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Nonlinear Adaptive Correction of Continuous Path Speed of the Tool for High Efficiency Robotic Machining

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Abstract

The proposed new structure of the control system for a robot that performs high-performance machining, for example milling, deburring, grinding and polishing parts. This structure is based on the ideas of mechatronics and contains nonlinear adjustment-regulating feedback. The algorithm of generation of control actions, providing adaptive correction of continuous path speed of tool movement and the absence of overdriving the servo drives. The corrected value of the path velocity is calculated based on the change variables, taking into account the currents in the windings of all of the motors of the robot and of the tool. Computer simulation results have confirmed the conclusion that when using the proposed algorithms logical signal processing, filters and relay control law ensuring consistent operation of the drives, the required accuracy of the movements of tool and high performance.

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Keywords: Robot; adaptive control; mechatronic; drives

1. Introduction

It is well known that, in the world of manufacturing, machine-tools have held the dominant position as process equipment for decades [1]. But now there are enough arguments [1] for a number of specialists to concentrate their research on integrating industrial robotic systems in machining processes which offer a cost-effective and flexible

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solution [2]. Flexible automation based on Robotics is considered as an ideal solution for its programmability, adaptivity, flexibility and relatively low cost [3], especially for the fact that processing robots are widely applied for machining parts from plastics and light alloys. First of all, milling, fettling, removing burrs from cast billets, grinding and polishing should be allocated among the manufacturing operations performed by robots. Cutting force affects on the tools during machining parts and it depends on many factors such as cutting depth and continuous path speed [4, 5, 6]. The more these values can be, the more cutting force will be. It loads on the tool drive of robot and leads to moments of reaction forces acting on the servo drives of the robot.

Increasing of robotic machining efficiency can be achieved by raising the continuous path speed. The robot moves the tool in a given program path with this speed. However, we have to face a number of challenges. Changes of the cutting depth are due to dimensional deviations parts from nominal dimensions. The cutting force variations can be significant and often unpredictable for robot control system. It is essential that drive of tool and servo drives of robots are able to develop limited moments of forces. To protect overheating the servo motors, currents of phase windings is automatically limited to an acceptable level. For example, it can be achieved if the input signal currents of control loops are limited [7]. Current control loops include of PI controllers. Therefore, the cutting force can be increased and reactions to drives of the tool and of the robot will exceed the power capacity of some of them. It causes a braking movement, while the other drives are still able to maintain the desired speed. The danger of this phenomenon is that the coordination of movements is disturbed in different degrees of mobility of the robot. It leads to distortion the size and shape distortion of the part, the appearance of defective parts and functional failure of process equipments. If the longitudinal motion of the tool continues, the reduction in the frequency of the tool drive will lead to further increasing of the cutting force and it can cause of tool damaging.

We need to solve the problem of automatic control of continuous path speed of the tool. It helps to implement a high-performance machining process using robots and prevent overloading drives and the disturbance coordination of movements. Feature this challenge is that the robot has to ensure movement of the tool with the continuous path speed. This speed should be the maximum possible in the current situation, and none of the drives could be overloaded. It means that the value of the continuous path speed should adjust automatically so that it would the greatest, but the windings currents in the motor drives do not exceed the permitted levels. In machine control a similar problem is successfully solved as a result of the control of the cutting force [8], including the use of special sensors [9]. Taking into account only values of the cutting force, continuous path speed is sometimes regulated in robotic machining. But it is not enough, because drives are loaded differently in different configurations of the manipulator. To realize adaptive control we need to consider the windings currents for all the drives of the robot system. It is necessary to note that these researches were financed by Ministry of Science of Russia Federation within the state task in the sphere of scientific activity.

2. The structure of the processing robots system of drive and adaptive correction algorithm of continuous path speed of tool

To solve this problem, we propose to introduce nonlinear corrective links to the system. They carry automatic adaptive equalization of continuous path speed. Equalization depends of controlled motor currents and prevents motor overloading. This system includes a plurality of components of different physical nature and it involves the active use of control computers. Consequently, this kind of systems corresponds to the ideas of mechatronics and computer systems control movement of complex dynamic systems [7, 10]. It gives us opportunity to achieve consistent coordinated movements of all parts of the manipulator and to improve the performance of machining parts in fulfilling the requirements for the accuracy of the tool relative to the programmed trajectory.

