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Methodology for Designing Cyber-Physical Multi-Operation Robot Systems Operating in the Conditions of Digital Robust Control

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Abstract**:** *The article proposes an original interdisciplinary approach to the design and construction of cyber-physical robot systems for mechanical processing. From a methodological aspect, the goal is the unification of modeling/synthesis and simulation software of a robot system for mechanical processing operating under the conditions of digital robust control. The system includes industrial robots; modules for implementing technological operations and transport systems. Adherence to the principle of modular construction, reconfiguration, and multi-operation ensures high flexibility and quick response when readjusting the system, and the optimization criteria – minimizing idle moves of the robot, leads to a reduction in the work cycle. The robust control, simultaneously in the instrumental, configurational, and system direction, is a counteraction in the mode of uncertainty, both to external signal disturbances and to possible constantly acting, system reparametrizing factors. This creates prerequisites for maintaining and implementing in online mode both the technological and geometric parameters of the details processed.*

Keywords**:** *Cyber-physical system, Robotic system, Robot in machining, Multi-operational processing, Robust control.*

1. Introduction and problem status

The construction of a complex executive system and technology is a tricky interdisciplinary problem involving knowledge and engineering solutions from various scientific fields. The correct definition of the working environment (hardware and software) and the technological prerequisites that ensure the process of working of the technological system as a cyber-physical system in the conditions of multi-operation, robotization, and optimal control according to defined/set criteria is of fundamental importance.

Therefore, the development of such a complex methodology involves knowledge and engineering solutions from various fields: systems and technologies for mechanical processing; robotics; information technology; and control theory.

In the field of ***systems and technologies for mechanical processing***, as the main part of production systems, there is a growing tendency to combine various technological operations performed at one work position/machine/unit. The different versions of this type of machine are capable of multi-operation processing (turning, grinding, drilling, milling, countersinking, reaming, threading, etc.) of parts with a complex configuration in one unit [1-4].

The effectiveness of consolidating multiple operations into one workplace was demonstrated by Precision Group Inc., Rockford, Illinois, USA, through the so-called Team Key concept they created in November 1997, where, based on a winning project, they purchased 3 Mazak Multiplex 630 multipurpose machines with turning, milling, drilling, and threading. When processing 200,000 parts per year with different series (shafts, spindles, bearing rings, splined shafts, etc.) by both methods – each operation on a separate machine and all operations on one machine, it is shown that productivity increases by 30% [5]. In addition, multifunction machines also have greater flexibility in the realization of the production process.

Another trend is the principle of ***modular construction*** with possibilities for structural reconfiguration of machines. Based on modular construction with possibilities for reconfiguring the structure, a system creates great flexibility not only in construction but is efficient both economically and technologically. Reconfiguration can be considered in terms of technological process, control, software, machine, or system as a whole.

In the field of ***robotics***, the idea of applying Industrial Robots (IR), apart from serving or transporting, to perform specific technological operations (robots in machining [28]), such as welding, assembly operations, application of coatings, mechanical processing, etc., is becoming increasingly popular. [6-8]. This possibility was further strengthened as a result of the rapid development of computer and visual technology, which has created prerequisites for the synchronization of the movements of the end effectors (gripper), and the kinematic and dynamic capabilities of robots in the execution of complex movements.

In the field of ***information technology***, the methods for programming industrial robots can generally be divided into two main groups: 1) online and offline programming methods (through structured text and procedures performed by an operator; in a graphical environment; through demonstration); 2) Automatically programmable (self-learning) systems [9, 10].

In the field of ***control theory***, the idea is to create an approach for robust control of certain parameters to given requirements for stability, speed, and accuracy within a priori known uncertainty limits in the model of the controlled object in real-time [11, 12]. With a high degree of indeterminacy, systems (built on a signal-only interference strategy) cannot achieve high-quality requirements.

During reparameterization (result of parametric changes in the model in the adaptation approach) and restructuring (fluctuations in the order of the model in the model approach) of the controlled object to a higher upper limit, their quality indicators are lowered. Nevertheless, their operational efficiency is significantly higher than that of systems designed according to the signal countermeasure strategy.

2. Principles, means, and objectives of the methodology

The main objective of the proposed methodology is the integration of modeling/synthesis and simulation software and a *robot system for mechanical processing* operating under the conditions of digital robust control. The system includes industrial robots, executive technological modules for the implementation of various technological operations, and a transport system. Obtaining a synergistic effect in the processing of complex details, providing high flexibility and quick response when readjusting the system, is the result of observing the principle of modular construction, reconfigurability, and multi-operation.

