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Features of System-Information Models of the Mechanical Process Based on the Platform (USIS + PLSI) of Digital Twins

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Abstract

The features of system information models are considered based on the formalization of the uncertainty of system information of parameters of the cutting process based on the platform of the single information space USIS (Unified System Information Space) + PLSI (Product Lifecycle System Information) of the digital twin of technological operations. This platform is an information technology based on the formalization of the concept of “type of system information” and is used to manage both virtual and material production processes based on a software product (USIS + PLSI), systemically compatible with software of automated systems PLM (Product Lifecycle Management) technologies. The concept of “system information” is associated with the main forms of its manifestation: information process, a priori, and a posteriori system information. Data on the system information of virtual and material production parameters allows you to control the quality of the manufactured product with a digital twin based on the universal structure of the parameter model. An analysis of the uncertainty characteristics of the system information of the machining process parameters was carried out. It is shown that the parameter uncertainty changes its value during the technological process of product manufacturing, and the final value of the expanded uncertainty should not exceed the parameter accuracy tolerance. System information indicators of the intensity of processing system information during mechanical cutting are considered. It is shown that the same system information model can reflect a certain type of system information based on the standard unit of a physical quantity, accuracy tolerance, Planck unit, expanded uncertainty, and membership function of fuzzy sets. At the same time, the property of universality of system information models of processes and systems significantly expands the list of production tasks solved by a digital twin. Examples of the use of system information models of machining processes based on digital twins are given.

Keywords [1]

Digital twin, system information model, software product, mechanical processing, uncertainty of system information, technological operation

1. Introduction

Digital production models (“digital twins”) are multi-level digital models of technological and production processes and operate with a huge number of production facilities (equipment, employee workplaces, service departments, etc.). They are designed to help businesses detect physical problems faster, predict their results more accurately, and produce better products [1-3].

A digital twin of a machining process is a collection of interconnected digital twins of technological operations. A technological operation is the basic unit of production planning and accounting. Based on

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technological operations, the labor intensity of manufacturing products is determined, time standards and prices are established, the required number of workers, equipment, devices, and tools is set, the cost of processing is determined, production scheduling is carried out, and quality and timing of work are monitored. At modern machine-building enterprises, the labor intensity of mechanical operations accounts for more than 70% of the total labor intensity of product manufacturing. One of the types of technological operations is machining operations by cutting.

On the platform of the single information space USIS (Unified System Information Space) + PLSI (Product Lifecycle System Information) of the digital twin, production problems are solved using system information models of cutting processing using turning, milling, grinding, drilling, reaming, broaching, planning and others. The platform of a single information space (USIS + PLSI) of a digital twin is a system of information models, the elements of which are the parameters of processes and systems of real production [4]. The platform of a single information space is used to manage both virtual and material production processes based on a software product (USIS + PLSI), systemically compatible with the software of automated PLM (Product Lifecycle Management) technologies [5].

A key feature of the system information model is the formalization of the concept of system information. The nominal value of a parameter has a certain amount of system information when its value is within the expanded uncertainty interval. This characterization of the system information of the parameters of virtual and material production allows you to control the quality of the manufactured product with a digital twin based on the structure of the parameter model.

The expanded uncertainty of the parameter changes its value during the technological process of manufacturing the product, and the value of the expanded uncertainty should not exceed the parameter accuracy tolerance. The value of the ratio of the sensitivity threshold to the expanded uncertainty of a priori system information of a parameter characterizes the stability of the information connection of parameters in the system. This characteristic of the parameters of the information process is one of the indicators of the quality and efficiency of the technological operation of mechanical processing, both real production and digital twin.

The study of the uncertainty of system information models of the machining process and their impact on product quality and the efficiency of material production, based on the digital twin platform of a single information space (USIS + PLSI), is an urgent task.

2. Analysis of the State of the Issue

One of the tasks of scientific and technological progress that is currently being solved is the development of digital twins for flexible, highly automated computer-integrated production, which allows us to quickly adapt to the production of new products and provide the greatest economic and social effect. The term digital twin includes a broader concept than digital manufacturing [6, 7]. It provides a digital copy of all stages of the product life cycle, from marketing research to disposal or recycling of the product.

Digital manufacturing is the concept of technological preparation of production in a single virtual environment using tools for planning, checking, and modeling production processes. Digital manufacturing is one of the components of product lifecycle management (PLM) technology. Its main goal is the optimization of complex production processes. This category includes tools that allow you to transfer data from design systems to production systems, develop, model, and visualize production systems and processes, and plan and evaluate the quality of various technological processes. The set of digital production solutions belongs to the class of MPM systems (Manufacturing Process Management) - production process management.

