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Robust Control Application Possibilities For Machining Robots

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Abstract - *Working in a multi-operational and versatile environment, machining robots practically fall into the conditions of a priori uncertainty and multi-modality. This requires the control system to support certain requirements for stability, quick response and accuracy. This article offers a robust control application possibility for machining robots. The robust control system is based on a different strategy to counter interference (system and technology) in conditions of uncertainty.*

Keywords - *Control system, machine tools, robot for machining, robust control*

I. INTRODUCTION

As a main part of the production systems, the machine - building technology, respectively the technological machines /machine tools (MT), have a considerable influence on the level and efficiency of the entire production process. The development of the electronic, computer and informational technologies, the introduction of new materials and new component base, have also put deep trace in the development of the production techniques.

On the other hand, there is a growing tendency towards combining the machining operations performed on one machine, like workpieces processed on one installation/on one machine (example is Hard point concept of Erwin Junker Machinery Inc., Mori Seiki NL Series, Mazak Integrex Model 200-III ST, etc.) [6].

As a result, a process of series of innovations in the MT structural design has begun in the middle of the 1990s. Parallel kinematic MTs, as well as hybrid kinematic MTs, have been designed based on the well-known HEXAPOD manipulation structure. Another tendency in this direction is the reconfigurable MTs allowing an increase in both flexibility and productivity [1,8].

At the same time, the usage of modern robots has expanded in almost all of the sectors in the industry and public life. They first emerged as ancillary, but currently their use is increasingly required to perform specific technological operations such as welding, assembly, coating, etc. [5]. This possibility is further enhanced by the rapid development of computer technologies, which created prerequisites for the synchronization of the movements of the end effectors, the kinematic and dynamic capabilities of the robots while performing complex movements. On the other hand, the development of additional control systems (vision, force sense, teach pendant programming, tactile sensors, etc.) contributed to the increased importance and economic efficiency of the application of robots in the realization of technological operations (polishing, removal of screws, drilling, milling, etc.) [2].

In practice, there are two approaches for using a robot (robot for machining/machining robot) to perform technological machining operations: 1) by using multi-functional grippers (end effectors) with rotational movement positions for gripping the machining tools, or 2) by using a universal end effector for gripping the workpiece, as well as the feed motions to be performed by separate processing modules. In both cases, the mechanical process can be considered as multi-operational performed on one machine as well as the workpieces processed at one installation/on one machine. The advantage of such an approach is the reducing of the number of bases and fixations, which reduces the build-up of errors and the cycle time of processing.

Working in a multi-operational and versatile environment, machining robots practically fall into the conditions of a priori uncertainty and multi-modality. This requires the control system to support certain requirements for stability, quick response and accuracy. The possibilities of the technical tools for automation to work in these conditions can be realized through three approaches: adaptive [3], modelling (using models of the control process) [7] and robust systems [4]. Embracing each of these approaches as a strategy to counteract interference from external factors leads to certain problems.

In parameterization (a result of parametric modifications in the model) and restructuring (fluctuations in the order model) of the process control, as is the case with robots for machining, the indicators of their quality are decreased without adequate system to counteract the consequences of the occurrence of uncertainty. There is a connection between the quality of a system and the degree of uncertainty in operating conditions.

This article offers a solution for robust control of a robot for machining $T(p) \equiv MR$, based on a different strategy for disturbance rejection (system and technology) in conditions of uncertainty.

II. FORMULATION OF THE PROBLEM

For the purpose of this article, the second approach is chosen – the workpiece 2, which put into effect the feed

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motions in the forming, is placed in the end effector 3 in the robot 1 (Fig.1a).

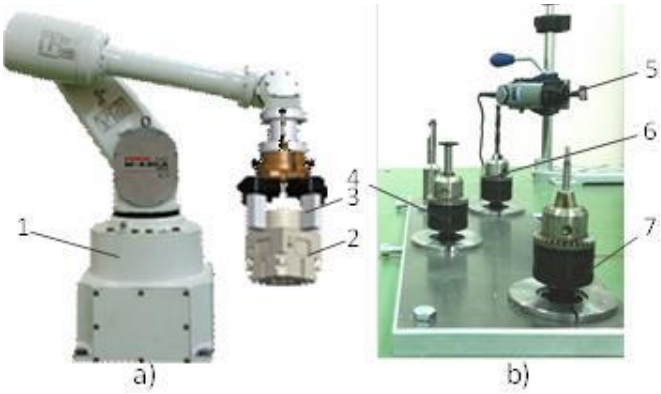


Fig. 1. Robot FANUC M430i-A/4FH and technological modules.