The main principles, means, and objectives of the proposed methodology are given in Fig. 1.

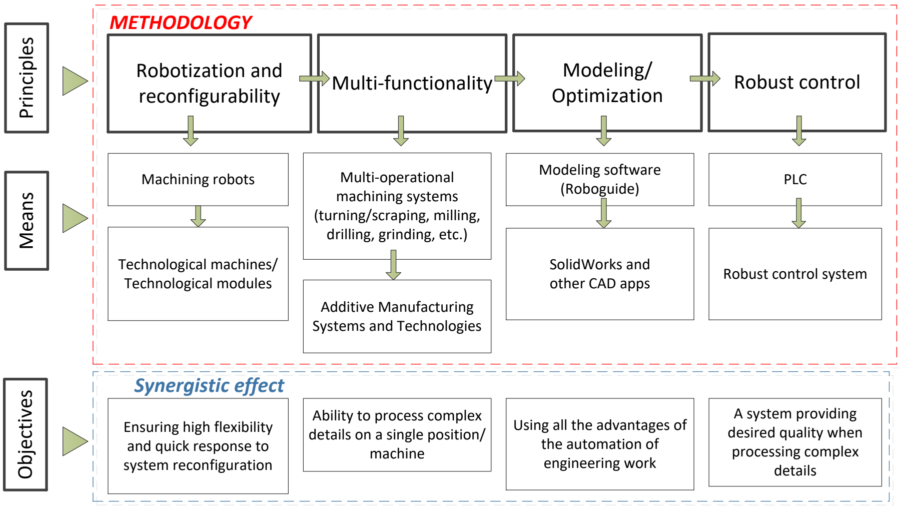


Fig. 1. General logic scheme

The principle of ***„Robotization and reconfigurability“*** meets the requirement for the use of robots as a technological unit and the modular principle of construction of the executive modules implementing various technological operations.

In the present methodology, according to a number of considerations [13, 14], the approach of establishing the processed object in the end effector of the robot (Fig. 2) is adopted. In this case, the movements of the robot are feeding, performing traversal of the working trajectory during the forming of the processed part.

The used approach is innovative and there are no similar studies found in the literature. Known research is related to the use of robots to perform specific technological operations [6, 7, 28].

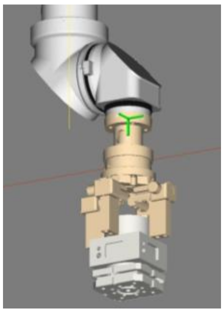


Fig. 2. End effector and workpiece

The operation of the robot under conditions of uncertainty and external disturbances leads to reparameterization and/or restructuring in its model, requiring the use of methods other than classical ones in its control. In the present methodology, the use of robust algorithms is proposed. The scheme for robust control of the robot, as a control object, is given in Fig. 3.