The production of high-quality products in modern production can only be ensured by continuously increasing the complexity of the design of products, increasing the accuracy and quality of their manufacture, reducing labor intensity, cost, energy, and material consumption, using new materials, increasing durability and reliability, etc. The listed requirements must be satisfied under conditions of frequent replacement of products and a reduction in their serial production. Reducing the time from issuing an application to manufacturing a new product while expanding the range and increasing the total volume of products.

The platform for a single information space (USIS + PLSI) Digital Twin is an information technology based on system information models of processes and systems of digital and material production [8]. The parameters of real objects and processes are directly related to their virtual representation based on Planck units of physical quantities, which ensures their high (sufficient) accuracy. It provides a constant stream of data that is used to forecast, model, and provide information to the plant manager.

The methodology of system information modeling of processes and systems is based on the concept of system information, which is characterized by a quantitative indicator of the communication ability of an object to exchange information with the environment [9, 10]. In the process of exchanging information, the object changes its state by an amount that is a multiple of the threshold of sensitivity to the influencing object.

From the standpoint of the theoretical foundations of system information modeling, system information is possessed by many properties of an object, the time of manifestation of these properties, and the place of their manifestation. The manifestation of information properties of a system occurs as a result of the interaction of objects, which is formalized by a mathematical system-information model. The formalization of interaction between elements is implemented based on information laws, patterns, and established rules. In this case, the information process of the system as a whole is considered, during which the transfer and redistribution of system information between its elements occurs [11].

One of the conceptual features of the system information modeling methodology is the possibility of representing system information of physical quantities based on Planck units. In the Planck system of units, the function of the ratio of fundamental physical constants is used as the basic units: $\hbar$ – Dirac constant; c – speed of light; G – gravitational constant; k is Boltzmann’s constant.

System-information models of the information process allow solving production problems based on knowledge of the source information parameters, which are informationally related to the receiver information parameters. We directly obtain knowledge of the parameters of the source information using the measurement method. The system information model of the information process has the form:

$$
\begin{gathered}
I(X_i) = I(X_j)\ , \\
f_i\left(\frac{X_{imax}-X_{imin}}{\Delta x_i}\right) = f_j\left(\frac{X_{jmax}-X_{jmin}}{\Delta x_j}\right)\ , \\
\frac{X_{imax}-X_{imin}}{\Delta x_i} = \frac{X_{jmax}-X_{jmin}}{\Delta x_j}\ , \\
\Delta x_i = \frac{(X_{imax}-X_{imin})\cdot \Delta x_j}{X_{jmax}-X_{jmin}}\ , \\
X_{max} = x\ ,\quad n = \frac{x-X_{min}}{\Delta x}\ ,\quad \Delta x = \frac{x-X_{min}}{n}\ , \\
\frac{(X_{imax}-X_{imin})\cdot n_i}{x_i-X_{imin}} = \frac{(X_{jmax}-X_{jmin})\cdot n_j}{x_j-X_{jmin}}\ , \\
log_2\left(\frac{X_{imax}-X_{imin}}{x_i-X_{imin}}\right) = log_2 \frac{(X_{jmax}-X_{jmin})\cdot n_j}{x_j-X_{jmin}}\ ,
\end{gathered}
\tag{1}
$$

where: X_i and X_j – parameters of the source (i) and receiver (j), Δx – sensitivity threshold, $I(X)$ – system information, $|I(X)|$ – information measure of communication ability.

From system information models of the source (i), all unknown knowledge (forecast) about the structure of the receiver’s system information up to this specific moment of transmission of system information without knowledge of previous experience is determined. That is, having received system information (the number of relationships between various data parameters of design documentation, technological documentation, and technological process), we predict knowledge that characterizes future production parameters. This forecasting principle is based on the information laws of transmitting system information without excess or loss [12-14].

