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General algorithm for optimal control of moving industrial robots

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Abstract. Control of robots in changing conditions is complex, and its main reason is, firstly, that the robot changes its manipulative behavior concerning the influence of the external environment, and secondly, that it does not have a clear model of motion. If the motion model is not clear, the control model will not be clear, and it will be difficult to determine the control parameters of the robot. Therefore, to overcome these shortcomings, the article presents a model of the motion of robots moving in changing conditions using mathematical methods and an algorithm for optimal control based on it.

1 Introduction

With modern information technologies' development, robotic systems are consistently used in all industry sectors. In particular, using robotic systems in extreme conditions to facilitate heavy human labor has become widespread [1].

It is known that the working body of robots moving in changing conditions, especially in extreme conditions, has a variable structure. Such robots are used in both scientific research and production [2].

Moving robots in changing conditions have to be adaptively controlled, considering technical vision systems, sensitivity, image detection, unknown technological barriers, and dynamic constraints [3].

An analysis of recent literature on industrial robots moving under changing conditions has revealed several shortcomings and gaps in their control methods [4].

1. Based on the given model, the action in the control is simple, but there is difficulty in checking the stability of the controlled system.

2. In the control based on the autoregression model, the reaction forces between the joints are not considered in the robots with hinged joints. This causes a deviation in the trajectory of the movement.

3. In deviation management, the model considers only deviations from the external environment. Deviations in the trajectory caused by the internal deviations of the system, damping, and vibration coefficients are not represented in the model.

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4. As a result of the methods developed for industrial robots under changing conditions not taking into account the kinematic and dynamic properties sufficiently, there was a need to improve optimization and adaptive correction methods to form short and safe motion routes.

The above shortcomings also affect the adaptive control of the robot. As a result, it causes interruptions in movement. Such gaps and shortcomings in the control models of a moving robot in changing conditions require additional research [5].

Self-adjusting systems, in turn, fall into two major classes: searchlight and non-searchlight. In search engines, a change in the parameters of the control device is present due to the search engine extremum under the quality criterion based on the search engine. Expected dynamic property models in non-searching systems are presented in explicit and implicit views [6].

2 Methods

The following methods are used to build adaptive control systems: the Lyapunov method, stochastic approximation method, target recursive inequalities method, a quadratic criterion of absolute stagnation, methods based on an identification approach, etc. [7].

Distribution of energy resources in the optimal motion of industrial robots moving in changing conditions. Traditional methods of controlling robots are based on a complete and accurate dynamic model of the robot's actuator and the known and accurate conditions in which it moves. In almost all cases, the appearance of the structure of the equation of motion of the robot, and even the values of the unknowns involved in the equations, are known and clear. The control algorithm implementing such a system cannot maintain the required control quality when deviations occur under different influences. As a result, accuracy in robot movement decreases, stagnation disappears, and vibration in transition processes increases [8].

Before moving on to the synthesis of optimal control algorithms for robot movement, what will change the robot control system when the control quality is affected by initial and unknown parametric deviations? In answering this question, if the load level of the robot increases, the difference between the given trajectory and the real trajectory increases under the influence of parametric deviations, resulting in an increased probability of the robot hitting a technological barrier or in some cases falling into emergency mode. This necessitates scientific research on the control model of a robot moving in changing conditions [9].

In general, let the equation of motion of an industrial robot working arm moving under variable conditions be given by the following equation [10]:

$$A(q,\xi)\ddot{q}+b(q,\dot{q},\xi)=u \tag{1}$$

here $q-n-$ is dimensional generalized coordinate vector; $\dot{q},\ddot{q}-q$ are 1st and 2nd order derivatives of the vector in time; $u-n$ is control vector on dimensional moments;

ξ is industrial robot working arm and vector of load parameters moving from one point to another (link length, link weight and torque inertia, load weight, and torque inertia, etc.);

$A(q,\xi)$ is industrial robot status detector $(n\times n)$ is dimensional matrix function;

$b(q,\dot{q},\xi)$ is representing the moments of the industrial robot worker hand links; n is dimensional vector function.

Suppose, $q_{\partial ac}(t)$ let the programming trajectory be given. The problem is that the torque control algorithm is designed to provide a shift along a given trajectory with accuracy. In parallel, there are issues such as optimizing energy resources in the management of moments and the correct distribution of energy resources across the links. [11].

Solving such problems under a clear initial condition and at unknown parametric deviations poses a complexity.

Let the initial condition of the deviations equivalent to the exact initial condition be as follows [12]:

$$z(t_0)=\begin{pmatrix} q(t_0)-q_{\partial ac}(t_0) \\ \dot{q}(t_0)-\dot{q}_{\partial ac}(t_0) \end{pmatrix}.$$

Parametric deviation $\left|\xi-\bar{\xi}\right|$ measured in magnitude, here $\bar{\xi}-(3.3)$ equation ξ parameter evaluation.

