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System of Automated Design of Control Mechanism for Manipulators Having High Dynamic Accuracy

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ABSTRACT

The computer-aided automated design (CAD) system with some new original methods of synthesis of adaptive control system and formulated regulations for choosing these methods in dependance on the features and requirements to the manipulator to be designed are considered in this paper. The peculiarity is that with the help of CAD system it is possible to fast choose one method or many methods of designing and to synthesize regulators, ensuring the given dynamic accuracy of control at a given velocity and trajectory of manipulators movement by using the simplest ones with the aim to put into practice arrangements or algorithms of control. The results of the usage of the system developed confirmed its high effectiveness in designing arbitrary manipulation systems.

1. INTRODUCTION

To raise manipulated robot productivity or to use them in performing operations on speedy production lines it is necessary to develop such control systems that could provide the dynamic precision of contour control at significant influences between manipulator degrees of freedom. At present there are different ways of synthesis of adaptive control systems, permitting to solve the problem mentioned above, however, all of them possess different properties, different labour-consuming nature, but regulators of different practical realization complexity can be synthesized with their help. As a result, designer has a problem of choosing a method of synthesis, that, depending on manipulator configuration, its velocity movement, the type of the actuator used, requirements to the transient process quality and others, permits to synthesize such types of regulators that could ensure the definite (high) accuracy of dynamic control and could have the least complexity of practical realization.

This problem can be solved with the help CAD system. To increase velocity and to simplify the solution of the problem mentioned above with the help this system, as well as to carry on research on the manipulators designed in their standard regimes of work the developed CAD system has effective algorithms in solving direct and inverse dynamic problems, having the least computing complexity among the known approaches. The use of screw theory while writing equations for manipulator dynamics and the use of new recursive for simplifying the calculation processes permits to considerably reduce computational complexity while solving those problems.

At first, in this paper a generalized approach to the synthesis and new original methods of synthesis of adaptive control systems are considered. This approach is the basis for working out CAD system mantioned.