In the presence of a finite set of sources and the transfer of system information to the receiver, the system information model of the process with independent parameters of the sources has the form:

$$I(X_i) = \sum_{j=1}^{N} I(X_j)\,, \quad |I(X_i)| = \prod_{j=1}^{N} |I(X_j)|\,,$$
$$|I(X_i)| = \frac{X_{imax}-X_{imin}}{\Delta x_i} = \frac{\prod_{j=1}^{N}(X_{jmax}-X_{jmin})}{\prod_{J=1}^{N}\Delta x_j}\,. \tag{2}$$

The system information model of the process with dependent parameters of system information sources has the form:

$$I(X_i) = \sum_{j=1}^{N} I(X_j)\,,$$
$$|I(X_i)| = \frac{X_{imax}-X_{imin}}{\Delta x_i} = \frac{\prod_{j=1}^{N}(X_{jmax}-X_{jmin})}{\prod_{J=1}^{N}(\Delta x_j+\Delta x'_j)}\,, \tag{3}$$
$$\Delta x'_j = \frac{X_i \cdot \prod_{j=1}^{N}\Delta x_{N-j}}{\prod_{j=1}^{N}(X_{N-jmax}-X_{N-jmin})}\,.$$

In a closed system with many elements X, with $X \rightarrow N$ dependent elements, $\Delta x \rightarrow X_{max}$, and $I(X) \rightarrow 0$ information connections between the elements of the system tend to zero equilibrium.

The general approach to system information modeling has special cases depending on the type of information that is formalized. This happens when the value of the set X is an argument of a function of a certain particular type of information $B(I_i) = f_{I_i}(X_i)$.

System information models are divided into types depending on the value of the object's sensitivity threshold [15]:

1. When the sensitivity threshold of an object is a function of the standard physical quantity $\Delta x = f(I^{st})$ representing the value $X_{min} = 0$ and $X_{max} = x$ of a discrete variable with an information measure
$$|I(X)| = \frac{x}{\Delta x} = \frac{x}{I^{st}}\,.$$
2. When $\Delta x = f(IT)$ is a function of the tolerance on the accuracy of the parameter.
3. When $\Delta x = f(PL)$ is a function of the Planck unit.
4. When $\Delta x = f(U)$ is a function of the extended uncertainty interval of a physical quantity.
5. When $\Delta x = f(\mu_A(x))$, $x \in X$, where $\mu_A(x)$ is the membership function of fuzzy sets.

A certain type of system information model requires the development of various methods for solving the production problems of a digital twin, which are determined by specific requirements and production conditions.

The concept of "system information" is associated with its three main states: information process, a priori, and a posteriori system information. Each object has a priori system information equal to

$$I_{pr} = log_2 \frac{x}{\Delta x}\,, \tag{4}$$

and a posteriori system information as a result of the information process, equal to

$$I_{post} = \frac{\Delta y}{U(y)} log_2 \frac{y}{\Delta y}\,, \tag{5}$$

where: y – receiver parameter value; Δy – sensitivity threshold; $U(y)$ – expanded uncertainty; $\Delta y/U(y)$ – information communication coefficient.

In the model of a priori system information, the sensitivity threshold Δx has a deterministic value. A priori system information includes system information that is "reflected" on tangible media. For example, system information about product parameters in the design documentation and the manufactured product itself. In technical objects, the parameter sensitivity threshold is equal to the accuracy tolerance $\Delta x = IT$ and has a deterministic value. A priori system information is characterized by the completeness of the information carried by a given stationary medium.

In the model of a posteriori system information, the value of the sensitivity threshold Δy is stochastic. For example, in nature the sensitivity threshold is equal to the expanded uncertainty $\Delta y = U$, $y = \mu \pm U$. The stability of information connections of system elements is determined based on the information connection coefficient of a posteriori system information, which is characterized by the ratio of the sensitivity threshold value to the expanded uncertainty $\Delta y/U(y)$. If $\Delta y/U(y)$ = 1, there is a stable connection; if $\Delta y/U(y) < 1$ – the connection is not stable enough; if $\Delta y/U(y)$ >1 – excessively stable connection. These indicators characterize the probability of the existence of information connections between elements of the system, that is, they determine the probability of the existence of the system as such. The indicator of change in the state of the system is determined by the value of the coefficient of information stability of the state of the system $K_{Inf} = \Delta y/U(y) - 1$.

The presence of parameter uncertainty in system information models allows, based on the information stability coefficient, to manage the quality of the system and its operating efficiency in space and time based on the Digital Twin platform of a single information space (USIS + PLSI).

3. Features of system information models of a digital twin with uncertainty of system information of parameters of the machining process

The parameters of the machining process under conditions of uncertainty of system information are influenced by the features of system information models of the digital twin. Therefore, we will consider the characteristics of the uncertainty of system information of the parameters of the mechanical processing process, the main indicators of system information of technological processes, as well as system-information indicators of the intensity of processing of system information.

Examples based on system information models relating to the digital twin of the technological process of processing parts on metal-cutting machines. When developing technology for manufacturing parts, the issues of calculating allowances for processing, operational dimensions, and tolerances on them are of paramount importance [16].

