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Dynamic Control of Manipulating Robots. Dynamic Control by Standard Corrections

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I. Methods for dynamic control of manipulating robots – basic problems and approaches for their decision.

The main problem arising with the control of the manipulating robot based on the dynamic model is the level which is necessary to keep with rendering in account the dynamics of the system when the control law is being chosen.
The dynamic model of the manipulating robot has the form

(1) $$A(q,d)\ddot{q} + h(q,d) = u,$$

(2) $$A(q,d)\ddot{q} + b(q,\dot{q},d) = u,$$

where $A(q(t), d(t)) \in R^{n,n}$ is a symmetric positively determinated generalized inertia matrix; $h(q,(t), \dot{q}(t), d(t)) \in R^n$ – a vector of the coriolis and centrifugal forces; $g(q(t), d(t) \in R^n$ – a vector of the potential forces; $u(t) \in R^n$ – a vector of the driving forces or torques; $d(t)$ – a vector of the mechanic system parameters.

In the general case the dynamic model (1) leads to very complex nonlinear system of differential equations. That makes the problem of forming the dynamic model of manipulating robot in real time also very complex and hence there are lots of efforts to simplify this model. Some parts in the equations coming from the dynamic model have to be neglected in order to reduce the calculations for the control law in real time. Frequently it is done for the centrifugal and coriolis components $b(q,\dot{q},d)$ – they are inessential during the manipulating robot motion in the neighbourhood of the aiming state, because the velocity of the mechanical system's parts is very little then. But during the motion which needs tracing out on trajectories with high precision and velocity, these parts that depend of the velocities have to be compensated. Therefore, for following out of trajectories with given necessary precision and velocity, the whole dynamic model of the manipulating robot must be used with corresponding possibility of doing that, when the control law is synthesized.

A survey of existing methods of dynamic control is given in [2,3]. Between the examined methods of non-adaptive control the method of calculating moment [6,7,8,9,10,11,12] is especially popular. It has become a base for development of lots of other algorithms and methods of dynamic control, including methods for adaptive control of mani pulating robots. The main problem in using the method of calculating moment is the necessity of calculation of the whole dynamic model at every interval of the time discretization. This requirement can be realized very hard for manipulating robots with complex structure of its mechanical system. Because of that there exist some approaches using a approximate model of the robot's dynamics. The moments of inertia that express the interaction between the parts of the mechanical system by the inertia matrix $A(q,d)$ are being neglected. The same is done for the centrifugal and coriolis forces, i.e. the dynamic model is reduced to the level of the diagonal matrix A and the vector of potential forces $g(q,d)$ only. In this case the calculations are considerably decreased but for some kinds of manipulating robots are still so large. However, such an approach is correct with respect to the control quality only for slow motions of the robot close to the aiming position. For fast working out on the trajectories it is necessary to compensate the centrifugal and coriolis dynamic effects. Compensation of the whole dynamics of the robot can be done by introducing a force feed-back connection. The forces or torques acting at the kinematic joints of the robot can be measured directly [2]. The inertia matrix $A(q,d)$ is calculated during the process of control. After that, as the acceleration $\ddot{q}(t)$ is being measured, on the base of equation (2) there can be compensated the gravitational, coriolis and centrifugal forces $b(q,\dot{q},d)$. To realize this idea, however, the force sensor noise-proof has to be guaranteed. Also some constructional hardships arise and they influence the price of the sensor system that has been always kept in wind. Consequently, the use of programming microprocessor controllers that give a possibility to realize different laws of control, has some advances in comparison with the force feed-back connection for compensation of the robot dynamics.

Side by side with the main hardship – the calculation of the robot dynamic model in real time, another problem exists for non-adaptive methods of dynamic control – the complete vector d of the mechanic system parameters has to be known. But when these parameters are unknown or changeable during the robot functioning, it is problematic whether the control influence (sythesized for a set of parameters d) will be sufficiently effective (robust) for all the changes of these parameters. Moreover, there exist other effects, that cannot be calculated because of their probability nature – noise of measurements, oscillations, coming from the elastic features of the robot's links, inertia and gravitational effects arising from different objects the robot's grip works with (indetermined disturbances).

The main difficulty of the dynamic control – the large volume of calculations in real time, can be successfully overcome in some cases using the strategy of decentralized (independent) control. The manipulating robot is considered as a combination of independed subsystems, where each of the subsystems is connected to the particular degree of freedom of the mechanical system and the influence between them is ignored. For every subsystem a local control law is synthesized that ensures stability of the free (independent) subsystem. This approach is effective for the task of positioning and following the trajectories slowly. But in the general case the interaction between the simultaneously moving links can essentially make worse the quality of the system as a whole and can increase the error when the desired trajectory is followed. The disturbances with unknown amplitude that can be caused for instance by catch or grip of an object with unknown mass and inertia moment, also make worse the quality during the motion on the followed trajectory and can break the stability of the whole system as well.