The main idea of the correction is to transfer system to high-frequency switching mode if at least one of the signals that are functionally related to motor currents exceeds the permissible level of restriction. In this mode each time to avoid overloading the drives it is formed maximum possible value for the average component of continuous path speed automatically and with high accuracy. In this case, from a practical point of view, the variable component of the continuous path speed tool movement has small the amplitude of the oscillations. And it doesn't have negative influence to the quality of the machining and operating capacity of the manipulator. Due to this thesis all servo drives movements remain consistent. It contributes to get the required tool position accuracy. Continuous path speed meets the requirements of high efficiency robotic machining.

Nonlinear corrective links depends on vector currents I in motor of robot drives and depends on current I_U in motor of tool drive (fig.1). Link is introduced to the structure of the control system of the robot tool movement process. These currents react to moments of reaction forces M_R due to moment applied to the arm of the manipulator M .

By-turn, these moments have components caused by the vector F components of the cutting force and caused moments of forces acting on the tool. Note that the vector of moment of forces M is determined by the matrix equation

$$M = J^T(q)F \tag{1}$$

where $J^T(q)$ – Jacobi's transposed matrix. It depends on vector q of generalized coordinates of manipulator. It characterizes the properties of the manipulator with fixed tool on it in the current configuration. Universal processing robots usually have 6 degrees of mobility and are always used for machining process. Vectors F and q for this type of robots have the dimension (6x1).

The signal processing unit of sensor current generates correction signal influences the calculation of the current value of V_K the required continuous path speed. Formation of the correction signal is based on a logic variable, and the use of additional corrective filters. Boolean variables characterize the complex status of all motors of the whole system. Correction filters affect the frequency and amplitude of the fluctuations of the tool position in the mode of adaptation continuous path speed and limit of motor currents. Calculation is done taking into account the maximum possible value V_0 of continuous path speed.

The essential feature of this control system of robot tool motion is that the change of desired position values of tool coordinates is described by polynomial models. They are presented as a function of the tool path along a desired path. It is necessary for the effective regulation of the contour speed and to provide high accuracy tool motion to the desired trajectory. In this case, the control response passes vector of signals β to complex of robot servo drives, these signals carry information about the desired positions of the manipulator arms. These signals generate angles of rotation vector α of drive output link and cause the required values of the components of the vector of generalized coordinates q of the robot.

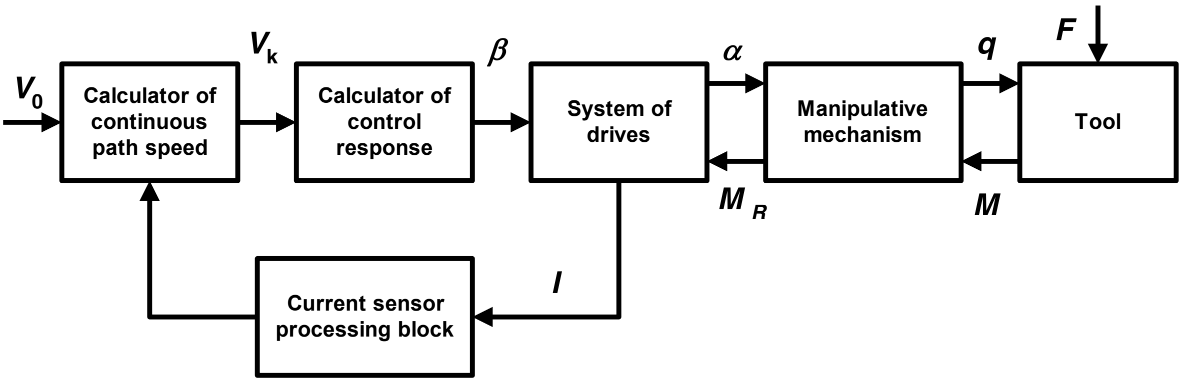

Fig. 1. Structural scheme the control system of processing robots tool movement.

Arrays of the tool coordinate values are the basis of the robot motion program. In the future, they can be specified in the robot learning process. They are given for control points of the desired path of tool movement during the technological operations planning. It based on the machining parts drawing. In the future, they may be specified in robot training. The desired generalized coordinates of the manipulator are calculated and saved in the robot control unit on the basis of the tool coordinate.