The uncertainty of the rigidity of the machine-device-tool-workpiece system, cutting modes, mechanical properties of the material, geometry, and resistance properties of the tool material, and other factors affect the accuracy of individual stages of part processing [17]. Problems of precision processing of parts based on system information models relate to the probabilistic method for solving dimensional chains.

The presented system-information models of the shaping are based on empirical formulas of cutting modes used in mechanical engineering technology. They allow, under conditions of uncertainty of influencing factors, to calculate the coefficient of information stability of cutting parameters [18]. This approach to models of a digital twin of a technological process makes it possible, at the first stage of design, to solve problems of processing accuracy for individual processing stages with unknown statistical characteristics.

3.1. Characteristics of uncertainty in system information of machining process parameters

The definition of uncertainty has many interpretations depending on the object to which it refers. In its broadest sense, uncertainty characterizes a lack of definition or information about something. For example, uncertainty in the sciences (mathematics, physics, economics, biology, and others), measurement uncertainty in metrology, uncertainty in works of art, etc. [6]. The widespread and established understanding of uncertainty in the scientific community is considered a measure of information.

According to the methodology of modeling, the system information possessed by the elements of the set X is characterized by the interval between the upper X_{max} and lower X_{min} boundaries of its manifestation, as well as the sensitivity threshold $\Delta x = X_{min} - 0$, where x is the variable value of X in the interval $X_{max} - X_{min}$.

System information of an object is characterized by an information measure that is equal to the proportion of the ratio of the general value of the property to its particular value. It indicates information about a private place, in general. Information measure $|I(X)|$ is a function of the qualitative and/or quantitative proportion of the ratio, where $\Delta x = X_{min} - 0$:

$$|I(X)| = f(\frac{X_{max}-X_{min}}{\Delta x}) .$$

An information measure is a dimensionless quantity in any system of physical quantities. The result of the measurement is a number.

System information $|I(X)|$ is a logarithmic function of the information measure

$$I(X) = log_2(\frac{X_{max}-X_{min}}{\Delta x})$$

and measured in bits.

Thus, uncertainty can be considered as a measure of system information when the sensitivity threshold is a function of the expanded uncertainty of the physical quantity $\Delta x = f(U)$:

$$I(X) = log_2(\frac{X_{max}-X_{min}}{U_x}) .$$

The uncertainty in measuring the parameters of the machining process is related to metrology [4]. Unlike the classical theory of accuracy, the concepts of true, actual value of the measured quantity, and measurement error are not considered here. Instead, “doubts about a measurable quantity” are expressed quantitatively. The reasons for the emergence of the concept of uncertainty were the emergence of new non-traditional areas of measurement - analytical chemistry, psychology, sociology, pedagogy, medicine, and others. The developed theory of uncertainty led to the appearance of the document of the International Organization for Standardization (ISO) "Guide to Expression of Uncertainty in Measurement", published in 1993.

The uncertainty of the measurement result is characterized either by the standard deviation (RMS) or by symmetrical boundaries. The distribution of uncertainty components by assessment method is divided into components of categories A and B, which are based on probability distribution functions. The ISO guidance document defines uncertainty - a parameter combined with a measurement result that characterizes the dispersion of the values of a measured quantity. Uncertainties for category A components are estimated using statistical methods. Uncertainties for category B components are assessed using non-statistical methods.

The rules for assessing the uncertainty of parameters of system information models when solving type B production problems are as follows:

1. The expanded uncertainty U is obtained by multiplying the total standard uncertainty $u_s(x)$ by the coverage factor k,: $U_s = k \cdot u_s(x)$.
2. The uncertainty of physical quantities of type B is equal to

$$u_c(x) = \frac{q}{4\sqrt{3}},$$

where q is the division price of the measured value.

3. The uncertainty of coefficients according to type B is equal to

$$u_c(x) = \frac{q}{2\sqrt{3}}.$$

4. The uncertainty of parameters X_i of type B processing is equal to

$$u_c(x) \leq \frac{IT}{k},$$

where IT is the tolerance for the accuracy of the parameter, and k is the coverage coefficient under normal distribution.

5. In mechanical engineering technology, based on production experience, accuracy standards have been established, in which the functional dependence U of the expanded processing uncertainty on D of the shaft diameter is determined

$$U(x) \leq \ k\sqrt[3]{D} .$$

where IT is the tolerance for the accuracy of the parameter, and k is the coverage coefficient under normal distribution.