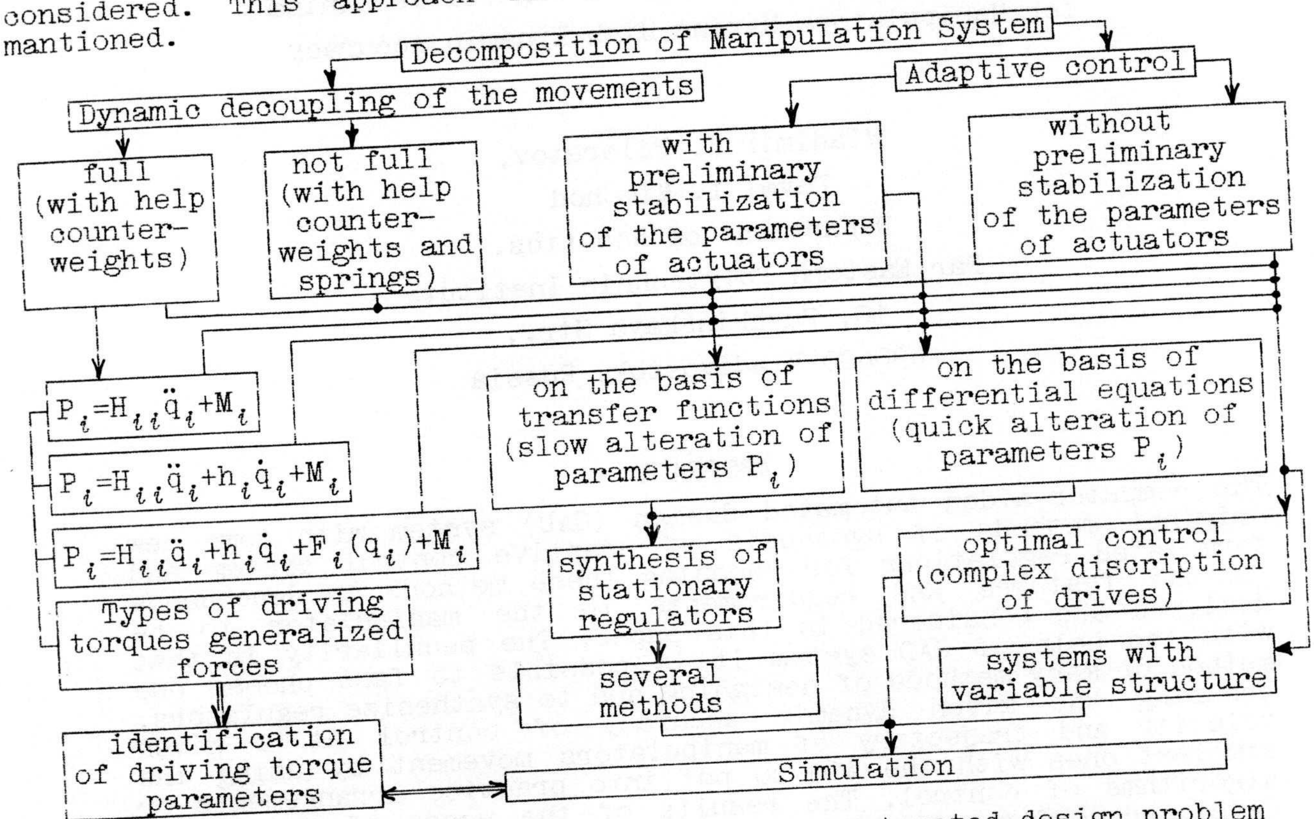

Fig.1. A generalized scheme to solve the automated design problem of effective control systems for any manipulators

2. THE CHOICE OF WAYS TO SOLVE SYNTHESIS PROBLEM

The researches carried out showed, that at present time there is not any universal approach, that could give a possibility to synthesize effective, but rather easy realized control systems for any manipulator structures. Probably, in designing manipulation systems (MS) it is expedient to have a number of methods, each of them ensuring the synthesis of effective regulators for definite class or for even definite degrees of freedom of MS.

The analysis done showed that for control of MS is better to use algorithms for constructing adaptive systems (AS) with the open loop of self-adapting. They are effective for synthesis of control systems with the fast change of parameters and realized with the help of rather simple technical means, however, it requires information about all current parameters of the objects controlled.

A generalized scheme of suggested ways for solving the problem of control manipulator sythesis is represented in Fig.1. Here P_i are the generalized forces (driving torques) acting on the i-th degrees of freedom; H_{ii}, h_i, Q_i are inertial, speedy and gravitational constituents, accordingly; M_i is the action of external perturbation, being not a function of the coordinate q_i and its derivatives; $F_i(q_i)$ is nonlinear constituent P_i; $\dot{q}_i$, $\ddot{q}_i$ are the velocity and acceleration of the generalized coordinate q_i, accordingly; i is the number of the generalized coordinate.

On the basis of that scheme one of the approaches to regulator synthesis, meeting all the requirements of dynamic accuracy and quick-response with the aid of easy realized AS, is chosen. However, this choice depends on requirements to control dynamic accuracy and peculiarities of actuators used, interaction moment types between the degrees of freedom and velocities of their parameter changes, as well as transient process desired.

In developing AS synthesis methods the decomposition principle known was used. Due to this principle the complex MS was decomposed into several local subsystems (separate actuators), for which the regulator synthesis was realized. However, a complete or at least dominating interaction between all the degrees of freedom was kept and taken into account. That decentralization allows to significantly simplify the regulator structure and to keep the high control performance effect.

To simplify the form P_i, and, therefore, to synthesize AS, where it is possible, it is necessary to choose either kinematic schemes of MS, or with the help of automatic mechanical devices to realize a dynamic decoupling of its degrees of freedom. Several methods of automatic mechanical arrangement constructions are considered in this paper. They secure dynamic decoupling actuators of MS. As a result, in robot actuators the change of inertia moments and external moments in the function of load gripped mass m_g takes place only. In that case P_i takes the simplest form

$$P_i = H_{ii}\ddot{q}_i + M_i.$$

In dependance on peculiarities of MS and the type P_i in synthesizing AS two approaches to be appliedare are offered.

The first approach is, that, first of all, with the use of adaptive correction all the parameters of MS actuators are stabilized at the nominal level. Then, using the known methods, stationary regulators, securing the given accuracy for the actuators with the parameters having been stabilized before, are synthesized.

The second approach does not mean the preliminary stabilization of robot actuator parameters at the nominal level, and allows to elaborate regulators taking into account all current changes of those parameters. In Fig.1 two different versions of that approach are considered.