For machining robots there should be some models of control response that meet two requirements. Firstly, they must be resistant to noise introduced by the operator when he is programming training method. Secondly, they must allow differentially take into account the information about the geometry of the desired motion and process information about law of the desired continuous path speed in different parts of the motion path. Therefore, to form a model of defining effects on the robot servo drives, for example, it should be used cubic polynomials as a function of the path traversed by the tool to the desired trajectory. It lets interactively control robot motion of all the degrees of mobility and tool with just one value - the continuous path speed. And it is fundamentally important to provide accurate motion of the tool as a result of avoidance drive overloading due to adaptive update of continuous path speed.

In this case, problem of control robot motion is solved in two stages. When we program, information about the control points of the trajectory is converted to values of the coefficients of the polynomials. They approximate the generalized coordinates of the manipulator dependence on the path between the control points. These coefficients are saved. To implement of the motion saved values of the coefficients are extracted from the device control robot memory. So in real-time control response on the drives complex is calculated. At each step of control desired continuous path speed value is calculated taking into account the state of control process. The desired value of the path traversed by the tool along the trajectory is calculated by integration of the speed.

Model of changes generalized coordinates q_i of the manipulator ($i = 1,..., N$) is taken as a polynomial form

$$q_i = \frac{a_{ik}}{6} l_k^3 + \frac{b_{ik}}{2} l_k^2 + c_{ik} l_k + d_{ik}, \tag{2}$$

where l_k – path along the segment k considered part of the trajectory, measured from the reference point *k* to point *(k + 1)*; $a_{ik}, b_{ik}, c_{ik}, d_{ik}$ – approximation parameters characterizing the motion between the reference points k and *(k + 1)*. The maximum value l_k is L_k, therefore, in the k reference point must satisfy the boundary conditions:

$$q_i = q_{ik}^o, \; \frac{dq_i}{dl_k} = \dot{q}_{ik}^o,$$

where q_{ik}^o – reference value in the point k; $\dot{q}_{ik}^o$ – required value of derivative q_i with respect to l_k in the point *k*. For a reference point *(k + 1)* boundary conditions are:

$$q_i = q_{i,k+1}^o, \qquad \frac{dq_i}{dl_k} = \dot{q}_{i,k+1}^o,$$

where $q_{i,k}^o$ and $\dot{q}_{i,k+1}^o$ – the coordinate value and its derivative q_i with respect to path in *(k + 1)* point.

As a result, we have the following approximation parameters which depend on quantities characterizing the reference points:

$$\begin{cases} d_{ik} = q_{ik}^o, \\ c_{ik} = \dot{q}_{ik}^o, \\ b_{ik} = \dfrac{2}{L^2}\left[3(q_{i,k+1}^o - q_{ik}^o) - L(2\dot{q}_{ik}^o + \dot{q}_{i,k+1}^o)\right], \\ a_{ik} = \dfrac{6}{L^3}\left[L(\dot{q}_{ik}^o + \dot{q}_{i,k+1}^o) - 2(\dot{q}_{i,k+1}^o - \dot{q}_{ik}^o)\right]. \end{cases} \tag{3}$$

We propose to determine the values of $\dot{q}_{i,k}^o$ and $\dot{q}_{i,k+1}^o$ by the second-order polynomials approximation of the two short segments of the trajectory, at the same time involving *k* and *(k + 1)* reference points. Obviously than shorter the value L is then the more accurate approximation is. For first section with reference points, which have coordinates $q^o_{i,k-1}$, $q^o_{i,k}$, $q^o_{i,k+1}$, we obtain $\dot{q}^o_{i,k} = (q^o_{i,k+1} - q^o_{i,k-1})(2L)^{-1}$ and for the second section with the coordinates $q^o_{i,k}$, $q^o_{i,k+1}$, $q^o_{i,k+2}$, we get $\dot{q}^o_{i,k+1} = (q^o_{i,k+2} - q^o_{i,k})(2L)^{-1}$.

Taking into account these ratios expression (3) is converted to the form

$$\begin{cases} d_{ik} = q^o_{ik}, \\ c_{ik} = \Delta_{1ik}(2L)^{-1}, \\ b_{ik} = (6\Delta_{0ik} - 2\Delta_{1ik} - \Delta_{2ik})L^{-2}, \\ a_{ik} = (-12\Delta_{0ik} + 3\Delta_{1ik} - 3\Delta_{2ik})L^{-3}, \end{cases} \tag{4}$$

where $\Delta_{0ik} = q^o_{i,k+1} - q^o_{ik}$, $\Delta_{1ik} = q^o_{i,k+1} - q^o_{i,k-1}$, $\Delta_{2ik} = q^o_{i,k+2} - q^o_{ik}$.