The main production tasks using system information models of processes and systems in a single information space of digital production include forecasting, optimization of new production, production preparation, control and management of production processes, and control and optimization of technical and economic indicators of production (KPI) [19].

3.2. Main indicators of system information of technological processes of mechanical processing

These indicators characterize the qualitative perfection of the technology being developed or adopted and the control of the machine being designed or the universal technology being developed, applicable for a large number of different products:

1. Information processing speed indicators (characterize the quantitative measure of processing system information per unit of time):
   - cutting speed during rotational and translational motion;
   - basic technological time and piece technological time;
   - cutting speed for a fixed service life of the cutting tool, piece technological time, utilization rate of the starting material, surface roughness, and processing accuracy.
2. Information indicators of processing intensity (determine system information of the depth of technological impact carried out in one processing cycle, i.e. in one pass): cutting depth, width of the cut layer, depth of hardening obtained after processing.
3. Information indicators of surface roughness (characterize system information of the required parameters of surface roughness by established values).
4. Information indicators of processing accuracy (determine the tolerance range (expanded uncertainties) on linear dimensions, volume, mass, and physical and chemical characteristics of the manufactured object, which provide the assessed technological process).
5. Information indicators of stability (i.e., defect-free, reflect the ability to maintain process parameters in the range of expanded uncertainty values, in which the probable percentage of manufactured products does not exceed the acceptable level).

Additional information quality indicators are the coefficient of material utilization, indicators of roughness, accuracy, and stability of processing.

The conditions and factors influencing the main information indicators of the quality of the technologies being developed are as follows:

- power and rigidity of the machine;
- configuration of the workpiece;
- the geometry of the cutting tool;
- the material from which the parts and tools are made;
- accuracy of machine settings;
- degree of heating of the workpiece and cutting tool, etc.

The given information indicators can be used to characterize the quality of technology and control the technology being developed and can be used for a large number of different products.

3.3. System-information indicators of the intensity of processing system information during machining by cutting

System information models of machining by cutting are used in algorithms for solving production problems in digital twins of technological operations. In mechanical engineering, from a technological point of view, the elements of an operation are installation, technological transition, auxiliary transition, working stroke, auxiliary stroke, and position. Cutting processing methods refer to technological transitions.

One of the main indicators of technological transition is processing productivity. The productivity of a working machine is the amount of products produced per unit of time T. If during the working cycle period T the machine produces one product or a batch of products, then its cyclic productivity W_{cyc} (assuming uninterrupted operation) is equal to

$$W_{cyc} = \frac{1}{T} = \frac{1}{(t_{wor} + t_{id1})},$$

where T is the time during which a certain portion of a product is produced (pieces, units of length, area, volume, weight); t_{wor} – time spent on working strokes when processing a part (time of cutting and deformation of metal, etc.); t_{id1} – time spent on idling during the entire part processing cycle (tool approach and removal, material supply, activation of individual mechanisms, etc., i.e. cyclic time loss).

Depending on the purpose of the working machine and the type of processing, the quantity of machine products processed can be measured in various units - pieces, length, volume, weight, etc. Each of the above units can be expressed by the amount of information:

1. Amount of system information of length $I(l)$:

$$I(l) = log_2 \frac{l}{IT_l},$$

where l is the length that the cutting tool travels; IT_l – tolerance for length accuracy.

2. Amount of system information area $I(V)$:

$$I(S) = log_2 \frac{S}{IT_s},$$

where $S_n = b \cdot l$, b – width of the processed surface area, l – length; $S_n = \pi \cdot D$, D – part diameter; IT_s – area accuracy tolerance.

3. Amount of system information volume I(V):

$$I(V) = log_2 \frac{V}{IT_V},$$

where $V_n = b \cdot l \cdot t$, t – thickness of the cut layer, l – length; $V_n = \pi \cdot D \cdot l \cdot t = b \cdot l$ – for a cylindrical surface; IT_V – volume accuracy tolerance.

In the steady state of operation of technological equipment, system information of the intensity of information processing can be represented, respectively, as the ratio of system information of length $I(l)$, area $I(S)$, and volume $I(V)$ to system information of the main technological time T_0:

$$W_{Vcyc} = \frac{I(V)}{I(T_{0v})}, \quad W_{Scyc} = \frac{I(S)}{I(T_{0s})}, \quad W_{lcyc} = \frac{I(l)}{I(T_{0l})},$$
$$W_V(I) = \frac{1}{\sum_{j=1}^{N} I(V)}, \quad W_S(I) = \frac{1}{\sum_{j=1}^{N} I(S)}, \quad W_L(I) = \frac{1}{\sum_{j=1}^{N} I(L)}. \tag{6}$$

Information cyclic intensity W_{cyc} is defined as the ratio of system information (V – volume, S – area, L – length) to system information of the main time. Information intensity W(I) is defined as the ratio of a unit of time to the processed system information *V, S, L*.

