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An Increase in Accuracy of Robotic Milling

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Abstract. The results of the theoretical research and the computer simulation, aimed at increase in accuracy of robotic milling, are presented in the article. An analysis of the mathematical models of the system «technological robot – milling process» is conducted. The prospects of the usage of precision geared dual motor servo drives and trajectory-impedance control systems are underlined. A computer research of the tool movement accuracy during the robotic cylindrical up-milling process, depending on path velocity of the milling cutter and rated value of the cutting depth, has been carried out. Two types of manipulators have been considered: a manipulator with traditional geared servo drives with one motor and a manipulator with the suggested precision dual motor drives. In order to measure accuracy of movements during the computer simulation process a deviation of the tool, normal to the desired trajectory of its movement, has been defined. The results testify the facts that dual motor servo drives allow us to significantly increase dynamic stiffness of technological robots and they promote increasing accuracy and performance of robotic milling.

Introduction

At present time application of technological robots for milling is of great interest [1, 2]. Robotic milling has its advantages if parts have complex shapes of surfaces and large sizes. In this case, a crucial role is played by the ability of technological robot to implement complex spatial movements of its tool in large workspace, while the quantity of metal in robot is less than in machine tool. However, the robots, which are widespread in industry and which have an open kinematic chain, and also the drives with closed position control loops of their motor shafts have relatively low stiffness. Therefore, cutting forces cause large deviations of the actual position of the tool from its desired position, set by a control program. This fact often leads to inadmissible decrease in accuracy of the machined part. The reduction of feed velocity promotes rise in accuracy, however it results in drop of performance, which is not always acceptable.

Manipulators with closed kinematic chain have significantly larger accuracy and they are also applied in milling tasks [3, 4]. However, they have limited workspace.

As a rule, the usage of gears in robot drives improves weight and size, energy and value indicators of robots. However, the mechanical transmission in this case is beyond the closed position control loop. Elasticity and backlash of mechanical transmissions have the greatest influence on accuracy of the tool movements of the manipulator with open kinematic chain [5, 6]. The suggestions of improving properties of servo drives with elastic gears on the whole concern introduction of various corrective and compensative links which are not always efficient in practice due to the influence of nonlinearity of the type "dead zone" which describes the backlash.

One of the approaches to compensating the backlash influence is to adjust the control impacts, generated by CNC [7, 8]. In this case, accuracy cannot be raised significantly too, especially at frequent variations of directions of the control object movement. Another approach suggests implementing drives with two coordinately controlled motors [9, 10], closed by position control loops of the manipulator links. Implementation of impedance control [11, 12] allows us to increase dynamic stiffness of the drives and to damp oscillations in their mechanical subsystems. It is important to provide a research, which confirms the fact that this approach allows us to obtain high accuracy and stiffness of the robot with improved weight, size, energy and value indicators.

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Accuracy and Performance Requirements to Robotic Milling

It is feasible to aspire to achievement of the highest productivity of robotic milling, while the requirements to accuracy of the machined part are met. Accuracy depends on several factors. The most significant among them are the forces, applied to the manipulator tool during the milling process. They lead to a deviation δ_T of the instrument, normal to the desired trajectory of its movement, and they change size and shape of the workpiece surface. The greater the removal rate of workpiece material is, the higher the performance of the robotic milling is, which can be calculated by the formula

$$Q = BhS, \tag{1}$$

where, h – cutting depth; B – width of the removed layer; S – velocity of longitudinal feed of the tool (path velocity). The cutting force F_C is often calculated by empirical formulas. For instance, in case of milling with end mill the following relation can be used

$$F_C = k_F B^{n1} h^{n2} S^{n3}, \tag{2}$$

where, k_F – proportional coefficient, which takes into account material properties of the machined workpiece and the tool, diameter D, number of teeth z and rotation frequency n; $n1, n5, n3$ – exponent indexes. So, accuracy and performance of robotic milling are interrelated, as we see in (1) and (2), and increase in performance is possible until the accuracy requirement to milling is met

$$|\delta_T| \le \delta_{T.ADM}, \tag{3}$$

where, $\delta_{T.ADM}$ – admissible deviation of the tool. We note that the deviation δ_T decreases when the cutting force is reduced. This fact can be achieved by a reduction of path velocity S. However, at the same time performance decreases too. We see the most attractive way here in raising accuracy and performance of robotic milling by increasing stiffness of the dynamic system «technological robot – milling process».