Argument l_k of polynomial model is calculated by integrating over time the required continuous path speed $V_K(t)$. So the values q_{1k}, q_{2k}, ... q_{1N}, ... are identified, which are used to define the components of the vector β. This vector set the impact to robot drivers. As soon as you reach level $l_k = L$, is held reset to zero of l_k and replacing values of the parameters d_{ik}, c_{ik}, b_{ik}, a_{ik} to the new values $d_{i,k+1}$, $c_{i,k+1}$, $b_{i,k+1}$, $a_{i,k+1}$, for the next segment of the trajectory of motion. Thus, the tool is able to continuously move with high accuracy for a given program trajectory with required and time-varying continuous path speed.

The proposed non-linear correction forms the required continuous path speed V_K of motion by trajectory of robot tool. Correction depends on the set of its maximum value V and the current measured values of motor currents of robot drives I_1, I_2,..., I_N and current I_{N+1} of tool drive. Here N is degrees of mobility robot, typically equal to six. Exceeding the permissible levels of motor currents $I_{1.tol}$, $I_{2.tol}$,..., $I_{N+1.tol}$ is performed by means of logical variables R_i, which are calculated based on the equation

$$R_i = \begin{cases} true, & if\ |I_{i.F}| > I_{i.tol}, \\ false, & if\ |I_{i.F}| \le I_{i.tol}, \end{cases}$$

where $i = 1,..., N+1$ and values $I_{1.F}$, $I_{2.F}$,..., $I_{N+1.F}$ are generated using the digital correction filter continuous analogue [7] which has a transfer function $W_{Fi}(s)$:

$$I_{i.F}(s) = W_{Fi}(s) I_i(s), \quad i = 1,..., N+1,$$

what is more s is Laplace variable.

Continuous path speed V_K is determined based on the value of the switching signal R, which depends, in turn, from the logical variable R_Π characterizing the state of the system drive. Calculation of the signal R is produced by the following algorithm

$$R_\Pi = R_1 \vee R_2 \vee ... \vee R_{N+1},$$

$$R = \begin{cases} 1 & when \quad R_{\Pi} = true, \\ 0 & when \quad R_{\Pi} = false. \end{cases}$$

We first calculate the intermediate value of continuous path speed V_{Π} varies according to the step function

$$V_{\Pi} = \begin{cases} V_0 & when \quad R = 0, \\ 0 & when \quad R = 1, \end{cases}$$

where V_0 is maximum allowed value of the continuous path speed. Magnitude V_{Π} is smoothed using a digital filter. This is done based on the next equation

$$V_K(s) = W_{F0}(s)V_{\Pi}(s),$$

where $W_{F0}(s)$ is the transfer function of the continuous digital correction filter in the forming network of continuous path speed.

It is important to note that if all drives work without overload ($R = 0$), then the algorithm described above does not manifest itself, and the tool moves at the maximum allowed speed V_0. In situations where the signal R becomes equal to 1, i.e. it is necessary to adjust the continuous path speed, automatic formation the required continuous path speed occurs in the oscillation mode. Their average component is useful, but a variable component should be made as small as possible. Research has shown that fluctuations in the tool position intensively suppressed integrator, which transforming the continuous path speed to required path along the trajectory, correction filters and closed loop of drive, containing relatively low-frequency mechanical subsystem. Therefore, the amplitude of the first harmonic fluctuations of the tool position is inversely proportional to the frequency of the oscillations exponentiation 4. Thus, it is advisable to try to increase this frequency. At the same time, however, it is desirable to limit the amplitude of the oscillations of the currents in the motor windings. This can be achieved by using corrective filters added to the control loop of continuous path speed. The structure and parameter values of corrective filters are chosen so as to increase the frequency and reduce fluctuation amplitude of the tool position.