From the point of view of the robot considered (FANUC M430i-A/4FH), the implementation of the feed motions is defined by the type of trajectory, by coefficients depending on the synchronization of the drives of the regional and local robot system (joint, linear and circular movement, fig.2).

Additional motion parameters are the speed $v(tr)$ of the end effector on the trajectory and the corresponding coordinate axes X , Y и Z. They have a direct impact on the robot's dynamic behavior and the accuracy of the movement on the specified trajectory.

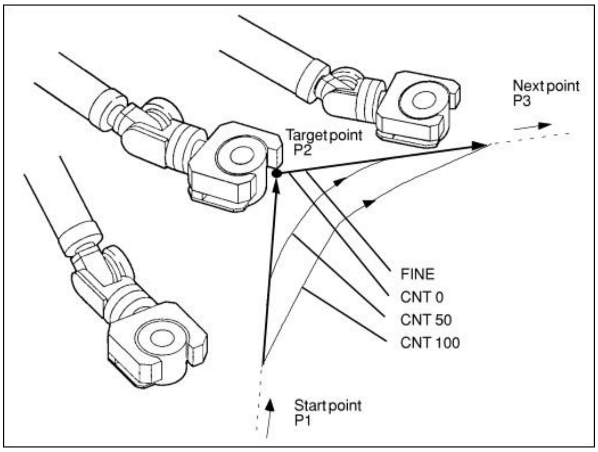


Fig.2. Defining the trajectory using coefficients.

The primary motions (mainly circular) are performed by the technological modules 4 to 7 (fig.1b).

The principle scheme of the whole system is given in fig.3.

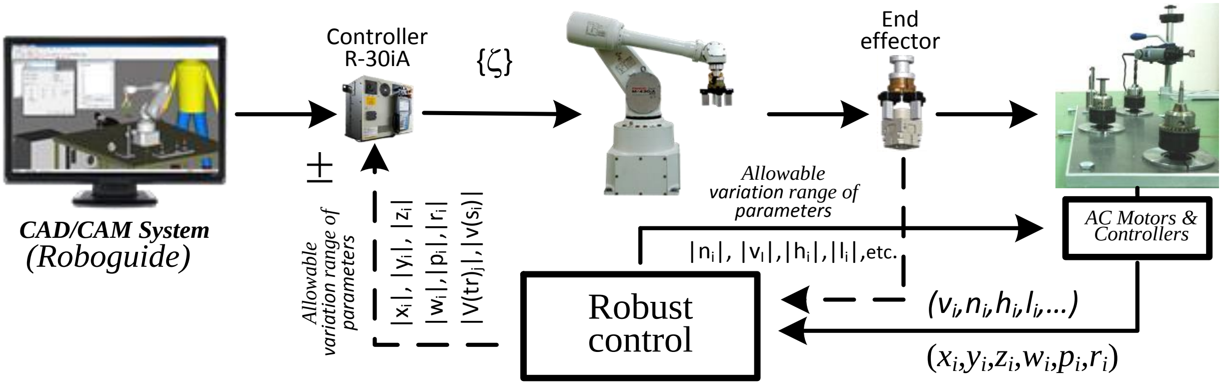


Fig.3. A principle scheme of the entire robotic system.

III. SOLUTION ALGORITHM

The proposed solution, combined in instrumentation, configuration and system direction, is simultaneously directed to counteract against external signal interference and other permanently parameterization (restructuring) system factors $\{\zeta_i\}$ (e.g., inhomogeneity of the processed materials (uh_i), Brinell hardness of the material (HRB), depreciation of the technological modules/systems used (d_i), cutting tools wear (w_i), electromagnetic and electrical interference from the industrial environment (el_i) , included reconfiguration modules (m_i), etc.) (Fig.4).

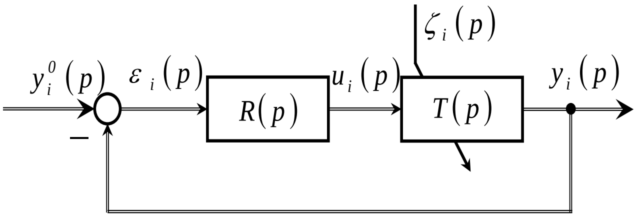


Fig.4. Robust system

As a control process, the synthesis of the robust control system of the robot for machining is carried out by calculating the algorithm $R(p)$, which creates the control influence $u_i(p)$ to $T(p)$. It is performed under the criteria of robust stability and robust performance of the system for a predetermined set of acceptable ranges $\{|\Delta_i|\}$ change of the controllable y_i technological (coordinates of the robot trajectory (x_i , y_i , z_i , w_i , p_i , r_i) speed v_i , feed s_i etc.), geometric (h_i , l_i ,…), structural (m_1 , m_2 ,…) and other parameters.