Increase in Accuracy of Technological Robots, Built on Precision Dual Motor Drives, on the Basis of Impedance Control

In order to increase accuracy and performance of robotic milling we propose using robots, built on precision drives, closed by position control loops of the manipulator links. The research results [10, 12] allow us to recommend dual motor servo drives with two position control loops and two position sensors in this case. In such servo drives one of the motors is a part of the primary servo system, closed by a position control loop of the manipulator link. The other motor is a part of a torque drive – a loader which is an active controlled backlash eliminating devise. The main feature of the suggested type of servo drives is in fact that there is an integral controller in the outer position control loop of the manipulator link. It controls the inner subsystem which represents a drive, closed by a position control loop of its motor shaft. The loader allows us to eliminate self-oscillations in the primary servo system. Due to the primary feedback position control loop of the manipulator link the robots with such drives obtain considerably higher dynamic stiffness than the robots, built on servo drives with traditional structure of the control means.

The usage of the precision drives described above in combination with impedance computer control gives a possibility to realize the highest performance when the accuracy requirements to actuated movements are met. It is also important to note that the positive effect is achieved while the structural elasticity of the gears is constant. The impedance control is implemented as a result of introduction of corrective velocity control loops of the manipulator links which change the impedance of the system «technological robot – milling process» in a desired way and which damp resonant oscillations of the manipulator links. It allows us to obtain the highest possible stiffness in a direction, normal to the desired trajectory of the movement, and also the highest controlled stiffness for the movements along the trajectory with a sufficient damping level.

Increase in accuracy of robotic milling can be revealed as a result of analysis of the linearized mathematical model of the system «technological robot – milling process» (Fig. 1). There are 3 impacts applied to the drive system: a vector of reference impact Δq_{REF}, a vector of moments M_{FH}, applied to the manipulator link and caused by nominal cutting force, a vector of deviations Δh_0 of the height of the workpiece surface which is defined along the normal direction to the machined surface. The equation, which links an error vector δ of the servo drive to the above-mentioned impact vectors, is the following:

$$\delta = C_{Eq}^{-1}(q,p)[Q(q,p)\Delta q_{REF} - M_{FH} - G(q)\Delta h_0], \qquad (4)$$

where, $C_{Eq}(q,p)$ – transfer matrix of the equivalent dynamic stiffness of virtual spatial spring, which characterizes elastic and damping properties of the system «technological robot – milling process»; $Q(q,p)$ – stiffness matrix, which characterizes an influence of the vector Δq_{REF} on the vector of the resulting moments of forces acting on the manipulator links; $G(q)$ – column matrix of coefficients of influence of the deviation Δh_0 on the moments M_F acting on the manipulator links; p – differential operator.