3.4. Examples of using system information models of machining processes based on digital twins

Let's consider examples of the use of system information models in the technological process of processing parts on metal-cutting machines, which are based on empirical formulas of cutting modes used in mechanical engineering technology and refer to digital twins. We investigate the influence of system information communication of cutting parameters for tolerance of parts accuracy. This may affect the change in the uncertainty of the cutting parameter, which may lead to a change in the accuracy tolerance of the part.

Example 1. Determine the information stability coefficient k_{inf} for cyclic intensity during turning.

Conditions. Use a system-information model of part processing by turning, developed based on empirical formulas for calculating cutting conditions provided that the sensitivity threshold $\Delta x = f(U)$ is a function of the expanded uncertainty interval of a physical quantity. Coefficient values for system information models of mechanical processing should be taken from reference books on mechanical engineering technology.

$$
\begin{gathered}
I(T_{0tur}) = ln\frac{T_0}{IT_0} = ln\frac{L}{IT_1} + x_V \cdot ln\frac{t}{IT_t} + ln\frac{D}{IT_D} - \\
- ln\frac{1000}{U} - ln\frac{C_V}{U_{C_V}} - ln\frac{K_V}{U_{K_V}} - ln\left(\frac{1 - Y_V}{U_{Y_V}}\right) - ln\frac{S_0}{U_{S_0}} + \\
+ ln\frac{\pi}{U_\pi} - ln\frac{m}{U_m} + ln\frac{T}{U_T} - ln\frac{R_Z}{U_{R_Z}} + ln\frac{X_V}{U_{X_V}}, \\
ln\frac{W_{tur}}{U_{W_{tur}}} = \frac{1}{I(T_{0tur})}, \quad W_{tur} = U_{W_{tur}} \cdot e^{\frac{1}{I(T_{0tur})}}, \\
\frac{\Delta W_{tur}}{U_{W_{tur}}} \geq 1, \quad \cup \quad \Delta W_{tur} = \frac{\Pi(IT_{(1,t,d,\pi,T,x_v)})}{\Pi(\cup_{(C_V,K_V,Y_V,S_0,m,R_Z),})}, \\
U_{W_{tur}} = \sum(IT_{(1,t,d,\pi,T,x_v)}, \cup_{(C_V,K_V,Y_V,S_0,m,R_Z),}), \\
k_{inf} = \frac{\Delta W_{tur}}{U_{W_{tur}}} - 1 \geq 0.
\end{gathered}
\tag{7}
$$

From (7) it follows that at the value of the information stability coefficient $k_{inf} < 1$, the cutting modes for turning are recalculated with the establishment of new standards for the accuracy of the part parameters, and the uncertainty values of the coefficients for turning. The unit of time in productivity theory is the minute. In addition, in production conditions, the quantity of manufactured products is attributed to one work shift, to one hour, etc.

Thus, one of the main information tasks of mechanical engineering technology is to determine such patterns of information interaction between the parameters of a technological system so that they are in a stable correlation relationship during the production of products.

Example 2. Calculate turning cutting modes using a system information model, provided that the sensitivity threshold of the parameters is a function of the standard physical quantity $\Delta x = f(l^{st})$.

On a screw-cutting lathe, the end of the bushing with a diameter of D[mm] is cut to a diameter of d[mm]. Machining allowance (per side) h[mm]. Roughness parameters of the machined surface R_Z [µm]. Workpiece material hardness [HB]. The surface to be processed is without casting skin. The system "machine – fixture – tool – workpiece" is rigid. It is necessary to select a cutting tool; assign a cutting mode (the speed of the main cutting movement allowed by the cutter v^u and the power N_R, spent on cutting); and determine the main time.