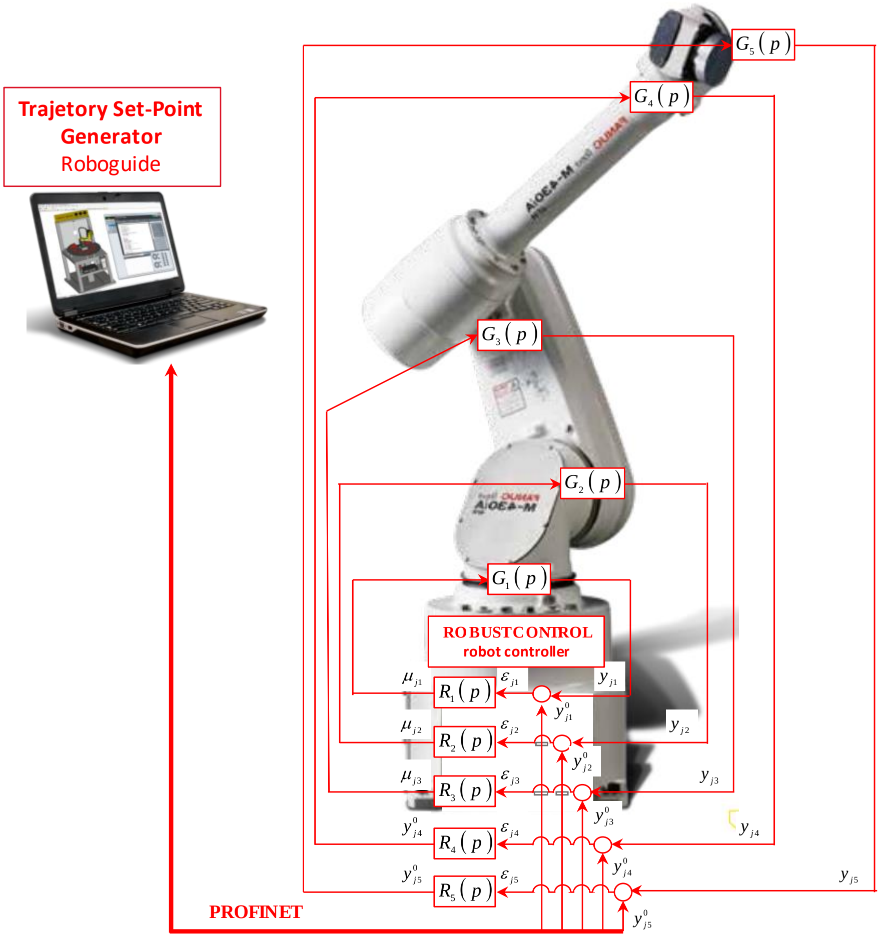


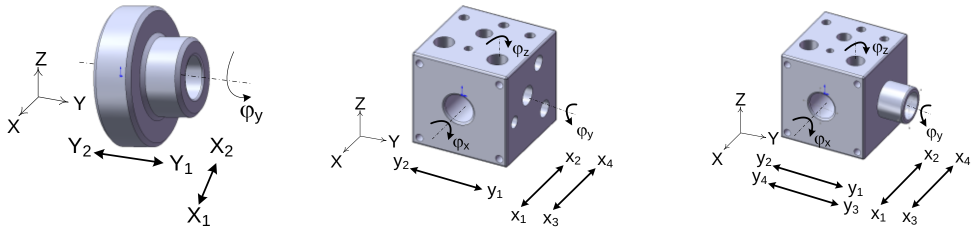
Fig. 3. Principle scheme of the robust control of the robot

For a multidimensional object of this type – a robot with five independent control coordinates (5-DOF)), the input values are the control $\mu_{Ji}\left(i\in\left[1,5\right]\right)$ signals to the motors, and the output values are the positions $y_{Ji}\left(i\in\left[1,5\right]\right)$ of the robot's axes. External disturbances can be accounted for by the mechanical load $M_c \equiv \varsigma_m$ on the shaft of the motors driving the respective lower pair (prismatic/cylindrical or revolute joint) along the coordinate axes of the respective robot arms. G_i in the structure indicates the transmission functions of the electromechanical drive of the robot arms [18, 27].

Regarding **technological systems** implementing various technological operations, the modular principle of construction is adopted. This principle creates prerequisites for system reconfiguration and flexibility of the route technology through the executive system of technological modules when reconfiguring the system to realize various technological operations. An example of such a production system is given in [15].

The principle of **multi-functionality** is implemented through the use of technological modules for the realization of various technological operations, as well as the use of systems and technologies for additive manufacturing. The aim here is the processing of complex details of a single position/technology module.

Thus defined, the robotic system will have the ability to process rotationally symmetric details (Fig. 4a), prismatic body details (Fig. 4b) and complex details (Fig. 4c), having both prismatic and rotary surfaces.



a) b) c)

Fig. 4. Type of processed details

Fig. 5 shows the forming movements that are implemented respectively by the robot and the technological module depending on the type of technological operation (turning/scraping, milling, drilling/ribbing/ countersinking/thread cutting, grooving, grinding/polishing. From Fig. 4 and Fig. 5, the number of required controlled robot coordinates and technological modules is determined.

The control of the technological modules and the transport system (conveyor), as non-linear objects of control, in the digital robust control environment is carried out according to the structural scheme given in Fig. 6. Each of the technological modules has its own robust control of the revolutions and/or the speed of the drive motor, and the control algorithms are programmed in the PLC module.