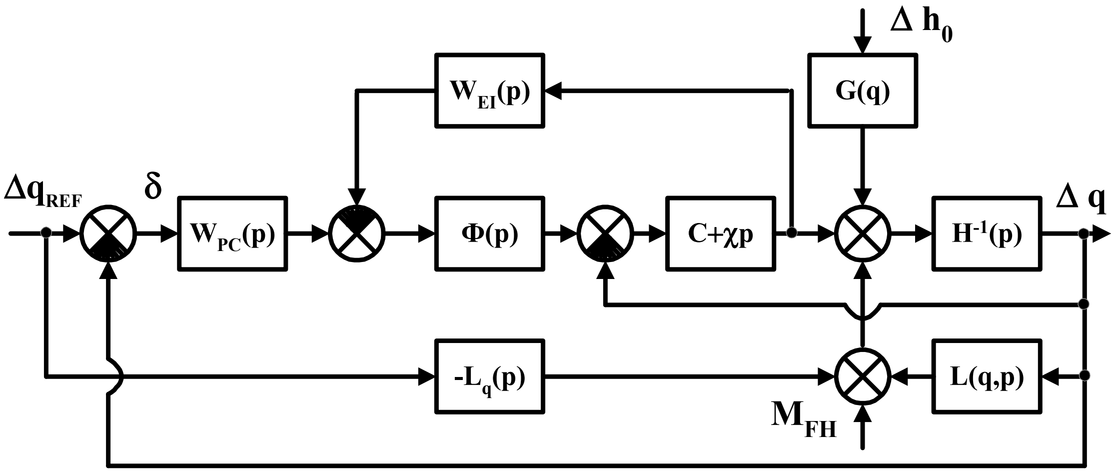

Fig. 1 The system «technological robot – milling process».

The matrix $C_{Eq}(q,p)$ is defined in the following way:

$$C_{Eq}(q,p)=\{H(p)-L(q,p)+[I+(C+\chi p)\Phi(p)W_{EI}(p)]^{-1}(C+\chi p)[I+W_{PC}(p)\Phi(p)]\}, \qquad (5)$$

where, I – unity matrix; $\Phi(p)$ – diagonal transfer matrix of the internal subsystem of the servo drives closed by position control loops of their actuating motor shafts; C, χ – stiffness matrix and internal viscous friction matrix of the mechanical transmission; $W_{EI}(p)$ – diagonal transfer matrix of natural feedback loops conditioned by reactions of the elastic mechanical transmissions applied to the motor shafts; $W_{PC}(p)$ – diagonal transfer matrix of outer position controllers of the system of servo drives; $H(p)$ – operator matrix of the linearized dynamic model of the manipulation mechanism which has the form

$$H(p)=\left[A_M(q_0)p^2+B_M(q_0,\dot{q}_0)p+C_M(q_0,\dot{q}_0,\ddot{q}_0)\right], \qquad (6)$$

where, A_M, B_M, C_M – matrices of coefficients which respectively depend on values of components of vectors $q_0, \dot{q}_0, \ddot{q}_0$ of generalized coordinates, velocities and accelerations of manipulator at the supporting point of trajectory. $L(q,p)$ – equivalent dynamic stiffness of the spatial "technological spring" of the system «technological robot – milling process» which depends on the Jacobean matrix $J_R(q)$ and the vector q of the generalized coordinates of the manipulator. The elements, caused by the spatial "technological spring", have dynamic nature and occur only during the tool movement in contact with the machined object.

The matrix $Q(q,p)$ can be calculated by an equation

$$Q(q,p)=\{\, H(p)-L(q,p)+L_q(q)+[E+(C+\chi p)\Phi(p)W_{El}(p)]^{-1}(C+\chi p)\,\}, \qquad (7)$$

where, $L_q(q)$ – matrix of coefficients of the influence of reference impacts Δq_{REF} variations on the moments M_F. This matrix depends on the Jacobean matrix $J_R(q)$. The column matrix in (4) – (7) has dimensions (6×1), the rest matrices have dimensions (6×6).

The form of the matrix of the controllers $W_{PC}(p)$ significantly affects the matrix of the system dynamic stiffness $C_{Eq}(q,p)$. In a steady-state regime the relations $W_{El}(0)=0$, $L(q,0)=L_q(q)$, $H(0)=C_M$, $\Phi(0)=I$, $Q(q,0)=C+C_M$ take place. Therefore, on the basis of (5) we have

$$C_{Eq}(q,0)=C[E+W_{PC}(0)]+C_M-L_q(q). \qquad (8)$$

The form of formula (8) testifies the fact that increase in stiffness of the system can be achieved as a result of selection of the matrix $W_{PC}(p)$ of the form

$$W_{PC}(p)=N_{PC}^{-1}(p) \qquad (9)$$

with components $N_{PCii}(p)=T_{ii}p$, where T_{ii} – time constant of integral position controller of the *i*-th manipulator link; i = 1,..., N while N – number of degrees of freedom (DOF) of the manipulator. We note that at $p=j\omega\to 0$ the components of the matrix $|W_{PC}(j\omega)|$ tend to infinity. Therefore, $C_{Eq}^{-1}(q,p)=0$. So, in a steady-state regime of movement the vector of errors δ strives to zero. This statement also testifies the fact that $\delta_T\to 0$. At variable power impacts on the tool the smaller the error is, the smaller the value of the time constant T_{ii} is. Rise in potential accuracy can be used in order to increase the permissible feed velocity of the tool, which leads to increase in the machining performance.