When the robot works in partly determined conditions – for instance when it works with details whose weight is unknown, then the algorithms for adaptive control have to be often used. The adaptive controllers give larger possibilities, but the algorithms of adaptive control are more complex in respect to calculations needed for their realization in comparison with the classical algorithms of control. At the same time it is so complex to prove the stability of the system at all. Hence, the adaptive algorithms have to be used only when the classical methods for dynamic control cannot ensure the necessary features of the controlled system.

Two general approaches exist for solution of the problem about adaptive control [2]. The first one is connected with self-learned (self-setting-up) systems [13,14] where the improvement of the model's accuracy is ensured by methods for estimation of the controlled system parameters in real time and after that this model is used for the aims of the control by feed-back connection (parametrical adaptation [3]). The main problem of this strategy is to ensure the similarity of the parameters' estimations for the whole time during the motion is realilized. Also at the beginning of the motion's trajectory the estimated parameters are changing essentially. It leads to sudden changes of the control signals – "unevenness" of the motion at the beginning of the working task. Besides when the parameters of the system change with a jump (for instance when heavy load is caught), the stability of the system can be broken.

The second approach is an adaptive control with standard model [15,16, 17, 18,19,20]. Here the aspiration for the closed system's behavior is to correspond with the behavior of the previously chosen model in the sense of some kind of criterion (adaptation with the signal). The manipulating robot is considered not as an unknown object but as an object the dynamic characteristics of which are partially known and can be calculated in real time. This approach ensures better transitional processes in comparison with the self-setting-up systems. But the main disadvantage here is the large volume of calculations needed to realize the control law.

II. Method for Dynamic Control by Standard Corrections – specific features. Comparison with non-adaptive and adaptive methods for dynamic control about ability of calculation

The method for control by standard corrections (like a number of other methods for dynamic control) is developed on the base of the method of the calculated moment. But the great difference between them is the existence of a new component in the control signal [1], which does the estimation of the system deviation from the desired motion. Such a deviation can be caused both by the inexactnesses and by the ignored parts of the manipulating robot dynamic model and also by other disturbances, but this component makes corrections to the joint variables of the mechanical system $-\Delta u(t)$ on the basis of that estimation. The inexactnesses in the model come from variations of the parameters d, from approximate valuation of some of the dynamic model parts. And the ignored parts of the model aim to decrease the volume of calculations in real time. The valuation is being done with the help of standard trajectories for the joint variables of the mechanical system. They have been generated in dependence of concrete working task and feed-back coefficients of the joint position and velocities. After that the standard corrections are formed for the joint variables on the base of that valuation [1].

The existence of the component mentioned above in the control signal makes clear the priority of the method for control with standard corrections with respect to the methods of dynamic control between the calculated moment method's group. The comparison between these methods in calculating aspect leads to the following results (the data refer to the calculation of the control signal for every interval of discretization of time about the regional structure of the robot PUMA; it is done [2], [5] with a microprocessor

INTEL 8086/8087, 8 MHz) :

Method of calculating the moment [2]

a) when the whole dynamic model is calculated

additions – 55; multiplications – 91; time of calculations – 9.03 ms,

b) when the vector $b(q,\dot{q},d)$ from (1) is ignored

additions – 31; multiplications – 35; time of calculations – 4.07 ms;

Method of control with standard corrections

a) when the whole dynamic model is calculated

additions – 85; multiplications – 67; rotations [1] –18,

time of calculations – 9.43 ms;

b) when the approximate valuations of the matrix $A(q,d)$ and the vector $b(q,\dot{q},d)$ from (2) is used

additions – 63; multiplications – 18; rotations – 18; time of calculations – 5.03 ms.

The use of a central adaptive control with standatd model for the regional structure of PUMA robot needs the following calculations [2]:

additions – 64; multiplications – 133; time of calculations – 12.23 ms.

The realization of centralizing indirect adaptive control (by using regressor matrix [21,22]) needs the following [2] :

additions – 232; multiplications – 325; time of calculations – 34.39 ms.

From the data above mentioned it can be seen that if the whole dynamic model is calculated, then the calculation time is with 0.4 ms greater for the method of control with standard corrections compared to the method of calculating moment. But in this case the third component of the control signal $\Delta u(t)$ aims to compensate the influence of the undeterminated effects on the closed system behaviour. However, when approximate valuations are used the time of calculations is considerably less. As a result inexactnesses are introduced in the model, but nevertheless the closed system goes on the desired motion exactly that can be seen from the results given in [1] and [4]. The use of such an approximate valuations is possible due to the existence of the component $\Delta u(t)$.