The first version is based on the security of invariant property to the changeable parameters of load. This property is ensured by means of construction AS with variable structure, in which the sliding regimes with maximum possible velocity for the current parameters of the load appears. Thus, the monotonous character of the transient processes is ensured. The second variant is based on the assumption, that when MS moves, the control object parameters are quasi-stationary. In this case for all possible combination of changeable parameters of actuator load at the design stage the synthesis and computer storage of AS parameters are realized, that change in further changing of load parameters.

The mentioned approaches will be considered below.

3. METHODS OF SYNTHESIS OF ADAPTIVE CONTROL SYSTEMS

3.1 Synthesis of Adaptive Control Systems, Stabilizing Actuator Parameters at Nominal Level

The paper presents two methods of adaptive control synthesis, stabilizing actuator parameters. The first method is based on stabilization of transfer function parameters, while another one - on stabilization of differential equation parameters describing the actuators of corresponding degrees of freedom of MS (see Fig.1).

In using the first method the hypothesis about quasi-stationary parameters of actuators is assumed. That enable to use the traditional transfer functions. In this case at the process of synthesis of AS the conception of compensation of pole parameter being changed by means of adjustment of "mobile" null parameter is used.

By introducting an adaptive corrective element with the transfer function $W_k(s)$ into the direct servodrive branch with essentially variable parameters and transfer function $W_p(s)$, the transfer function of the adaptive servodrive takes the form

$$W_{as}(s) = W_k(s)W_p(s) = \frac{k}{(T_1 s+1)(T_2 s+1)},$$

where k=const, T_1=const, T_2=const.

The paper presents the transfer functions obtained and on their basis structural schemes of adaptive correcting elements (ACE) are created for various d.c. electro-drives. The transfer function image and corresponding ACE are also shown here, as well as their practical realization. All these significantly depend on the value of electric time constant.

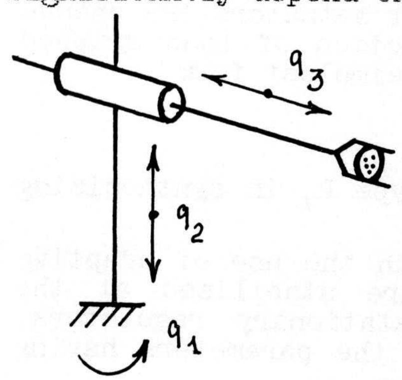

Fig.2 Kinematic scheme of robot

For example, when $(H^*+J)R \geqslant (h^*+k_v)L$, $T_m >> L/R$, the transfer function of ACE for robot turn drive, kinematic scheme of which is in Fig.2, can be written in the form

$$W_k(s) = \frac{1}{k_p k_w} \cdot \frac{(T_m s+1)}{(T_1 s+1)}, \tag{1}$$

where $T_m = (H^*+J)R \,/\, [(h^*+k_v)R + k_m k_w]$;

$k_p = k_m/[(h^*+k_v)R + k_m k_w]$; $h^* = h_i/i_r^2$; $H^* = H_{ii}/i_r^2$; J is inertia moment of engine rotor and rotating parts of reductor; R, L are the active resistance and inductivity, accordingly; k_w, k_m are coefficients of counter-electromotor force end torque, accordingly; k_v is the viscous friction coefficient; i_r is the reducing ratio of reductor.

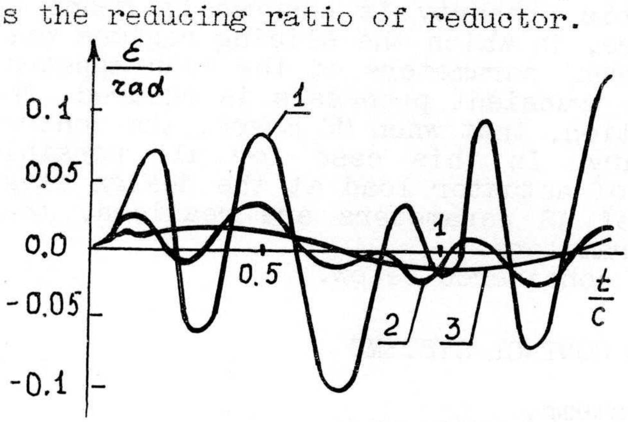

Fig.3 Errors of rotation servoactuators

The numbers 1 and 2 in Fig.3 stand for the errors $\mathcal{E}$ of the servoactuator of the turning (see Fig.2) respectively without adaptation and with the developed ACE (1), when q_1 and q_3 coordinates have been changed according to the laws

$$q_1 = 0.5(1-\cos(4t)),$$
$$q_3 = 0.25(1-\cos(16t)). \tag{2}$$

From Fig.3 you can see, that the developed ACE enables to considerably increase dynamic accuracy of actuators by the significant interactions between degrees of freedom.