The Results of Computing Experiments

A computer research of the tool movement accuracy during the robotic milling process, depending on path velocity of the milling cutter and the rated value of the cutting depth, has been carried out in order to clarify the possibilities of the two previously discussed approaches to creating robotic milling systems. The first approach is based on the usage of traditional servo drives with one motor, closed by position control loops of their motor shafts. The second approach contains precision dual motor drives, closed by position control loops of the manipulator links, and the controlled torque loaders. A cylindrical up-milling process of the lateral surface of the workpiece, which is a rectangular plate of aluminum alloy D16T (AlCu4Mg1), has been considered. The milling cutter has 5 teeth and diameter 6 mm. Length of the working part of the cutter is 12mm, angle of the helical chip grooves is 20°, frequency of the tool rotation– 10000 rpm. The robot moves the cutter along a linear path. Its length is 200 mm. Width of the removed layer is 12 mm.

The manipulator of the robot, considered in the actual research, has four DOF (Fig. 2). Three of them are provided by a planar mechanism of the angular type with 3 DOF. One more degree of freedom is implemented by the rotation of the column link around the vertical axis. The masses of the «shoulder» and the «elbow» links equal to 38 and 35 kg respectively. Their lengths are the same and equal to 0.68 m. There is an assumption that the links of manipulator mechanism are absolutely rigid. The milling process occurs when the configuration of the manipulator, characterized by the angle between the «shoulder» and «elbow» links, is approximately equal to 45°.

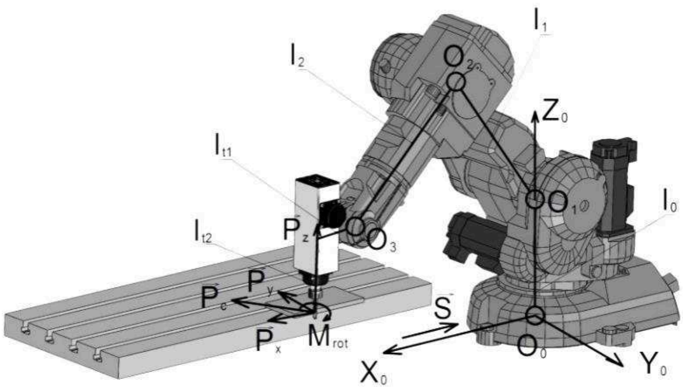

Fig. 2 Schema of the simulated robot.

Motors model 44.SM.203-34B5 by KEB and gears model HFUC-50-2A-GR by Harmonic Drive have been selected as a basis for creating mathematical models of drives of the manipulators column and «shoulder» links. The gear ratio of such drive is 120. Rated power is 2,67 kW, rated torque – 8.5 Nm, rated rotation frequency – 3000 rpm. Stiffness coefficient of gear is 400000 Nm/rad, backlash equals about 1 arc. min. The similar motors and gears are used for the primary drive and the loader. Motors model 42.SM.203-34B5 by KEB and gears model HFUC-40-2A-GR by Harmonic Drive have been selected for the «elbow» link drive. The gear ratio of such drive is 120. Rated power is 1,44kW, rated torque – 4.6 Nm, rated rotation frequency – 3000 rpm. Stiffness coefficient of the gear is 130000 Nm/rad, backlash equals about 1 arc. min. The PWM frequency of the frequency converter, used for vector control of the drives, is 16 kHz. A resolver with resolution of 2047 discrete per revolution is used in closed position control loop of the motor shaft. The closed position control loop of the manipulator link is realized by means of the encoder with resolution 250000 discrete per revolution.