1. Select a cutter.
2. Determine the length of the cutting stroke L[mm].
3. Let us take the value of the parameter sensitivity threshold $\Delta x = f(l^{st})$ (depending on the required accuracy of calculation of cutting modes) equal to one (in this case, the cutting modes will have the units of measurement currently accepted in mechanical engineering technology).
4. Determine the value of the system information of the main technological cutting time:

$$
\begin{gathered}
ln\, T_0 = \ln \pi + l \cdot lnD + m \cdot \ln T + x_V \cdot \ln t - \\
- \ln 1000 - ln\, C_V - ln\, K_V + (y - 1) \cdot ln\, S_0 - ln\, L.
\end{gathered}
$$

5. Determine the value of the cutting speed system information:

$$
I(V) = ln\, V = ln\, C_V + ln\, K_V - m \cdot \ln T - x_V \cdot \ln t - y \cdot ln\, S_0.
$$

6. Determine the value of the spindle speed system information:

$$
I(V) = ln\, n = ln\, 1000 + ln\, V - \ln \pi - ln\, D.
$$

7. Determine the value of the cutting force system information:

$$
\begin{gathered}
I(P_Z) = ln\, P_Z = ln\, 9.81 + ln\, C_{P_Z} + x_{P_Z} \cdot ln\, t + \\
+ y_{P_Z} \cdot ln\, S_0 + n_{P_Z} \cdot lnV + ln\, K_{P_Z}.
\end{gathered}
$$

8. From the tables we determine the values of the coefficients $C_{P_Z}, x_{P_Z}, y_{P_Z}, n_{P_Z}, K_{P_Z}$, and

determine the value of the cutting force:

$$P_Z = e^{\sum I(N)}.$$

9. Determine the value of the system information of the power spent on cutting:

$$I(N) = ln\, N = ln\, P_Z + ln\, V - ln\, 6120.$$

10. Determine the cutting power value:

$$N = e^{\sum I(N)}\ [W].$$

The main production tasks using system information models of processes and systems in a single information space of digital production include:

1. Forecasting. Forecast of technical and economic indicators (KPI) and the amount of necessary resources to launch a new product into production at the early stages of the life cycle based on the parameters of the design documentation of the new and old product.
2. Optimization of new production. Optimization of resource costs for technological preparation of production based on the parameters of design documentation and technological system of existing production.
3. Pre-production. Development of technological processes for processing a product and selection of control methods and parameters based on the parameters of the design documentation of a new product and existing technological processes of production.
4. Control and management of production processes. Monitoring the parameters of product processing modes and optimizing the control parameters of technological equipment in real-time based on the parameters of the product and the technological process of production.
5. Monitoring of technical and economic indicators (KPI) in real-time and optimization of corrective control of the production technological process. Analysis of controlled parameters of finished products to identify technological production reserves.

Thus, system information models of mechanical processing processes reflect a certain type of system information, which is characterized by an information measure depending on the sensitivity threshold function. The same system information model reflects system information: units of the standard of a physical quantity, accuracy tolerance, Planck unit, expanded uncertainty, and membership function of fuzzy sets. The universality of system information models significantly expands the list of production tasks with a digital twin.

Example 3. Let's consider an example of engineering calculations when performing mechanical processing of products by milling. Face milling is performed using a 6T85G machine with the following initial parameters:

B = 65 mm; e = 225 mm; t = 1,5 min; R_a = 3,2 mcm; 170HB; S_0 = 1,17 mm/rev;
S_z = 0,12 мм/too; C_v = 57,6; q_v = 0,7; x_v = 0,5; y_v = 0,2; u_v = 0,3; P_v = 0,3; m = 0,25;
T = 180 min; C_P = 30; x_p = 0,83; y_p = 0,55; u_p = 1; w_p = 0; q_p = 0,83; n_p = – 0,55;
K_p = 0,94; v_D = 49,5 m/min; n = 269 min^{-1}.

1. Determine the amount of power expended on shaping by milling at a sensitivity threshold equal to a function of the standard unit $\Delta x = f(l^{st})$:

$$ln\, N_{cut} = ln\, C_p + x_p \cdot \ln t + y_p \cdot ln\, S_z + u_p \cdot \ln B + ln\, K_p -$$
$$- q_p \cdot \ln D - w_p \cdot \ln m - ln\, v_D - \ln 6120 = \ln 30 + 0.83 \cdot \ln 1.5 + 0.2 \cdot \ln 0.12 +$$
$$+ ln\, 0.65 + ln\, 0.94 - 0.83 \cdot ln\, 63 - ln\, 49.5 - ln\, 6120 = -8.64\, nit,$$
$$N_{cut} = e^{-8.64} = 1.816 \cdot e^{-3}\ kW.$$