If the velocity of the gripper movement increases (becomes more than 1.5-2 m/s), then the transfer function will not ensure the required dynamic accuracy. In this case, to keep the required control quality is better to use the second method, that allows to stabilize the differential equation coefficients.

That is, the task is to choose such control law U_k, for which the differential equation with variable parameters, for example, for rotational servoactuator of robot (see Fig.2)

$$L(H^*+J)i_r\dddot{q}_1+[R(H^*+J)+L(h^*+\dot{H}^*+k_v)]i_r\ddot{q}_1+$$
$$+[k_mk_w+R(h^*+k_v)+L(\dot{h}^*+\dot{k}_v)]i_r\dot{q}_1+RM_f+L\dot{M}_f = k_uk_mU_k,$$

transforms into a differential equation with constant desired parameters in the form

$$\frac{LJ_n}{k_m}\cdot i_r\cdot\dddot{q}_1 + \frac{RJ_n}{k_m}\cdot i_r\cdot\ddot{q}_1 + k_w\cdot i_r\cdot\dot{q}_1 = k_uU,$$

where k_u is the coefficient of the power amplifier; M_f is a dry friction moment; U_k, U are signals at exit and input ACE, accordingly.

Such control law has the form

$$U_k = \frac{L(2h^*+k_v)}{k_mk_u}i_r\ddot{q}_1+\left[\frac{k_w}{k_u}\left(1-\frac{H^*+J}{J_n}\right)+\frac{R(h^*+k_v)+L\dot{h}^*}{k_mk_u}\right]i_r\dot{q}_1+\frac{R}{k_mk_u}M_f+\frac{H^*+J}{J_n}U. \quad (3)$$

Control law (3) differs from ACE (1) because it stabilizes precisely dynamic properties of drivers at any velocity of changing h^* and H^* (see curve 3 in Fig.3).

After the stabilization of actuator manipulator parameters at nominal level one may use various stationary correcting elements (SCE) with the purpose to further increase the dynamic control accuracy. The peculiarities of SCE introduction are considered with the use of ACE.

3.2 Synthesis of Adaptive System with Variable Structure

In this chapter the problem of ACE synthesis is solved. Those ACE don't allow to have overshoot at MS. In contrast to traditional approach, this paper considers AS with variable structure (ASVS), providing robot drives maximum fast action (in sliding regime) taking into account current values of load parameters. The idea of self-adaptation is that, when changing the parameters of actuators one need to change the position of switching hypersurface with the purpose of securing both the sliding regime and maximum fast action. There were attempts of creating ASVS before, however, the current information about system parameters have not been used. As a result, synthesized regulators proved to be either rather complicated or less effective.

This paper presents a new method of constructing ASVS of different types. They are designed for various operation regimes of MS. The structure complexity of ASVS being created depends on the complexity of equations, which are used to describe electrodrives, on type of moment influence, as well as, permissible value of linear zone of power amplifier.

For robot turn drive (see Fig.2) adaptive control law has the form ($L\cong0$)

$$U_k=(|\mathcal{E}|+k_s|M_f|+k_g|\ddot{q}^*_1+a\dot{q}^*_1|)\mathrm{sign}(S), \quad (4)$$

where $\mathcal{E}=q^*_1-q_1$; $\ddot{q}^*_1$, $\dot{q}^*_1$ are the desired values of coordinates $\ddot{q}_1$ and $\dot{q}_1$, accordingly; $S=(\dot{q}^*_1-\dot{q}_1)+c(q^*_1-q_1)$; $c=\mathrm{var.}$; $a=[k_mk_w+ R(k_v+h^*)][R(J+H^*)]^{-1}$.

For meeting requirements of existence of the sliding regime in the ASVS it is necessary to fulfil the correlations

$$\dot{c}-c^2+ac = k_m k_u [Ri_r(J+H^*)]^{-1}\cdot \mathrm{sign}(S\cdot\mathcal{E}), \tag{5}$$

$$k_s \geqslant R(k_u k_m)^{-1};\ k_g = Ri_r(J+H^*)(k_m k_u)^{-1}.$$

Mathematical simulation showed that by introducing adaptation it is possible to considerable increase fast action of drive ≈2 times (in sliding regime). In this case it is not required to ensure preliminary stabilization of their dynamic properties, that enable maximum usage of energetic capacity of engines with the purpose to increase fast action of MS.

