 kg*m^2 and M =100 N*m;
3 – SAC with OD at the same values of J and M of load

In expressions (11) for formation of the moment of the motor M_m according to expression (2) the armature current of motor i_a which values are measured by the current sensor with transfer coefficient k_c is used.

The block diagram of the load adaptive SAC of the drive consisting of a CO (9), control algorithm (10), OD of identification of variables of load (11) is shown in Fig. 3.

Let's consider the stability of the adaptive OD of identification of J^{-1} and M variables. Let's use the following designations

$$e = \omega_m - \hat{\omega}_m, \quad \nu = (1/J) - \left(1/\hat{J}\right), \quad \mu = M - \hat{M}$$

and take into account that

$$s\omega_m = \dot{\omega}_m = d\omega_m/dt = (1/J)(M_m - M),$$

then the operation algorithm of the identification OD in e, ν and μ coordinates can be described by the equations:

(12) $$de/dt = (1/J)(M_m - M) -$$

$$-\left(1/\hat{J}\right)\left(M_m - \hat{M}\right) - \lambda_1 k_s e,$$

$$dv/dt = -\delta_1 \left(M_m - \hat{M}\right) k_s e,$$

$$d\mu/dt = \alpha k_s e.$$

At the same time we will accept initial conditions:

$$e(0) = 0, \quad \nu(0) = J^{-1} - J_0^{-1}, \quad \mu(0) = 0,$$

and on the basis of a hypothesis of quasistationarity [4] we will consider that on the time interval corresponding to transition process in OD the J^{-1} and M variables do not change.

Let's prove that the position of balance of system of the equations (12) is asymptotically steady, i.e.

$$\lim_{t\to\infty} e = 0, \quad \lim_{t\to\infty} \nu = 0, \quad \lim_{t\to\infty} \mu = 0.$$

Let's consider a positive-definite function of Lyapunov of a following form:

$$V = \tfrac{1}{2} e^2 + \tfrac{1}{2\delta_1 k_s} \nu^2 + \tfrac{1}{2\alpha k_s J} \mu^2,$$

where $J = const$ - because it corresponds to a quasistationarity interval.

Considering that

$$\mu = M - \hat{M} = \left(M_m - \hat{M}\right) - (M_m - M),$$

let's write down a full derivative of function V with respect to time on the basis of system of the equations (12):

$$dV/dt = -\lambda_1 k_s e^2.$$

Let's show that at $e \equiv 0$ there are also $\nu \equiv 0$ and $\mu \equiv 0$. For this purpose we will consider at $e \equiv 0$ the system of equations (12):

$$0 = (1/J)(M_m - M) - \left(1/\hat{J}\right)\left(M_m - \hat{M}\right),$$

$$dv/dt = 0, \qquad d\mu/dt = 0.$$

The equality of zero of the first expression means $1/J = 1/\hat{J}$ and $M = \hat{M}$, therefore at $e \equiv 0$ the identical equality to zero the $\nu = (1/J) - \left(1/\hat{J}\right)$ and $\mu = M - \hat{M}$ parameters is obviously. Therefore the function dV/dt is negative-definite and at construction the OD of identification according to expressions (11) the $1/\hat{J}$ and $\hat{M}$ estimations asymptotically approach to their actual values of the moment of inertia $1/J$ and the external moment M of load of the drive. The convergence of process of estimate depends on λ_1, δ_1 and α coefficients, which can be practically always chosen from a condition that the estimate processes in OD occur quicker than the main transition process in SAC of the drive.

4. Results and Discussion

Simulation of dynamics of control of the drive of rotation of a link of MR is carried out by method of numerical integration of the equations (9) of the drive and writing the program on the computer. For this purpose equation (9) of CO with accounting of the kinematic relations (8) was considered as the following system of differential equations:

$$d\omega_m/dt = (1/J)(-k_m k_\omega R_a^{-1}\omega_m + k_m k R_a^{-1} u - M),$$

$$d\varphi/dt = \omega_m/i.$$

In the program of simulation the different values of the moment of inertia J and the external moment M of load are set in this expression (9), these given values of load are estimated in identification OD on an algorithm (11) and used for formation of a control algorithm (10). Therefore, for simulation are necessary the equations (9)-(11) and the ratios (8).

Results of simulation of dynamics of control of a rotation link drive of MR at variable values of mechanical load are given in Figures 2, 3 and 4. Modeling was carried out at the following parameters of the electric drive with dc motor and OD: k = 10; i = 1; k_p = B/rad; k_s = 3,5 Vs/rad; k_m = 0,7 N*m/A; k_ω = 0,8 V*s/rad; R_a = 3 Ohm; T = 0,03 s; λ_1 = 38; δ_1 = 0,0009; α = 3000; J_0 = 16,5 kg* m^2. So, in SAC without adaptation to load ($\hat{J}$= const = J_0, $\hat{M} = 0$ - isn't used) at working off of an input signal $\varphi^*(t) = 1(t)$ with increase in values of load happens the deterioration in characteristics of the transitional functions $h(t)$ of SAC (duration, overshoot and steady-state error increase) – in the Fig. 2: a curve 1 at J =7 kg*m^2 and M =10 N*m; a curve 2 at J =25 kg*m^2 and M =100 N*m.

While in SAC with OD at these different values of mechanical load corresponding to different configurations of MR and masses of moved payloads, characteristics of transitional functions don't change (the Fig. 2, a curve 3), i.e. independent of changes of load in SAC with OD the set duration and overshoot of desired transition process always take place, and the steady-state error of the SAC is completely eliminated.