As $y_i^o(p)=\{X_i,Y_i,Z_i,w_i,p_i,r_i,v_i,s_i,...\}\Lambda\{|\Delta_i|\}$; $\{\zeta_i\}\in\{uh_i,d_i,w_i,el_i,m_i,...\}$; $\varepsilon_i(p)=|y_i^o(p)-y_i(p)|$.

The algorithm for robust control has the form:

$$R(p)=k\left(1+T_D\,p+\frac{1}{T_I\,p}\right)\frac{1}{(T_F\,p+1)}, \qquad (1)$$

where k, T_D, T_I and T_F are the parameters of the controller (respectively coefficient and time constants of differentiation, integration and filter). Their determination depends directly on the parameters of the controlled process and the acceptable ranges $\{|\Delta_i|\}$ of the change of the controlled technological parameters [4,7,9].

The set tool RPM (revolutions per minute) in position 6 (fig.1) are $n_6=690\,min^{-1}$, $|\Delta n_6|=\pm 20\,min^{-1}$. Position 6 is driven by an adjustable AC motor, as in this case $T(p)\equiv AC$.

Disturbance parameters in the controlling may be the following impacts of a probable nature:

- Change of load time on AC (T_m), where $|\Delta T_m|=\pm 10\%$. The load moment depends on both the mass and the hardness (resulting in increased resistance) of the processing material;
- Fluctuation around the nominal value of the voltage (U) of the power supply $|\Delta U|=\pm 10\%$. The asynchronous electromechanical motor is highly sensitive to supply voltage change, with the motor's electrical moment dependence on this change being quadratic;
- Hardness of the material by Rockwell HRB 32, $|\Delta HRB|=\pm 2HRB$, viscous friction, change of temperature, modification of the impedance of AC electric motor etc.

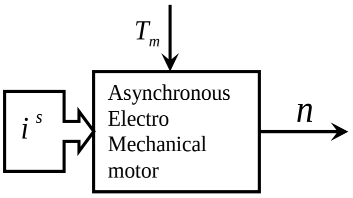
In the analysis of the dynamic energy transformation processes in the AC, the principle of orientation of the coordinate system on the rotor entrainment vector of the electric motor (in current control mode) is used in order to linearize the nonlinear mathematical dependencies

To stabilize the stator current, the stator winding is covered with additional negative current feedback and relay control is applied ignoring the non-linear parts in the stator equations.

In addition, it is assumed that the rotor magnetic flux (Ψ^r) is with constant value so that the linearized structural model of the module $(T(p))$, includes the basic parameters of the AC electric motor - viscous moment (T_v), moment of inertia (J), mutual (L_m) and inherent (L_r) rotor inductance and rotor magnetic flux (Ψ^r) (fig.5). The control influence $(u(p))$ is represented by the stator current (i^s) and the main disturbance impact $(\zeta(p))$ - by the load moment (T_m). The control structure of AC of the module is given in fig.5.

Because the steady state of a system depends mostly on the upper limit of the variance in the transmit coefficient and the time constant of the object:

- the nominal model (without disturbance) of the module (fig.5) is $G^*(p)=\dfrac{5.7827}{10\,p+1}$, and
- the model at the upper limit of the disturbance is $G^{II}(p)=\dfrac{6.939}{12\,p+1}$.



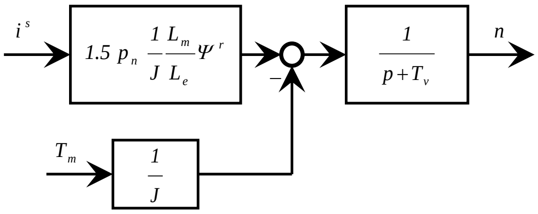


Fig.5. Control structure of AC of the module.

For the example under consideration $R(p)$, under the criteria of minimal integral square error $\{\min_R\|\varepsilon\|_2^2\}$ [9], the following formula is obtained:

$$R(p)\;=\;172{,}9\,\frac{1}{10\,p}\;\underset{\{\min_R\|\varepsilon\|_2^2\}}{\Leftrightarrow}\;G^*(p) \qquad (2).$$

In fig 6 is shown the control signal $u(t)$, in fig. 7 – the step response system $y(t)$ of the closed system Φ_i. The system features are shown in $G\hat{\equiv}G^*$ (with red color) and in $G\hat{\equiv}G^{II}$ (with magenta). In the disturbance mode, simultaneously are simulated a repatriation of the controlled object and a disturbance of the load moment T_m. The analysis of the quality in nominal and disturbance parametric modes of the system (fig.6) confirms that it meets the criteria $\{\min_R\|\varepsilon\|_2^2\}$.