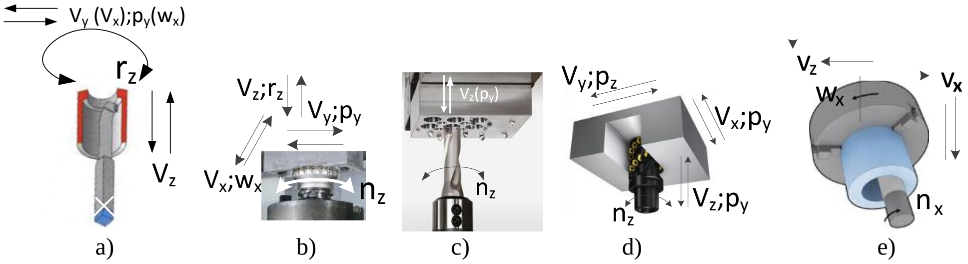


Fig. 5. Forming movements for various technological operations

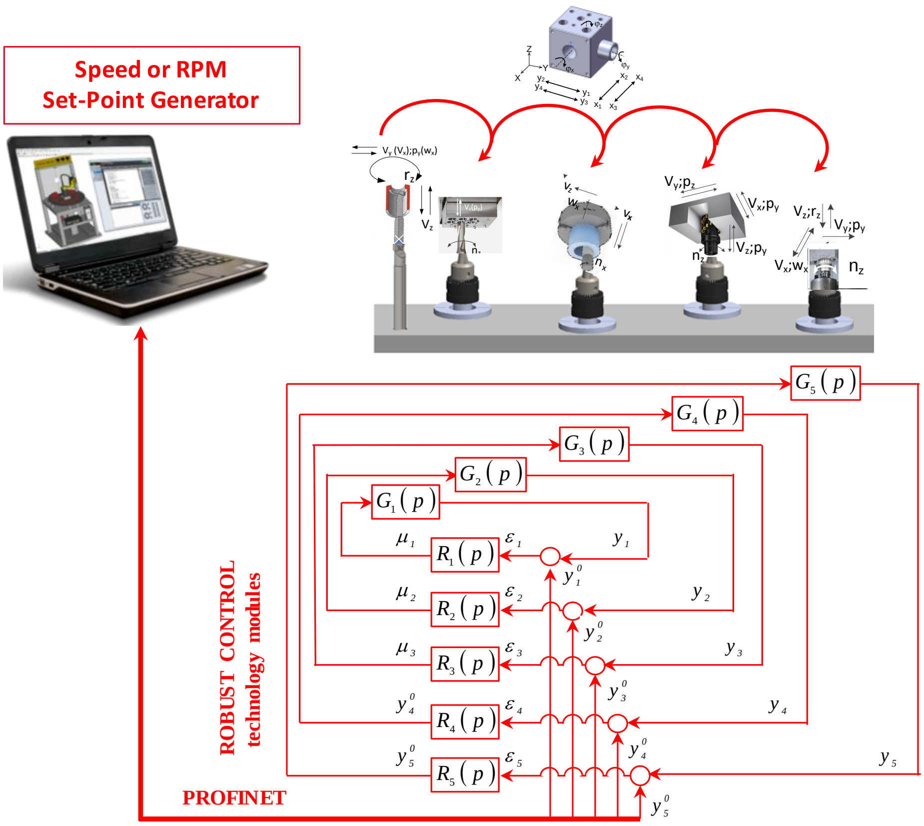


Fig. 6. Control scheme of the technological modules and the transpot system

Principle of modeling. In practice, there is a large variety of different software applications for modeling, simulating and controlling robots and robotic systems (Roboguide, RobotStudio, MotoSim, KUKA-Sim, CAIRob, 3D Studio, Delmia (Delcam), RobCAD, Robomaster, Robsim, Workspace 5, etc.) [15-17]. In the present case, the specialized program package Roboguide of FANUC company has been chosen.

Communication interfaces between the specialized software for modeling and simulation, external CAD models, the control system (processor) of the robot and technological modules have been created. The Industrial Robot (IR) is in on-line communication via Modbus TCP protocol with the controller that manages the technological modules and the transport system. A SCADA system with an OPC server is used, which allows the expansion of the system to SIL (Software in the loop); testing different algorithms without the need to reprogram the PLC for each experimental step, as well as increasing the efficiency of the systems and reducing the time for experimental work. All this allows direct control of the robot and the modules through the synthesized control programs for the optimization of the constructive and technological solutions, as well as visualization of the execution of the real technological process.