If $z(t_0)=0$ then $\xi=\bar{\xi}$, the industrial robot control system goes into a deterministic state. Accordingly, the appearance of equation (1) is as follows:

$$u_{\partial ac}(t)=A(q_{\partial ac})\ddot{q}_{\partial ac}+b(q_{\partial ac},\dot{q}_{\partial ac}) \tag{2}$$

For variable conditions, equation (2) is rare in practice.

In the expression of the equation of motion of an industrial robot are taken into account the dynamic coefficients, dampers, dynamic coefficients representing the force of gravity on the links when moving a load from one point to another, and coefficients of virginity determining the strength of the link. The equation considering the given coefficients is given in [1], and the conditions for these coefficients are derived.

Let Equation (1) be given in the Cartesian coordinate system and canonical form as follows:

$$\ddot{x}(t,\xi)+f(x(t,\xi),\dot{x}(t,\xi))\dot{x}(t,\xi)+c(x(t,\xi))=u(t,\xi), \tag{3}$$

here $f(\bullet)-$ has a first-order continuous product in n-dimensional space;
$c(\bullet)-$ continuous in n-dimensional space;

$$|u(\bullet)|\leq M\prec\infty.$$

By reducing the order of equation (3), the following system of equations is formed:

$$\dot{x}=y,\ \dot{y}=-f(x,y)-c(x)+u. \tag{4}$$

Since the system has a variable coefficient and its appearance is complex, it is necessary to determine the availability of the solution.

To do this, let's introduce a function that determines the power supply of an industrial robotic worker's hand [13]:

$$V(x,y)=\frac{y^2}{2}+\int_0^x c(s)ds, \tag{5}$$

expression of (5) on the links is as follows:

$$V_i(x,y)=\frac{y_i^2}{2}+\int_0^x c_i(s)ds, \quad i=1,2,\ldots,n. \tag{6}$$

Reducing energy consumption for an industrial robot is one of the main tasks.

$$\frac{dV}{dt}\le M|y|\le M\left(\frac{y^2}{2}+1\right),$$

$$\frac{dV}{dt}\left[V(t)+1\right]\le M\left[V(t)+1\right].$$

From the last inequality we can write the following:

$$V(t)+1\le\left[V(0)+1\right]e^{Mt} \quad \Rightarrow \quad V(t)\le\left[V(0)+1\right]e^{Mt}. \tag{7}$$

By using equation (5),

$$y^2\le 2[V(0)+1]e^{Mt}$$

(4) In the system of equations, the solution of equation 1 is as follows:

$$x(t)=x_0+\int_0^t y(s)ds\cdot$$

If the last inequality is used,

$$x(t)\le x_0+Ce^{M\tau}, \quad 0\le t\le\tau\,.$$

From inequality (7) $V(t)$ results in the limitation of the function. Further, (4) is a system solution $0\le t<\infty$ interval is determined.

Given the impossibility of setting the speed problem for a moving industrial robot in changing conditions, it remains to solve the problem of saving and properly distributing the above energy resources.

Let's consider that the trajectory of motion in robots operating in variable conditions is given in the form of one plot for each link movement. The conditional extremum problem is used to solve the problem of saving energy consumption and proper distribution.

(5) yields over time.

$$\frac{dV_i}{dt}=y_i\dot{y}_i+c_i(x)\dot{x}_i=-f_i(x_i,y_i)y_i^2+y_iu_i. \tag{8}$$

equation (8) is equal to zero, and $V_i(x, y)$ points that facilitate the function's extremum are identified.

$$\frac{dV_i}{dt} = y_i\dot{y}_i + c_i(x)\dot{x}_i = -f_i(x_i, y_i)y_i^2 + y_i u_i = 0,$$

$$y_i(-f_i(x_i, y_i)y_i + u_i) = 0.$$

$y_i \neq 0$ given that the second multiplication remains $-f_i(x_i, y_i)y_i + u_i = 0$.

And, from that $y_i = \dfrac{u_i}{f_i(x_i, y_i)}$ solution is determined.

Solution (6) is taken to the function, and the necessary solutions for the intermediate links are selected.

Optional $V_0 \geq 0$ Let's look at the curve in the spatial plane for [39]:

$$V(x, y) = \frac{y^2}{2} + G(x) = V_0,$$

here, $G(x) = \int_0^x c(s)ds$.

If $V_0 \geq 0$ If the case is taken into account, it becomes clear that the curve has two branches, and they are as follows:

$$y = \pm\sqrt{2(V_0 - G(x))}.$$

At the beginning of the coordinates will be $V_0 = G(x)$.

The solutions found by the conditional extremum provide the minimum and maximum consumption of energy resources in the discrete links.