The transfer function of the continuous analog filter which is in a straight chain of the system, taken as

$$W_{F0}(s) = \frac{T_{K1}s + 1}{T_{K2}s + 1},$$

where T_{K1}, T_{K2} are filter time constants. This filter has an integral differential character. Its lag element can effectively reduce the amplitude of oscillations of the tool position, but worsens the dynamics of change continuous path speed. Forcing component serves to increase the frequency of oscillations by compensating for the influence of phase shifts introduced by the closed loop drive. Therefore it is recommended to take $T_{K2} = 1/\omega_C$, where ω_C is cutoff frequency of the open loop servo drive. The transfer functions of the filters included in the motors-currents feedback system are identical and are of the form

$$W_{F1}(s) = W_{F2}(s) = ... = W_{F.N+1}(s) = \frac{T_{K3}s + 1}{T_{K4}s + 1},$$

where T_{K3}, T_{K4} are time constants. Forcing component of the filter is designed to introduce phase advance compensating lag due to the dynamic properties of subsystems to control the speed drive. Furthermore, this link contributes to the reduction of the currents amplitude oscillation. It allows to increase the frequency oscillation and bring it closer to the cutoff frequency of the open loop subsystem of the currents control. A further increase in oscillation frequency is problematic and impractical, because would increase the sampling frequency in the loop current and PWM frequency of the power converter. Aperiodic link limits the frequency band in which the forcing.

3. The results of computer simulation

Modeling and simulation becomes a powerful tool in the product design. Today's trends in mechatronics lead to integration of electronics and computer control with mechanical subsystems [11]. To solve our problem, we also used a mathematical modeling and simulation. Fig. 2 and 3 show calculation graphs of current in the motor winding of robot drive and required continuous path speed with nonlinear adaptive correction. Is seen that due to the action of correction the current limitation engine occurs at a level close to the setpoint which equal -18A caused by adaptive control of the forces acting on the tool.

Fig. 3 shows that the fluctuations of required continuous path speed V_K occur in areas where works nonlinear correction, preventing overload of the drive.

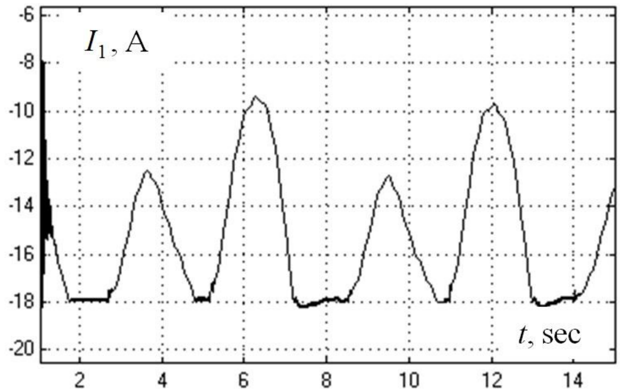

Fig. 2. Changes in the motor winding current of the robot drive.

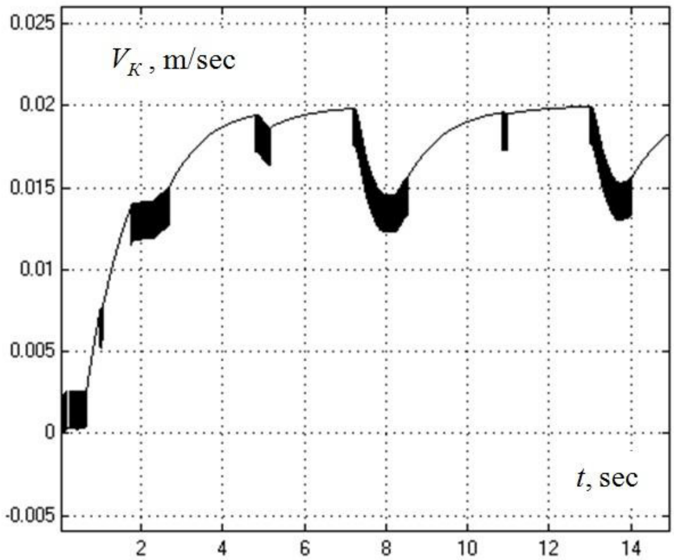

Fig. 3. The graph of the required continuous path speed changes.

By integrating of the calculated speed and filtering properties of drive the required continuous path speed almost equal to average component of these oscillations. In areas where the correction of speed is not required and the feedback does not occur, the required continuous path speed varies according to the dynamics of filter and tends to a maximum value of 20 mm / s.