In comparison with the central adaptive standard model of control the time of calculation here (with use of the method with standard corrections) decreased by 2.8 ms.

III. Computer simulation

In Fig.1 the joint coordinates q_i, i=1,2,3, are represented for the regional structure of the robot SCARA; in Fig.2 – the standard corrections to the joint coordinates, velocities and accelerstions of the 2nd rotation joint of the structure. The data of the structure needed for the computer simulation of the method of control with standard corrections, are taken for the assembly robot RMS232P. The results are obtained when valuations for $A(q,d)\ddot{q}$ and $b(q,\dot{q},d)$ (respectively $\hat{A}$ and $\hat{b}$) are equal to zero. It can be seen from the figures that as a result of the mechanism for estimation and compensation of the system deviation from the desired motion (the component $\Delta u(t)$) the structure executes the working task that in the concrete case is: transition from the initial state $q_i(0)=\dot{q}_i(0)=\ddot{q}_i(0)=0$, to the final state $q_1(T)=1$ rad, $q_2(t)=0.5$ rad, $q_3(T)=0.3$ rad, $\dot{q}_i(T)=0$ rad/s, $\ddot{q}_i(T)=0$ rad/s^2, $i=\overline{1,3}$. And the requirement of the transitional process is to have a critical-aperiodical character. The time of calculations is 3.86 ms.

In Fig.3 the joint coordinates q_i, i=1, 2, 3, are represented and the standard trajectories q_{ie}, i=1, 2, 3. The results are obtained under the same conditions as the results from Fig.1 and Fig.2. The difference is the missing of the component $\Delta u(t)$ in the control signal (Fig.3) and in Fig.4 the error for joints of the structure is shown.

IV. Conclusion

The method for control with standard corrections can be attached to the methods for adaptive control with standard model by its essence. The time for calculation of the control signal is shorter with respect to them and it makes this method more convenient for realization in practice. In comparison with the group of the calculating moments' methods, the method for control with standard corrections has undoubted advantage. It includes a possibility for valuation and compensation of the system deviation from the desired motion. This deviation can be caused by inexactnesses of the dynamic model as well as from the ignored model parts, including other undetermined disturbances. But as a result the calculating time for the control signal is commensurable with the time this group of methods used to work.

V. Appendix

Dynamic Control by Standard Corrections. Synthesis of the controlled law

The dynamic control is effected on the basis of motion equations of the manipulating robots (2).

The synthesis of the controlled signal $u(t)$ is executed in accordance with the presented in [1] method for servocontrol with standard corrections. The controlled signal consists of three components:

(3) $$u(t) = u_{fb}(t) + u_d(t) + \Delta u(t),$$

whose forming is executed as follows:

1. The component, formed from the feedback connections on the joint position, speeds and accelerations $- u_{fb}(t)$

(4) $$u_{fb}(t) = (\hat{A} - I)\ddot{q}(t) + \hat{b} - K_2\dot{q}(t) - K_1 q(t),$$

where $\hat{A}$ and $\hat{b}$ are valuations on the matrix $A(q(t))$ of the vector $b(q(t), \dot{q}(t))$ from (2); K_1 and K_2 are diagonal matrices of the feedback connections on the joint positions and speeds.

2. Component, which introduces information in the system for the desired motion $u_d(t)$.

(5) $$u_d(t) = \ddot{q}_d(t) + K_2\dot{q}_d(t) + K_1 q_d(t).$$

If (4) and (4) are replaced in (2) it follows:

(6) $$\Delta\ddot{q}(t) + K_2\Delta\dot{q}(t) + K_1\Delta q(t) = \Delta u(t) - \Delta f(t),$$

where with Δf, the sum $[(A - \hat{A})\ddot{q}(t) + (b - \hat{b})]$ is marked and $\Delta q(t) = q(t) - q_d(t)$.

If the valuations are precise, i.e. $\hat{A} = A$ and $\hat{b} = b$, there is no necessity for the third component in the controlled signal: in that case $\Delta f(t) \equiv 0$, and equation (6) of the closed system should be:

(7) $$\Delta\ddot{q}(t) + K_2\Delta\dot{q}(t) + K_1\Delta q(t) = 0,$$

where $0 \in R^n$, and with $q(0) = q_d(0)$ and $\dot{q}(0) = \dot{q}_d(0)$ working out with the desired motion is assured.