2. Determine the coefficient of information stability of power for shaping at $\Delta x = f(U)$:

$$ln \frac{N_{cut}}{\Delta N_{cut}} = ln \frac{C_p}{U_{C_p}} + x_p \cdot ln \frac{t}{U_t} + y_p \cdot ln \frac{S_z}{U_{S_z}} + u_p \cdot ln \frac{B}{U_B} + ln \frac{K_p}{U_{K_p}} -$$

$$- q_v \cdot ln\frac{D}{U_D} - w_p \cdot ln\frac{n}{U_n} - ln\frac{v_D}{U_{v_D}} - ln\,6120,$$

$$k_{inf} = \frac{\Pi U_i}{\sum U_i} - 1;$$

$$\Pi U_i = \frac{U_{C_p} x U_t x U_t x U_t x U_t \cdot}{U_t x U_t x U_t x U_t \cdot} = \frac{\frac{1}{2\sqrt{3}} x \frac{0.1}{4\sqrt{3}} x \frac{0.01}{4\sqrt{3}} x \frac{1}{2\sqrt{3}}_t x \frac{0.01}{2\sqrt{3}} \cdot}{\frac{1}{2\sqrt{3}} x \frac{0.1}{4\sqrt{3}} x \frac{0.01}{4\sqrt{3}} x \frac{1}{2\sqrt{3}} \cdot} = = 8.66 \cdot 10^{-3},$$

$$\sum U_i = U_{C_p} + U_t + U_{S_z} + U_B + U_{K_p} + U_D + U_n + U_{V_D} + U =$$
$$= \frac{1}{2\sqrt{3}} + \frac{0.1}{4\sqrt{3}} + \frac{0.01}{4\sqrt{3}} + \frac{1}{2\sqrt{3}} + \frac{0.01}{2\sqrt{3}} + \frac{1}{2\sqrt{3}} + \frac{0.1}{4\sqrt{3}} + \frac{0.01}{4\sqrt{3}} + \frac{1}{2\sqrt{3}} = 2.6932,$$

$$k_{inf} = \frac{\Pi U_i}{\sum U_i} - 1 = \frac{8.66 \cdot 10^{-3}}{2.6932} - 1 < 0.$$

From the above calculations it follows that the information stability coefficient of the shaping power by milling k_{inf} is less than zero, and the value of the sensitivity threshold ΔN_{cut} = 8.66×10^{-3} is significantly less than the value of its expanded uncertainty U_N = 2.6932. It follows from this that the power sensitivity threshold is in the range of uncertainty of the shaping power and does not in any way affect its nominal value.

Thus, the system information connection of cutting parameters does not affect the accuracy tolerance of the part provided UN ≥ 6σ (σ is the standard deviation). Otherwise, a change in the uncertainty of the cutting parameter leads to a change in the accuracy tolerance of the part and, as a consequence, to its rejection.

4. Conclusions

A digital twin of a production process is a set of interconnected digital twins of technological operations (elementary technological process) at the stages of the product life cycle. They are intended to help improve the accuracy and quality of product manufacturing, reduce labor intensity, cost, energy, and material consumption, use new materials, increase durability and reliability, etc. The listed requirements must be met in conditions of frequent replacement of products, reduction of their serial quantity, and reduction of time from the issuance of an application to the manufacture of a new product while expanding the range and increasing the total volume of products.

In modern machine-building enterprises, the labor intensity of technological operations of mechanical processing is more than 70% of the total labor intensity of manufacturing products. One of the types of technological operations is machining operations by cutting. System information models of cutting processes underlie the software of the platform of a single information space (USIS + PLSI) of the digital twin of technological operations. The platform for a single information space (USIS + PLSI) Digital Twin is an information technology based on system information models of processes and systems of digital and material production. The parameters of real objects and processes are directly related to their virtual representation in a digital twin based on Planck units of physical quantities, which ensures their sufficiently high accuracy. The (USIS + PLSI) Digital Twin platform provides a flow of data that is used to forecast, model, and provide information to the industrial plant manager.

A feature of the software (USIS + PLSI) Digital Twin technological operations is the use of system information models based on the concept of the type of system information of parameters of machining processes. The nominal value of a parameter has a certain measure of uncertainty in system information when its value is within the range of expanded uncertainty. This characterization of the system information of the parameters of virtual and material production allows you to control the quality of the manufactured product with a digital twin based on the structure of the parameter model.

The expanded uncertainty of the parameter changes its value during the technological process of manufacturing the product, and the final value of the expanded uncertainty interval of the parameter should not exceed the accuracy tolerance. The information stability coefficient characterizes the ratio of the sensitivity threshold value to the expanded uncertainty of the parameter. It determines the stability of information connections of parameters in a technological system. This characteristic of the system information model of a technological process parameter is one of the indicators of the quality and efficiency of mechanical processing of both real production and the digital twin.

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