During the simulation process the tool was being moved along X axis towards the robot base. A deviation of the tool, normal to the desired trajectory of its movement, which was implemented along the Y axis, was being defined in order to measure accuracy of movements during the computer simulation. The average value of the absolute value of the tool deviation from the trajectory d, measured along the Y axis, and the maximal value of the deviation $\Delta d_{\max}$ from d along Y axis, were considered as accuracy indicators of the movements. The values d and $\Delta d_{\max}$ were defined by the following formulas:

$$d = \frac{1}{T}\int_0^T |\delta_T(t)| dt, \tag{10}$$

$$\Delta d_{\max} = \max|(|\delta_T(t)| - d)|, \tag{11}$$

where, T – total time of the tool movement during milling of the workpiece.

The dependencies of the indicator d on the path velocity S at different rated values of the cutting depth h_0, obtained for manipulators with traditional drives with one motor, are presented in Fig. 3. They show large deviations of the milling cutter from the desired trajectory. The values of this indicator lie in the range between 156 and 425 μm while the velocity varies from 2 to 7 mm/s and the rated cutting depth varies from 0.5 to 1.5 mm. If we raise S and h_0, the deviations rise too. At the same conditions, the values of the indicator Δd_{max} lie in the range from 23 to 100 μm. In many practical applications such deviations are often inadmissible. The reasons of such deviations are in a cutting force component, acting along the Y axis and which values lie in the range of 16 … 151 N, and also in insufficient stiffness of the manipulator which lies in the range from 100000 to 356000 N/m depending on the values of S and h_0.

Due to the closed position control loops of the manipulator links, stiffness of the manipulator with the suggested dual motor drives increases significantly. As a result of the computing experiments, the obtained values of the manipulator stiffness along Y axis lie between $6{,}8 \cdot 10^8$ to $2{,}16 \cdot 10^9$ N/m. When there is a cutting force component acting along Y axis, which values lie in the range of 11 … 114 N, this fact gives us considerably higher accuracy of the robotic milling process. The dependencies of the indicator d on S and h_0 (Fig. 4) show that at variations of S from 2 to 7 mm/s and h_0 from 0,5 to 1,5 mm the values of d lie in the range of 0,0052…0,168 μm. At the similar conditions the value of Δd_{max} lie within the range of 0,01 … 0,048 μm.

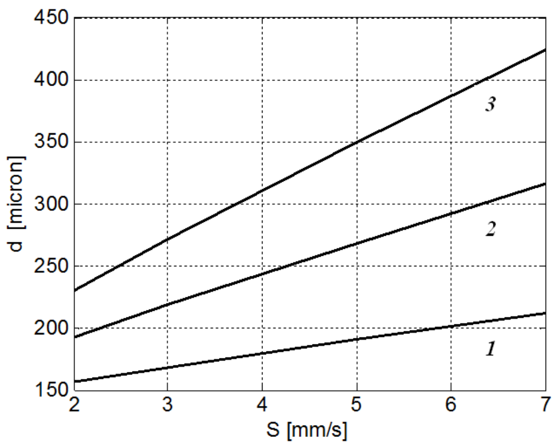

Fig. 3 The dependence of the deviation d on the path velocity S at h_0 = 0,5 mm (1), 1 mm (2), 1,5 mm (3) for the manipulator built on geared drives with traditional structure.

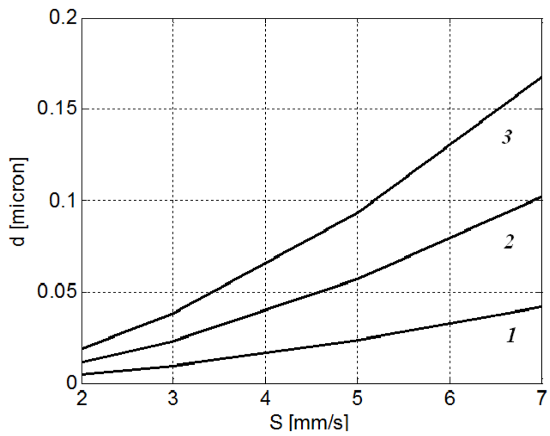

Fig. 4 The dependence of the deviation d on the path velocity S at h_0 = 0,5 mm (1), 1 mm (2), 1,5 mm (3) for the manipulator built on precision dual motor drives.