3.3 Synthesis of Adaptive Control Systems According to Quadratic Criterion of Quality without Preliminary Parameter Stabilization

This approach is an approximate one, however, it is well used for general (complex) form P_i, as well as for robot drives, which are described with the help of non-linear differential equations above of the third order. In this case, the use of the methods, considered above, resulted in considerable structure complication and realization of ACE. The method suggested allows to take into account all basic non-linearities P_i.

The researches carried out showed, that d.c. electro-drives of any degrees of freedom of any manipulators taking into account or not gaps and tensions can be described in the form of matrix differential equation

$$\dot{\mathcal{E}}=A\mathcal{E}+BU+F(\mathcal{E})+W, \qquad \mathcal{E}(t_0)=\mathcal{E}_0, \tag{6}$$

where $A\in R^{n\times n}$ is matrix of the system dynamic properties, $B\in R^n$ is vector of amplification coefficient at control action, $U\in R^m$ is vector of control actions, $\mathcal{E}\in R^n$ is vector of errors of system phase coordinates, $F(\mathcal{E})\in R^n$ is vector of any nonlinear constituents, $W\in R^n$ is vector of external perturbations.

Moreover, matrix A elements depending on the choice of drive phase coordinates are functions of separate elements of moments of interactions and, in some cases, their derivatives. It becomes the main criterion in choosing the phase coordinates, since it defines the complexity of practical realization of AS.

For the system (6) the problem of control law synthesis minimizing typical quadratic performance criterion is solved.

Synthesized drive control law ot the manipulator has the form

$$U_i = D_i^1(H_{ii},h_i,Q_i)\mathcal{E}_i + D_i^n(H_{ii},h_i,Q_i)F(\mathcal{E}_i) + D_i^v(H_{ii},h_i,Q_i)W_i, \tag{7}$$

where $D_i^1\in R^n$, $D_i^n=D_i^v\in R^n$ are vectors of corresponding amplification coefficients.

Thus, due to expession (7) the coefficients of amplification AS for any robots depend on at maximum of 3 elements P_i. These elements are calculated in advance at the stage of regulator synthesis in the function of values H_{ii}, h_i, Q_i and are stored in computer memory in the form of tables or approximated by functional dependencies. Further, in the process of control depending on the current values of H_{ii}, h_i and Q_i it is necessary to retrieve only the required amplification coefficients from computer memory.

Mathematical simulation showed that for the servoactuator of the turning (see Fig.2), when q_1 and q_3 have been changed according to the laws (2), due to self-adaptation it is possible to increase 6-8 times the operation accuracy for MS with complex kinematic scheme.

4. METHODS OF SOLUTION OF DIRECT AND INVERSE DYNAMIC TASKS

4.1 Solution of Inverse Dynamic Task

This paper considers manipulators, a kind of open kinematic chains, consisting of absolutely hard members jointed by fifth class hinges. Mass of each link m_i and its tensor of inertia T_i concerning mass centre are known. Main vectors used are shown in Fig.4, where $O_0X_0Y_0Z_0$ are absolute coordinate system connected with the manipulator platform.

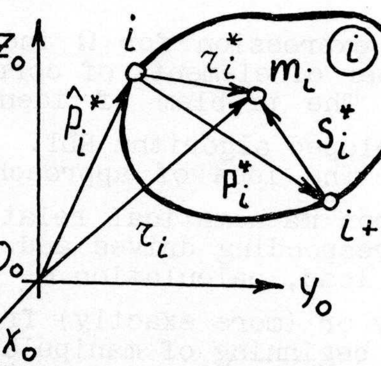

Fig.4 Presentation of basic vector

In solving reverse dynamic task (RDT) all calculations are done within the coordinate system connected with the corresponding manipulator links. As a result of usage of properties of vector product and modificated systems of coordinates named Denavit-Hartenberg, as well, because of introduction of intermediate vector $\hat{P}_i^*$ on the basis of well known approaches the following calculation algorithm was finally formed

$$\omega_i = A_i^{i-1}\omega_{i-1} + \dot{q}_i l_i \bar{\delta}_i, \quad \omega_0=0, \quad (i=\overline{1,n}),$$