Process of changing of the deviation from the required trajectory of the tool is shown in fig. 4. Research results show that by eliminating overcurrent the servo drives of manipulator work in unison. Impaired locomotor coordination does not arise, and the most loaded drive uses all its power capabilities.

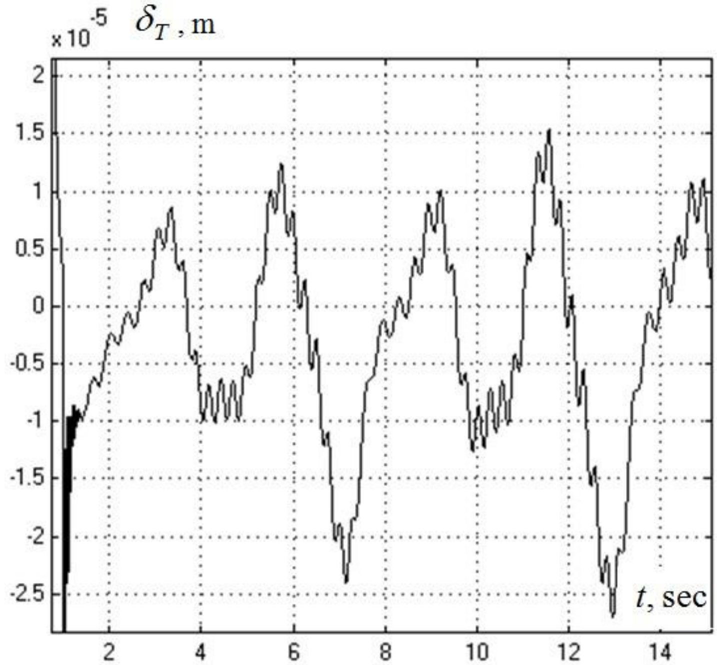

Fig. 4. Process of changing of the deviation from the required trajectory of the tool.

Therefore, a high accuracy of movement of the tool relative to the required path is achieved, and it is possible to perform the robotic machining process at the maximum allowable continuous path speed. Moreover, these continuous paths speed. Moreover, this circuit speed automatically adapts depending on the current profile of the part.

Conclusion

One of the problems of creating high-performance robotic machining is the danger of distorting the size and shape of parts, the appearance of defective goods and functional failures of process equipments. This problem is caused by the possibility of the disturbance coordination of movements in different degree of motion of the robot as a result of overload drives of the robot performing high-performance machining.

To solve this problem we consider that the torque acting on the drives depends on the continuous path speed of tool. The larger it is, the greater these torques and currents are which flow in the motor windings. At the same time, in absence of overheating and overloading of the drives these currents should not exceed the allowable levels. Therefore, we have proposed a system of adaptive correction of continuous path speed based on logical analysis and transformation of the sensor signals of the currents in the windings of motors, which provide information about the loads acting on the drives.

Proposed structure of the robot control system should be used to implement high-performance machining parts with use robotic technology. A feature of robot control system is corrective nonlinear relations, which was described. These relations allow carrying out the adaptive automatic regulator of tool continuous path speed depending on the currents of the motors. It enables to achieve the maximum possible path speed of the tool and overload of drive. It also makes to achieve concerted, coordinated movements of all parts of the manipulator and increase productivity machining parts. At the same time, the requirements for the tool location accuracy relative to the program trajectory are achieved.

We propose to form a program of robot motion based on polynomial models. These models describe the dependence of manipulator generalized coordinates from tool path along the required path. And this path is calculated by integrating by the time adaptive continuous path speed. It is necessary to maintenance of high accuracy of tool movement and to avoid drive overloading.

Nonlinear adaptive correction algorithm generates the required continuous path of robot tool. It depends on the set maximum speed and the current values of all the currents of the motors of robot drives and the current of tool drive. The structure and parameters of corrective filters are chosen so as to increase the frequency and reduce the oscillation amplitude of the tool position in a mode where continuous path speed correction is required. The development and results of a computer simulation of nonlinear adaptive continuous path speed correction algorithm is completed. It shows high efficiency and appropriateness for construction processing robots with high performance.

Further development of approach to design high performance robotic machining can be associated with its implementation in a computer system of robot control with a series of experimental researches. In particular, these researches may be aimed at clarifying the adaptive control algorithms taking into account the features of the surface shape of the parts and the values of the signal sampling period in time.

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