Principle of robust control. Regarding the chosen principle of control of the overall system (Fig. 7), the present methodology offers solutions based on a different strategy for countering disturbances and working in the mode of uncertainty. It is directed at the same time in an instrumental, configurational, and systemic direction to react to external signal disturbance, and to the possible constantly acting, reparameterizing (restructuring) system factors (e.g., non-uniformity of the processed materials, depreciation of the used technological machines/modules, wear of cutting tools and others.). For these reasons, the robust principle is adopted in the present methodology. This creates prerequisites for maintaining and realizing in offline mode, both the technological and the geometric parameters of the processed details.

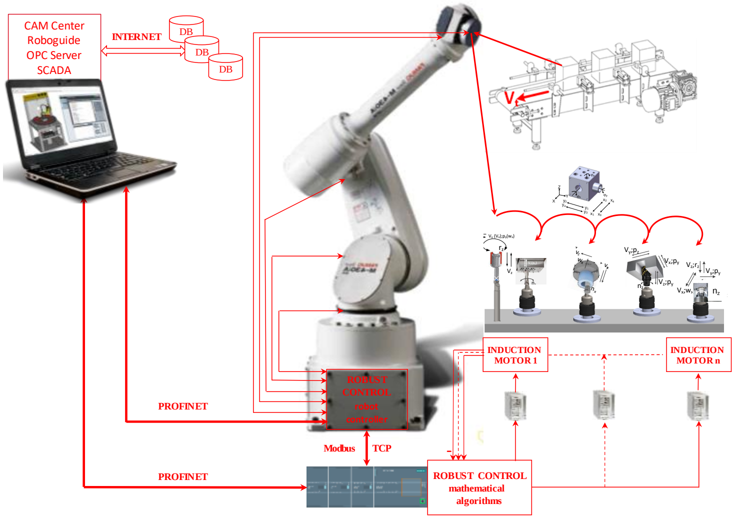


Fig. 7. Schematic diagram of a cyber-physical multi-operational robotic system operating under digital robust control

A mandatory condition for the effective application of robust algorithms is the availability of information about the range of parametric and structural disturbances in the controlled processes. With zero initial conditions, the changes in the object $G(p)$ as a result of the impact of disturbances are expressed by the next Equation (1), where $G^{\diamond}(p)$ models “top-bound disturbances” in the model of the control object $G(p)$, and $\Delta G^{\diamond}(p)$ – its variations around its nominal model $G^{*}(p)$:

(1) $$G^{\blacklozenge}(p)=G^*(p)+\Delta G^{\blacklozenge}(p),\ \left[\Delta G^{\blacklozenge}(p)=G^{\blacklozenge}(p)-G^*(p)\right].$$

From a number of studies of robust control methods [13, 19-23, 25, 26], effective in the conditions of the proposed methodology are the free parameter method [11], the method of the balance equation of stability [23] and the quantitative feedback theory method [24].

The control algorithms of the above methods are easy to program in the controllers/PLCs. The task of synthesis of robust systems is reduced to setting up a regulator when criteria $R(p)$ for robust stability and robust quality are fulfilled.

1. The so called "free parameter method" leads to design of regulator (2) on which the gain coefficient, the time constants of integration, of differentiation and of the robust filter depend. It is chosen so that the system fulfills the robustness criteria and the filter requirements (3):

(2) $$R_{(M)}(p)=k_{R_{(M)}}(\lambda)\left(1+T_D(\lambda)p+\frac{1}{T_I(\lambda)p}\right)\frac{1}{\left(T_F(\lambda)p+1\right)},$$

(3) $$\lim_{p\to 0}\frac{d^k}{dp^k}\left(1-F_\lambda(p)\right)=0,\quad 0<k<m.$$

2. The method of the balance equation of stability is used in the synthesis of robust systems with two constituents in the control $u(p)$ (4), etc., conditional feedback containing a robust filter $F_\xi(p)$ (5), where $R^*(p)$ (6) is a "nominal" regulator synthesized to the parameters of the nominal model of the control object $G^*(p)$, $R^{\blacklozenge}(p)$ (7) is an "disturbed at the upper limit" regulator synthesized to the parameters of the disturbances of upper limit model of the control object $G^{\blacklozenge}(p)$, at criteria $\sigma=\mathrm{const}$:

(4) $$u(p)=R^*(p)\varepsilon(p)+\left[R^*(p)\,G^*(p)\,\varepsilon(p)-y(p)\right]F_\xi(p),$$

(5) $$F_\xi(p)=-\frac{R^{\blacklozenge}(p)-R^*(p)}{1+R^*(p)\ G^*(p)},$$

(6) $$R^*(p)\Leftrightarrow G^*(p),$$

(7) $$R^{\blacklozenge}(p)\Leftrightarrow G^{\blacklozenge}(p).$$

3. The method of the quantitative feedback theory leads to the design of a robust regulator $R(j\omega)$ following a procedure that can be given by (8), respecting the requirement $\lim\limits_{\omega\to\infty} R(j\omega)G(j\omega)=k^{-\lambda}$, where λ is the difference between poles and zeros in the transfer function of the open system, and k is the coefficient of system amplification.