$$\dot{\omega}_i = A_i^{i-1}\dot{\omega}_{i-1} + [(A_i^{i-1}\omega_{i-1})x(\dot{q}_i l_i) + \ddot{q}_i l_i]\bar{\delta}_i, \quad \dot{\omega}_0=0, \quad (i=\overline{1,n}),$$

$$\ddot{\hat{P}}_i^* = A_i^{i-1}(\ddot{\hat{P}}_{i-1}^* + \Omega_{i-1}P_{i-1}^*) + (2\dot{q}_i\omega_i x l_i + \ddot{q}_i l_i)\delta_i, \quad \ddot{\hat{P}}_0^* = -g, \quad (i=\overline{1,n}),$$

$$\ddot{r}_i = \ddot{\hat{P}}_i^* + \Omega_i r_i^*, \quad (i=\overline{1,n}),$$

$$\hat{f}_i = A_i^{i+1}\hat{f}_{i+1} + m_i\ddot{r}_i - \tilde{F}_i, \quad \hat{f}_{n+1}=0, \quad (i=\overline{n,1}),$$

$$\hat{n}_i = A_i^{i+1}\hat{n}_{i+1} + P_i^* x(A_i^{i+1}\hat{f}_{i+1}) + r_i^* x(m_i\ddot{r}_i) + \tau_i\dot{\omega}_i + \omega_i x(\tau_i\omega_i) - c_i^* x\tilde{F}_i - R_i, \quad (i=\overline{n,1}),$$

$$\hat{n}_{n+1}=0, \qquad P_i = l_i^T(\hat{f}_i\delta_i + \hat{n}_i\bar{\delta}_i).$$

At present this algorithm possesses the least computational complexity among all known algorithms (n_m=95n-101, n_a=84n-97), where n_m, n_a are the number of multiplication and addition operations, correspondently; n is the number of degrees of freedom of manipulator; $A_i^j \in R^{3x3}$ is the direction cosines matrix; $\omega_i \in R^3$, $\dot{\omega}_i \in R^3$ are angular velocity and angular acceleration of the link i, respectively; δ_i=1, if the joint i is prismatic and δ_i=0, if it is revolute; $l_i=[0\ 0\ 1]^T$ is vector directed along the joint i axis; $g \in R^3$ is gravitational acceleration (given in absolute system of coordinates); $\hat{f}_i \in R^3$, $\hat{n}_i \in R^3$ are reaction force and reaction moment, acting at joint i, respectively; $\tilde{F}_i \in R^3$, $R_i \in R^3$ are the main vector and the main moment of external forces, respectively (without gravitation), acting on the link l; $C^*_l \in R^3$ is the vector of the point of acting vector $\tilde{F}_l$ according to joint l,

$$\Omega = \begin{bmatrix} -(\omega_2^2+\omega_3^2) & \omega_1\omega_2-\dot{\omega}_3 & \omega_1\omega_3+\dot{\omega}_2 \\ \omega_1\omega_2+\dot{\omega}_3 & -(\omega_1^2+\omega_3^2) & \omega_2\omega_3-\dot{\omega}_1 \\ \omega_1\omega_3-\dot{\omega}_2 & \omega_2\omega_3+\dot{\omega}_1 & -(\omega_1^2+\omega_2^2) \end{bmatrix}$$

(in expression for Ω index l is omitted and lower indices show at the number of elements of corresponding vectors).

The problem of identifuing unknown m_r is solved on the basis of developed algorithm RDT.

The idea of approach is that to seperate terms with unknown m_r in common mathematical relations. Then, using the information on moments in corresponding drives and moments which would take place if there were no any load, calculation m_r is done due to information either from one drive only or (more exactly) from the drives k of the degrees of freedom. If at the beginning of manipulator operation short duration stops are possible, the simpler method of identification m_r is suggested.

To form adaptive systems mentioned above with the use of algorithm for solving RDT the problem of determination in real time components of moment actions has been solved. Moreover, it was shown that in some cases this solution can be found with the help of simple technical means without using computers.

4.2 Solution of Direct Dynamic Task

The analysis done shows that the efficiency of the solution of direct dinamic task (DDT) doesn't depend on mechanical laws used, but fully depends on formation of calculation scheme of algorithm and the used mathematical model of the manipulator. That is why to reduce calculation complexity of DDT solution, it is more convenient to use the screw theory which has allready been well developed.