Suppose an industrial robot is subject to touch control. In that case, the following quality criterion is given to Equation (3) to optimize the consumption of energy resources in the continuous movement of its links:

$$C(u) = x'(T)Gx(T) + \int_{t_0}^{T}\left[\|x(t)\|_W^2 + \|u(t)\|_U^2\right]dt.$$

Equation (3) is solved based on Pontryagin's maximum principle under the qualitative criterion.

3 Results and Discussion

A generalized algorithm for optimal control of mobile industrial robots. The mathematical and software of optimal control of a moving industrial robot relies on three stages of industrial robot control, strategic, tactical, and executive stages. Mathematics and software deal with tactical and execution-related actions. At these stages, the sequence of actions is as follows: in the tactical stage, the kinematics of the industrial robot is considered, and a generation of models characterizing the spatial displacement of the robot actuator, regardless of force and torque, is introduced, and analyzed [13-18].

Step 1. The selected optimal trajectory is checked to ensure speed and positional accuracy. If the condition is met, then the industrial robot is directly involved in the technological operation or process. Otherwise, the robot's parameters are re-selected from the database, and the above sequence of actions is repeated.

Step 2. The initial data: kinematic and technical characteristics of an industrial robot $(D=\{d_{ij}(x,y), i,j=\overline{1,N}\};$ $h_i(x,y),$ $H_i(x,y),$ $S_i(x,y),$ $G_i(x,y),$ $c_i(x,y), i=\overline{1,N})$ of all links $t=t_0$ position coordinate and speed of movement in $t\in[t_0,T]$ for industrial robot links at the moment $(u_i(t), i=\overline{1,N})$ values of management parameters.

Step 3. Hamilton function is constructed.

$$H=\eta_1 z+\eta_2(-k_i^{''}z-k_i^{'''}e)+\eta_2 u.$$

A joint system will be created.

$$\begin{cases}\dot{\eta}_1=-\dfrac{\partial H}{\partial e}=k_i^{'''}\eta_2,\\ \dot{\eta}_2=-\dfrac{\partial H}{\partial z}=-\eta_1+k_i^{''}\eta_2.\end{cases}$$

Step 4. Under the initial conditions $k_i^{''}, k_i^{'''}$ are determined.

Step 5. $u(t)$ control function and its values are placed in a system of equations

$$\begin{cases}\dot{e}=z,\\ \dot{z}+k_i^{''}z+k_i^{'''}e=1,\end{cases}$$

$$\begin{cases}\dot{e}=z,\\ \dot{z}+k_i^{''}z+k_i^{'''}e=-1.\end{cases}$$

Step 6. Synthesizer of the resulting solutions $\Psi(e,z)$ following system is created using the function:

$$\begin{cases}\dot{e}=z,\\ \dot{z}+k_i^{''}z+k_i^{'''}e=\Psi(e,z).\end{cases}$$

Step 7. $"z>0"$.

If yes, $\begin{cases}\dot{e}=z,\\ \dot{z}+k_i^{''}z+k_i^{'''}e=-1.\end{cases}$

If "no", $\begin{cases} \dot{e} = z, \\ \dot{z} + k_i^{''} z + k_i^{'''} e = 1. \end{cases}$

Step 8. The optimality of the obtained solution is checked.
If "yes", it is acceptable for the technological process.
If "no", the sequence of actions starts all over again.
Step 10. That's it.
In this case, the curve of the switching connection is as follows (Figure 1):

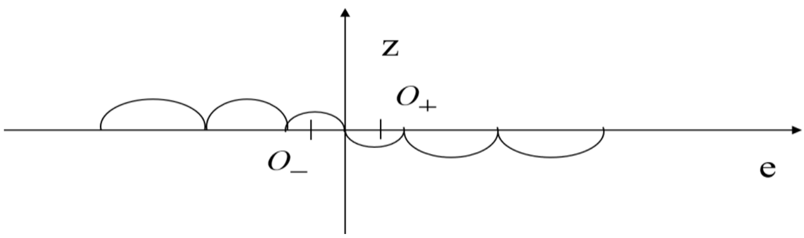

Fig. 1. Curve graph of switching.

Here for the case $|v| \le 1, \quad k_i^{''} - k_i^{'''2} < 0, \; k_i^{''} > 0, \quad k_i^{'''} > 0$.

4 Conclusion

The motion model of an industrial robot was challenged by speed. Based on Pontryagin's maximum principle, the dynamic coefficients of the model were given the problem of velocity under three different conditions. The Hamiltonian function and the system of joint equations were constructed and solved using the Runge-Kutta method. A system of equations was constructed based on the values of the control function at the boundary points, and it was solved by the Runge-Kutta method. To increase positional accuracy, the dimensions of the geometric figure characterizing the robot work area were taken as the boundary condition. The selected optimal trajectory was checked to ensure speed and positional accuracy. If the condition is met, then the industrial robot is directly involved in the technological operation or process. Otherwise, the robot's parameters are re-selected from the database, and the above sequence of actions is repeated.

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