(8) $$R(j\omega)\,G^*(j\omega)=\left(R(j\omega)\,G^*(j\omega)\right)_K=G^*(j\omega)\prod_{k=0}^{w}\left(k_kR(j\omega)\right).$$

Interaction between individual modules of the system. The joint work between the IR, the executive technology modules and the transport system can be visualized as shown in Fig. 8 and Fig. 9. The system includes an IR, a transport system and technological modules performing the technological operations from Fig. 5. There are two approaches for processing the workpiece: 1) Implementation of all technological operations sequentially for each side of the workpiece; 2) Sequential processing of each side by implementing all technological operations.

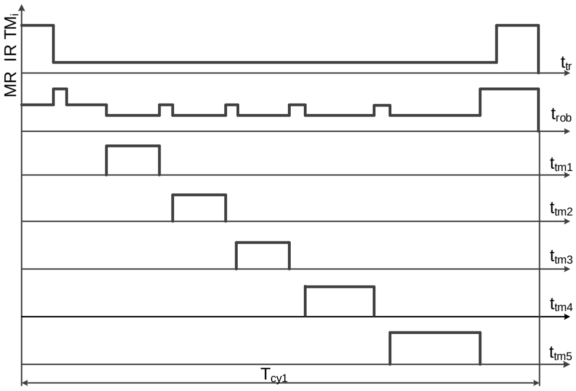


Fig. 8. Cyclogram of the joint operation of a robot system
for one work cycle for processing a complex part

Fig. 8 shows the cyclogram of the joint work between the modules of a robot system for one work cycle for processing a complex part of the type shown in Fig. 4c by the first approach. On the abscissa are given the times of the conveyor (t_{tr}), $\mathrm{IR}(t_{rob})$, executive technological modules for the implementation of various technological operations (from t_{tm1} up to t_{tm5}) and the total cycle for processing the detail (T_{cy1}). From the figure, it can be seen that the individual operation times of the technological modules t_{tmi} are much less than the operation time of the IR, and the idle times of the robot are large.

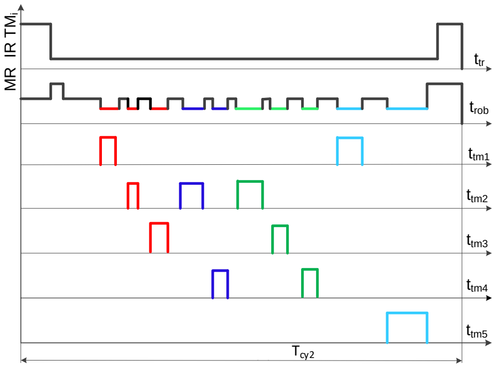


Fig. 9. Cyclogram of the joint operation of a robot system for one work cycle
under optimizicion criteria $T_{cy} \to \min$

5. Conclusion

For the second approach in optimization criteria $T_{cy} \to \min$, in order to shorten the non-working moves of the IR, it is necessary that the technological operations for each side of the detail are processed passing successively through all the technological modules, as shown in Fig. 9. The technological time for processing the individual sides of the workpiece are shown in different colors.

The figure shows that in this case the cycle for processing the same workpiece is smaller than the version shown in Fig. 8 $\left(T_{cy2} < T_{cy1}\right)$.

An original methodology is proposed for the design and construction of cyber-physical production robotic systems operating in the conditions of digital robust control, observing the following principles: multifunctionality of executive technological systems by uniting different technological operations performed at one workplace/machine; modular construction with options for structural reconfiguration of the production system; use of robots as a technological unit and a modular principle of construction of the executive modules implementing various technological operations; direct control in an on-line mode of the industrial robot and the executive modules through synthesized control programs through specialized software with the possibility of optimizing constructive and technological solutions, as well as visualizing the execution of the real technological process. The proposed methodology has been tested by developing a real robot system, and the obtained results, as well as a number of related studies, are reflected in [8, 13-15] and [18-23].

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