If velocity and gravitational forces are calculated separately with the help of developed algorithm of RDT, then, supposing $\ddot{q}_l=0$, the equations of manipulators dynamic can be presented in the matrix form

$$H\ddot{q}=T^*, \tag{8}$$

and the algorithm for finding T^* with the help of screw theory can be presented in the form

$$u_l=u_{l-1}+s_l\ddot{q}_l,\ u_0=(0,0),\ (l=\overline{1,n}),$$

$$f_l=f_{l+1}+\mu_l \circ u_l,\ f_{n+1}=(0,0),\ (l=\overline{n,1}),$$

$$T^*_l=(s_l,f_l)+J_l i^2_{rl}\ddot{q}_l,\ (l=\overline{1,n}),$$

where $H\in R^{n\times n}$ is the inertia properties matrix of manipulator, $T^*=P-\hat{h}$ ($T^*,P\in R^n$); $\hat{h}\in R^n$ is the vector of velocity and gravitational forces, $u_l=(\dot{\omega}_l,\ddot{r}_l+r_l x\dot{\omega}_l+\dot{r}_l x\omega_l)$ is the acceleration screw ($u_l\in R^6$), $f_l=(\hat{f}_l,\hat{n}_l+\hat{P}^*_l x\hat{f}_l)$ is the force screw ($f_l\in R^6$), $s_l=(l_l\bar{\delta}_l,\ l_l\delta_l+\hat{P}^*_l x l_l\bar{\delta}_l)$, $\mu_l: R^3xR^{6x6}$ is the inertia afinor; symbol o designating the product of afinor to screw, (s_i, f_i) is the scalar product of two screws.

Two methods of solving DDT are considered here. The first (direct method) is based on evident calculation of the matrix H elements and followed by solving the equation (8) by means of Holetsky method. The algorithm of calculation H_{ij} can be presented in the block-matrix form

$$I_i = I_{i+1} + \bar{\mu}_i,\ I_{n+1} = 0,\quad (i = \overline{n,1}),$$

$$\bar{\lambda}_i = I_i \cdot \bar{S} i,\qquad (i = \overline{n,1}),$$

$$H_{ij} = \bar{\lambda}_i^T \cdot \bar{S}_j + J_i l_{ri}^2 \delta_{ij},\quad (i = \overline{n,1};\ j = \overline{i,1}),$$

where $\bar{\mu}_i = \left[\begin{array}{c|c} \mu_{(22)i} & \mu_{(21)i} \\ \hline \mu_{(12)i} & \mu_{(11)i} \end{array}\right]$ $(\bar{\mu}_i \in R^{6x6})$, $\bar{s}_i = [l_i \bar{\delta}_i \,|\, l_i \delta_i + \hat{P}_i^* x l_i \bar{\delta}_i]^T$ $(\bar{S}_i \in R^6)$

are the block-matrix, consisting of the inertia afinor blocks (in brackets are indexes of afinor μ_i blocks), and the block-vector, respectively, δ_{ij} - Kroneker symbol; $I_i \in R^{6x6}$ is the block-matrix. This method has computational complexity proportional to n^3 $(n_m = (1/6)n^3 + (9/2)n^2 + (544/3)n - 155$, $n_a = (1/6)n^3 + (7/2)n^2 + (499/3)n - 159)$, that is why it is not always purposeful to use when large n, although at present it is most efficient one in its class.

The second method has computational complexity proportional to n. Here to determine q_i the well known pursuit method is used. Algorithm, realizing this method, has the final form

$$\ddot{q}_i = (\bar{s}_i^T K_i \bar{s}_i + J_i l_{ri}^2)^{-1} (P_i - \bar{s}_i^T K_i \bar{u}_{i-1} - \bar{s}_i^T G_i),\ (i = \overline{1,n}).$$