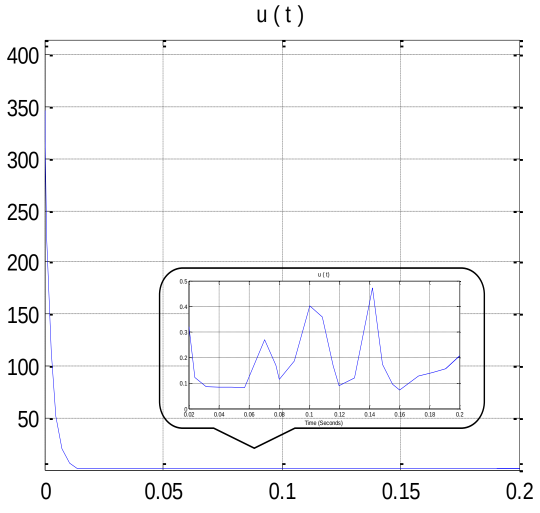


Fig.6. Plot of the signal $u(t)$.

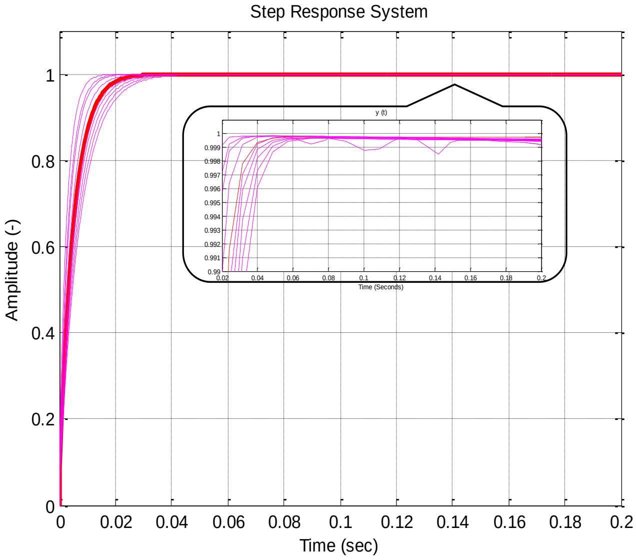


Fig.7. Plot of the signal $y(t)$.

The conditions for robust stability and robust performance for the set $\{|\Delta_i|\}$, (3) and (4):

$$RS(\omega) \Rightarrow |\, 1+G^*(\omega)R(\omega)\,| > r^0(\omega), \quad (\forall\, \omega, \omega \in [0, \infty)) \tag{3}$$

$$RP(\omega) \Rightarrow |\,1+G(\omega)R(\omega)| \geq |\,1+G^*(\omega)R(\omega)| - r^0(\omega), \quad (\forall\, \omega, \omega \in [0, \infty)) \tag{4}$$

are shown in fig. 8. The circles $\pi(j\omega_i)$ with rounds $\pi^0(j\omega_i)$, centers in the points ω_i and radius $r^0(\omega_i) = |\, l_m(\omega_i)R(\omega_i)G^*(\omega_i)\,|$, show the uncertainty in the controlled object.

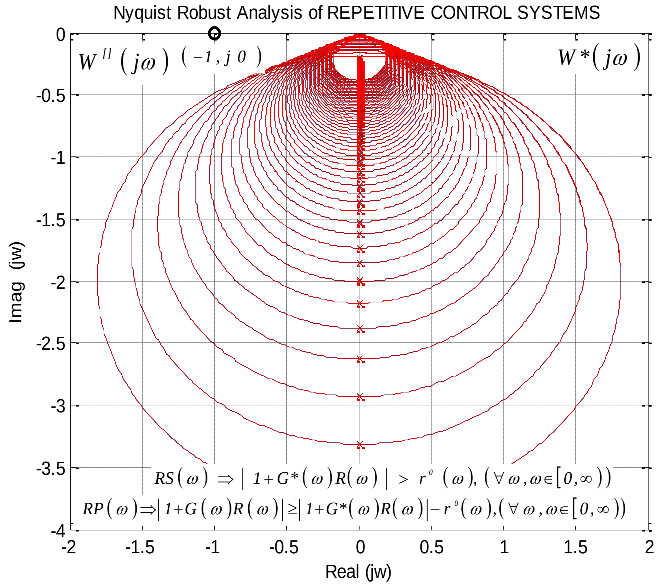


Fig.8. Robust analysis

CONCLUSION

1. A method for robust control of a production system based on a technological robot is proposed.

2. The method is illustrated by a specific example of synthesis, modeling and research of a robust control system of a manufacturing system based on a technological robot.

3. It has been proved analytically that under uncertain conditions the synthesized system has robust properties - stability and performance.

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