In the Fig.3 are shown curves 1 - 4 of transition processes in OD at the identification of unknown values of the moments of inertia J set in the drive model (9) together with the external moments M of load: 1 is the estimate of J =7 kg*m^2 at M =10 N*m; 2 is the estimate of J =10 kg*m^2 at M =40 N*m; 3 is the estimate of

J =20 kg*m^2 at M =70 N*m; 4 is the estimate of J =25 kg*m^2 at M =100 N*m. In the Fig. 4 are shown the corresponding curves 1 – 4 at the identification of unknown values of the external moment of load M set in the drive model (9): 1 is the estimate of M =10 N*m at J =7 kg*m^2; 2 is the estimate of M =40 N*m at J =10 kg*m^2; 3 is the estimate of J =20 kg*m^2 at M =70 N*m; 4 is the estimate of M =70 N*m at J =25 kg*m^2.

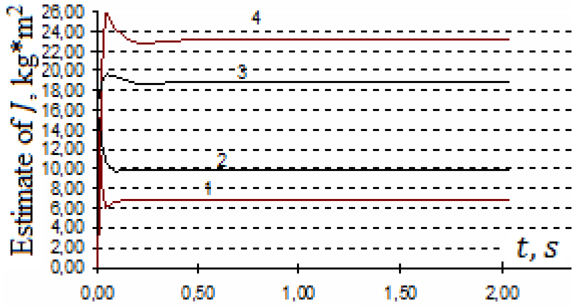

Fig.3 - Transition processes of identification of the moment of inertia of load
1 is the estimate of J =7 kg*m^2 at M =10 N*m;
2 is the estimate of J =10 kg*m^2 at M =40 N*m;
3 is the estimate of J =20 kg*m^2 at M =70 N*m;
4 is the estimate of J =25 kg*m^2 at M =100 N*m.

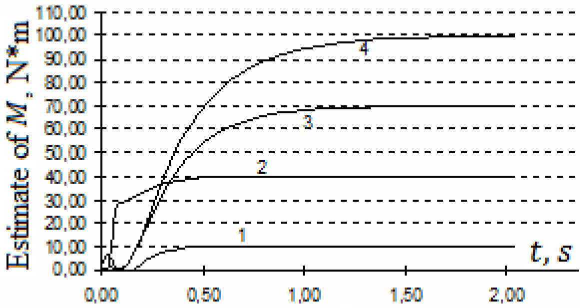

Fig.4 - Transition processes of identification of the external moment of load
1 is the estimate of M =10 N*m at J =7 kg*m^2;
2 is the estimate of M =40 N*m at J =10 kg*m^2;
3 is the estimate of J =20 kg*m^2 at M =70 N*m;
4 is the estimate of M =70 N*m at J =25 kg*m^2.

From curves in Figures 2, 3 and 4 it is also visible that process of estimate of unknown variables of the moments of inertia J happens quicker than transition process in the main contour of SAC, that is necessary for the steady work of a load adaptive SAC of the drive, and the estimated values of the unknown external moments M of load eliminate a steady-state error of the drive.

The graphs in Figures 2, 3, 4 of transition processes in OD at the identification of different values of the moment of inertia J and the external moment M of load set in model of the drive (9) have shown that the use of the values J and M estimated in OD to form an adaptive control algorithm (10) provides the invariable characteristics of transitional functions in the control system, i.e. independent of changes of mechanical drive load in SAC with OD the desirable transition process - a curve 3 in the Fig.2 always takes place.

5. Conclusion

Variable mechanical load of joint-drive of MR is characterized by changes of the moment of inertia and the external moment of drive load. The moment of inertia is the parameter and the external moment is the external disturbing signal of the SAC of the drive. Changes of these variables of load cause essential deterioration in dynamic properties (duration, overshoot and steady-state error increase) of the SAC. For the stabilization of desirable dynamic properties of the SAC of drive it is required to use the actual values of the moment of inertia and the external moment of load to forming a control algorithm of the drive. However when the MR is moving unknown payloads the values of these parameters of load will be unknown. For the identification of the unknown parameters and external disturbing signals of the SAC it uses the ODs [4]. So, in [5] the algorithm of work of OD of identification of unknown value of moment of inertia of load of dc electric drive is proposed. However in this OD described by the equations (3) the external moment M of drive load isn't considered, while it can cause the instability work of OD. Therefore in [6] by analogy with a “mechanical” part (1) of the drive the algorithm (4) of OD of identification of moment of inertia of load of drive is proposed in which the external moment M of drive load is considered. As in algorithm (4) the measurement of the external moment M is difficult to realize and it isn't always possible, in this report was proposed the algorithm (11) of the OD in which both the moment of inertia J and the external moment M of load are identified in common.

The proposed algorithm (11) of OD has asymptotically stability of identification of unknown values of the moment of inertia and the external moment of load of the drive during necessary time that allows their use in an algorithm of adaptive control (10) and provides elimination of their disturbing influence on dynamics of control of the drive (9) of a link of MR.

Results of simulation on the computer illustrate that, first, variables of the unknown parameters of load of joint-drive of MR cause inadmissible deterioration in dynamic properties of the SAC of drive, and secondly, use in a load adaptive algorithm (10) of control of the drive (9) instead of unknown values of the moment of inertia J and the external moment M of load of the drive their values $\hat{J}$ and $\hat{M}$ estimated in the OD described by the equations (11) provides stabilization of desirable dynamic properties of the SAC of link drive of MR. The set of a load adaptive drive control systems each of which is in the degree of mobility of MR will provide desirable dynamics of control of movement of end-effector of MR in the course of performance of production tasks.

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