The block-matrix $K_i \in R^{6x6}$ and block-vectors the $G_i \in R^6$, $\bar{u}_i \in R^6$ can be determined according to the scheme

$$\bar{u}_i = \bar{u}_{i-1} + \bar{s}_i \ddot{q}_i,\ \bar{u}_0 = (0 \,|\, 0),\ (i = \overline{1,n-1}),$$

$$K_{i-1} = \bar{\mu}_i + K_i - K_i \bar{s}_i (\bar{s}_i^T K_i \bar{s}_i + J_i l_{ri}^2)^{-1} \bar{s}_i^T K_i,\ K_n = \bar{\mu}_n,\ (i = \overline{n,1}),$$

$$G_{i-1} = G_i + \bar{\lambda}(r_{i-1}) [N_{i-1}^{\otimes} \,|\, F_{i-1}^{\otimes}]^T + K_i \bar{s}_i (\bar{s}_i^T K_i \bar{s}_i + J_i l_{ri}^2)^{-1} (P_i - \bar{s}_i^T G_i),$$

$$G_n = \bar{\lambda}(r_n) [N_n^{\otimes} \,|\, F_n^{\otimes}]^T,\ (i = \overline{n,1}),$$

where, $N_i^{\otimes} = \tau_i \dot{\omega}_i + \omega_i x (\tau_i \omega_i)$, $F_i^{\otimes} = m_i \ddot{r}_i$, $\bar{u}_i = [\dot{\omega}_i \,|\, \ddot{r}_i + \dot{r}_i x \omega_i + r_i x \dot{\omega}_i]^T$, $(N_i^{\otimes} \in R^3, F_i^{\otimes} \in R^3)$,

$$\bar{\lambda}(r_i) = \left[\begin{array}{c|c} E & \lambda(r_i) \\ \hline 0 & E \end{array}\right]\ (\bar{\lambda}_i(r_i) \in R^{6x6}),\ \lambda(r_i) = \begin{bmatrix} 0 & -r_3 & r_2 \\ r_3 & 0 & -r_1 \\ -r_2 & r_1 & 0 \end{bmatrix},$$

$E \in R^3$ is the single matrix. The index $\otimes$ shows that corresponding values are calculated at $\ddot{q}_i = 0$. In expression for $\lambda(r_i)$ indices 1,2,3 indicate numbers of the vector r_i elements.

Computational complexity of the last method is equal to n_m=249n-272, n_a=231n-294, at present it is the least one in its class too.

5. FEATURES OF CAD SYSTEM OF MANIPULATOR CONTROL MECHANISMS

The developed CAD system is intended for facilitating and accelerating the synthesis process of high-qualitative manipulator regulators, possessing high dynamical accuracy, and for investigating synthesized systems at real work regimes. The CAD system created has the properties of the expert system. That is, in dependence on the requirements to dynamic control accuracy and quality of transient processes, kinematic manipulator scheme and working velocity of its grippers removement, as well as, the type of the engines used and peculiarities of mechanical transmissions of this system allows a designer to make a search and a choice of such a synthesis method or methods, which meet not only all the requirements and conditions, but, also, has the least complexity of practical realization.

Rules to design the expert system are based on the structural scheme (see Fig.1). From the scheme it follows that the choice of the synthesis method and, consequently, the synthesis itself depends on the manipulator features enumerated above and on the tasks which to be solved with help of this manipulators.

It should be noted, that the CAD system considered contains not only methods of synthesis of adaptive control systems, which were described at the beginning of the present paper, but many others known approaches and algorithms of the synthesis. As it was noted before, this CAD system with the aim of facilitating and accelerating research processes of synthesized manipulators in different operation regimes comprises highly efficient above considered algorithms of solving direct and inverse dynamics tasks.

In addition to the mentioned above, the developed CAD system allows:

1. to create the file system with the parameters of different types of manipulators, engines, mechanical transmissions and regulators;
2. to create the file system with various types of manipulator movement trajectories;
3. to calculate the needed drive moments and powers to move manipulator grippers along the given trajectories;
4. to research any manipulator movements along any trajectories (includes, movements at any degree of freedom) at known regulator parameters;
5. to create the file system with the calculation and simulation results.

Dialogue between operator and CAD system is fulfilled with help of the main menu, facilitating the communication process.

6. CONCLUSION

The results of practical usage of CAD system developed confirmed its effectiveness in designing manipulators of various purposes. Along with it, new methods of synthesis of adaptive control systems allowed to considerably increase dynamic control accuracy of any manipulators at high velocities of their operations. Moreover, the synthesized adaptive control systems ensure not only high control quality, but have the least complexity of practical realization.

The developed algorithms to solve direct and inverse dynamic tasks allow not only to facilitate the procedure of researching of synthesized manipulators at real operation regimes, but also to ensure identification of parameter variables of drives loaded at real time. It is necessary for practical use of the synthesized adaptive regulators.