Such precise valuations of $\hat{A}$ and $\hat{b}$ are connected with the necessity of a large number of calculations, which is very hard to realize in real time in practice.

Therefore the existence in the right side of equation (6) of $\Delta f(q(t), \dot{q}(t), \ddot{q}(t)) \neq 0$ is leading to the appearance of different by valuation in the time deviations from the desired dynamics of the closed system, i.e. $\Delta q(t) \neq 0$, $\Delta \dot{q} \neq 0$ and $\Delta \ddot{q}(t) \neq 0$.

3. Component, which realizes valuation and makes corrections of the inexact and/or neglected members in the dynamic model $\Delta u(t)$.

For the forming of the last component $\Delta u(t)$ two steps must be realized:

a) generation of standard trajectories for the joint positions, speeds and acceleration $q_e(t)$, $\dot{q}_e(t)$ and $\ddot{q}_e(t)$.

b) obtaining of a valuation, which characterizes the deviation of the system from the desired motion for each interval of discrediting of the time $V(t_i)$ and numerical integrating of the differential equattion

(8) $$\ddot{z}(t) + K_2\dot{z}(t) + K_1 z(t) = KV(t),$$

when:

(9) $$V(t_i) = V_1(t_i) + V_2(t_i) + V_3(t_i)$$

and

(10) $$\begin{aligned} q(t_{i-1}) - q_e(t_{i-1}) &= V_1(t_i), \\ \dot{q}(t_{i-1}) - \dot{q}_e(t_{i-1}) &= V_2(t_i), \\ \ddot{q}(t_{i-1}) - \ddot{q}_e(t_{i-1}) &= V_3(t_i). \end{aligned}$$

The choice of the elements of the diagonal matrix K, connected with the size extent of the standard corrections, depends of the concrete problem executed by the manipulation robot.

The last component $\Delta u(t)$ as a result of the additional feedback connection on the joint position, speeds and acceleration, is formed by the so formulated after integration of equation (6) $z(t_i)$, $\dot{z}(t_i)$ and $\ddot{z}(t_i)$ as:

(11) $$\Delta u(t) = \ddot{z}(t_i) + K_2\dot{z}(t_i) + K_1 z(t_i).$$

When in equation (6) $\Delta u(t)$ is replaced by the expression (11), the motion in the system is described with

(12) $$\ddot{\varepsilon}(t) + K_2\dot{\varepsilon}(t) + K_1\varepsilon(t) = -\Delta f(t),$$

where $\varepsilon(t) = \Delta q(t) - z(t)$. In that equation the sum $[\ddot{z}(t) + K_2\dot{z}(t) + K_1 z(t)]$ compensates the influence of the inexacts Δf with the help of corrections, introduced by $z(t)$, $\dot{z}(t)$ and $\ddot{z}(t)$ toward $\Delta q(t)$, $\Delta\dot{q}(t)$ and $\Delta\ddot{q}(t)$.

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Динамическое управление манипуляционными роботами. Динамическое управление с эталонными коррекциями

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В работе рассмотренны методы динамического управления манипуляционными роботами. Рассмотрены также основные проблемы для их практической реализации и подходы решения этих проблем. Далее описан метод динамического управления с эталонными коррекциями. Сравненые вычислительная сложность различных методов. Представлены результаты компьютерного симулирования.

Fig.1. Joint position q_i, i=1, 2, 3. The curve with no mark – the graphics of q_i – $Q1$, the curve with * – the graphics of q_2 – $Q2$, the curve with Δ – the graphics of q_3 – $Q3$.

Fig.2. Standard corrections to joint positions, speeds and acceleration of joint 2. The curve with no mark – the graphics of the valuation, which characterizes the deviation of the joint 2 from the desired motion – W; the curve with * – the graphics of the standard correction to the joint position of joint 2 – Z2; the curve with Δ – the graphics of the standard correction to the joint speed of joint 2 – Z22; the curve with □ – the graphics of the standard correction to the joint acceleration of joint 2 – DZ22.

Fig.3. Joint position q_i and standard trajectories for joint position q_{ie}, i=1, 2, 3. The curve with no mark – the graphics of q_1 – $Q1$, the curve with * – the graphics of q_2 – $Q2$, the curve with Δ – the graphics of q_3 – $Q3$, the curve with □ – the graphics of q_{1e} – $Q1E$, the curve with < – the graphics of q_{2e} – $Q2E$, the curve with ∇ – the graphics of q_{3e} – $Q3E$.

Fig.4. Errors for joint position. The curve with no mark – the graphics of $(q_1 - q_{1e}) + (q_2 - q_{2e})$ – ERR, the curve with * – the graphics of $(q_3 - q_{3e})$ – ERRT.