The increase in accuracy of the milling cutter movements opens more opportunities for the growth of the robotic milling performance. For example, if we restrict the permissible deviation from the desired trajectory at 180 μm, then by means of the traditional approach we cannot exceed the values of S = 2 mm/s and h_0 = 0,5 mm. The new approach, based on dual motor drives, allows us to implement milling at S = 7 mm/s, h_0 = 1,5 mm and to have a large accuracy margin at that. The performance gain is not less than 10,5. We make a conclusion that the usage of technological robots with the suggested dual motor drives promotes significant increase in accuracy of the tool movements and allows us to speak about the possibility of realization of high precision and high performance of the robotic milling process.

Conclusion

The provided research shows possibility and feasibility of increasing accuracy and performance of robotic milling by the usage of the technological robots built on precision dual motor servo drives and closed by position control loops of the manipulator links. In order to improve the dynamic properties of such robots it is feasible to apply impedance control, which can be realized by introducing corrective control loops of the manipulator links velocity. The suggested solution allows us to significantly increase static and dynamic stiffness of the robot by control means without any changes in mechanical robot components. This fact gives a possibility to reduce the influence of cutting forces on the deviation of the tool from its desired trajectory and to increase performance of the robotic milling process on this basis. The results of computing experiments have shown a considerable increment in accuracy and tenfold gain in performance of the suggested solution in comparison with the robot with traditional structure of servo drives closed by position control loops of their motor shafts. The obtained result is especially important at the usage of robot analytical programming, which is one of the most promising approaches to programming robots for the milling process.

References

[1] T. Daun. Iterative Learning Control for Milling with Industrial Robots in Advanced Manufacturing. Lund (2014) pp. 122.

[2] M. Milfelner, J. Kopac, F. Cus, U. Zuperl. Intelligent system for machining and optimization of 3D sculptured surfaces with ball-end milling. J. Achiev. Mater. Manuf. Eng. 14(1-2) (2006) 171-177.

[3] C. Reinl, M. Friedmann, J. Bauer, M. Pischan, E. Abele, O. von Stryk. Model-based Off-line Compensation of Path Deviation for Industrial Robots in Milling Applications. 2011 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM2011). Budapest, Hungary, (2011), pp. 367-372.

[4] M. Petko, G. Karpiel, K. Gac, G. Góra , K. Kobus, J. Ochonski. Trajectory tracking controller of the hybrid robot for milling. Mechatron. 37 (2016) 100–111.

[5] U. Schneider, M. Ansaloni, M. Drusti Experimental investigation of sources of error in robot machining, CCIS, 371(1) (2013) 14–26.

[6] M. Slamani, I. Bonev, Characterization and experimental evaluation of gear transmission errors in an industrial robot, Ind. Robot: Int. J. 5 (2013) 441-449.

[7] S. Xiaolong, H. U. Jiaying, Z. Mingjun, Z. Laixi, Experimental study on Backlash Compensation of CNC Machine Tool, Adv. Mater. Res. 580 (2012) 419-422.

[8] T. Wescott, Applied Control Theory for Embedded Systems, Elsevier, 2006, pp. 320.

[9] S. G. Robertz, L. Halt, S. Kelkar, K. Nilsson, A. Robertsson, D. Schar, J. Schiffer, Precise robot motions using dual motor control, in: IEEE International Conference on Robotics and Automation, Anchorage, (2010), pp. 5613-5620.

[10] Yu. V. Ilyukhin, Yu. V. Poduraev. Improving the Precision of Mechatronic Robot Drives. Russian Eng. Res. 36(4) (2016) 328–334.

[11] Y. Ilyukhin, R. Kolesnichenko. Impedance Control of High-Precision Geared Servo Drives with Two Motors for Technological Robots. 26th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2015. pp.1-10. Procedia Engineering 1877-7058 © 2016.

[12] C. Chen, H. Nie, J. Chen, X. Wang, A velocity-based impedance control system for a low impact docking mechanism (LIDM), Sens. 14(12) (2014) 22998-23016.