Theory of the technological machine state recognition by the criterion of resource uncertainty

N Sevryugina¹,³, A Apatenko¹, and S Revyako²

¹Russian State Agrarian University – Moscow Timiryazev Agricultural Academy, Moscow 127550, Timiryazevskaya st., 49, Russia
²Don State Agrarian University, 346493, Persianovski set., Octyabrski district, Rostov region, Russia
E-mail: ³nssevr@yandex.ru

Abstract. The solution to the problems of assessing the technical condition of special equipment is presented at a multidisciplinary level, as a combination of scientific and technical, practice-oriented research. The purpose of study: development of a digital mechanism for assessing the uncertainty of the state of special equipment systems with real-time monitoring of the intensity of parameter changes, recognition and predictive notification of the probability of risk-failure. It has been established that, in accordance with the theory of probability, there can be only one failure in a unit at a time, even if several damages are diagnosed, and then there is always a single cause. The introduction of the concept of “integrated parameter” supplemented the characteristics of functional and structural multiparameter connections of the state of the unit and made it possible to substantiate the mechanism for recognizing the uncertainty of the state of special equipment systems as a whole. A diagnostic model has been built based on the use of the main provisions of information theory, which represents the unit as a system containing the risk of uncertainty in terms of failure, which is distributed over all structural elements of the unit. An algorithm for recognizing the spatial displacement of uncertainty zones is proposed, the translation of which into a digital format with the introduction of a characteristic criterion will provide a search for a defect (risk-failure). The practical implementation of the risk-failure recognition mechanism is carried out on a simulation model of a change in the state of a technical system using the example of a cardan joint of a technological machine, which is under severe operating conditions during reclamation work. The inclusion in the design of technological machines of a digital module for monitoring the technical condition of the unit is substantiated, including: a module for recognizing the elemental structure; a software shell with a calculation algorithm for evaluating parametric changes; module of interface predictive notification of risk-failure; service control module by state.

1. Introduction
Special equipment, in terms of its design characteristics, is a combination of complex technical systems characterized by geometric, structural and functional parameters, the values of which are determined during the operational period, after commissioning, it passes into the category of partially determined in the presence of a built-in control and measuring apparatus for assessing the state or uncertain indicators, in its absence [1-5].

Uncertainty of the state of a technical system is manifested in the following cases:
• lack of information on the reliability of equipment (high error of values);
• human factor (operator errors), etc.

Scientific developments of the solution to the indicated problem can be represented in the following areas:

• functional efficiency of technical systems:

A.P. Kuznetsov and others in the work [6], research in the field of resource saving was carried out, an energy information model was developed with the basic criterion - the efficiency of the functioning of a mechanical system. In this vein, results were obtained on the development of a mechanism for managing technological changes, carried out by Hsin-HuiChou and JudyZolkiewski [7].

Niko Siltala, Eeva Järvenpää, MinnaLanz, substantiate that an integral part of resource assessment is the concept of executable capabilities, which describes the resource management interface in a vendor-neutral form [8].

S.I. Chalaganidze, J.B. Katsitadze, G.G. Kutelia show the importance of reliability for agricultural machinery, which operate in harsh soil-climatic and dynamic conditions, in contrast to some other industry machinery and equipment [9].

• theoretical solution by developing mathematical models [10-11]:

Valerie C.Y. Zhu, LinyanSun, LinhuiSun, Xiaohong Li, presented a model of the system quality change as a function proportional to a linear function of time through a polynomial solution to minimize the total resource consumption within the given limiting limits [10].

• - innovation [12-14]:

Xiangxiang Sun et al. Assess the impact of market segmentation on the practical implementation of technological innovations, especially in small towns and rural settlements with a low technical level of life support [12].

Hung-ChunHuang, Hsin-NingSu solving a similar problem, prove that technological rootedness incubates innovative potential and proposes to pay special attention to brokerage technological positions, bringing them out as an innovative support for interdisciplinary innovation [13].

In order to reduce innovation risks Delu Wang, XianTong, YadongWang propose to combine the coefficient of variation method, system clustering and combine multiclassifiers for early risk warning with 20 indicators in three dimensions with a decrease in the indicator. The significance of the system-forming property of a self-organizing intelligent data analyzer is substantiated in comparison with traditional single-classification models (logistic regression, machine-like systems, neural network, decision tree) and six commonly used methods of merging multiclassifiers (such as expert judgment, Bayesian method and genetic algorithm) [14].

Considering the system as a combination of elements structured to perform a separate function, when solving problems of performance assessment, the variability of the state is taken, which in the model is characterized both quantitatively and qualitatively by comparing with the normalized values of the parameters [15-18].

The purpose of the analysis of the uncertainty of the state of special equipment is to assess the functional parameters, identify uncertainty factors and make assumptions on the mechanism of using this knowledge in assessing the risk of failures. To achieve this goal, it is required to solve a number of systemic problems, key ones, the problems of searching for the identification of sources of uncertainty, modal analysis of the information content of the results and their presentation in the
algorithmic form of digital recognition are defined to develop a mechanism for managing the risk of failures of machines as a whole.

2. Materials and methods

2.1. Modal analysis of the uncertainty of the technical system state

Each of the specified parameters over time transfers the system from normal operation to a state of non-critical parameter change, and then to a pre-failure state and system failure: $D_0 \Rightarrow D_1$.

Diagnosis of the unit state by a single parameter $X$ obeys the following rule if $X_{\text{min}} \leq X_{\text{nom}} \leq X_{\text{max}}$ -

$\Rightarrow x \in D_0$

The good condition of the unit is - $D_0$, parametrically set by the standardized value when designing the unit as functionally justified and confirmed by certification tests.

The presence of a defect leading to failure - $D_1$, parametrically expressing the limit deviation of the normalized value.

The complexity of monitoring the change in values is solved by compiling a table of the parameter significance in terms of the risk-failure effect on the functionality as a whole.

In accordance with the theory of probability, it is generally accepted that there can be only one failure in the unit at a time, even if several damages are diagnosed, and then there is always a single cause, i.e. chain reaction failure [16].

As noted above, functional and structural relationships are characterized by a different number of parameters, therefore, the concept of an integrated parameter is introduced, which to a greater extent will characterize the state of the unit.

In logarithmic form, this has the following form:

$$\ln \frac{f(x|D_0)}{f(x|D_1)} = \ln \frac{P_{D_1}}{P_{D_0}}$$

$$f\left(\frac{x}{D_0}\right) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-x_1)^2}{2\sigma^2}};$$

$$f\left(\frac{x}{D_1}\right) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-x_2)^2}{2\sigma^2}};$$

where $x_1$, $x_2$ - parameter of mathematical expectation $x$ to values $D_0$, and $D_1$, which corresponds to the normalized state or pre-failure (failure);

$\sigma$ - root-mean-square deviation of the parameter $x$.

The choice of this value is also influenced by the availability of measuring instruments; at present, this issue is being solved by installing digital monitoring and control modules.

Any digital block includes a logical scheme for receiving information, comparing it with normalized values and making a decision on the criticality of the deviation of the result. When constructing a diagnostic model, the basic provisions of information theory are used, which characterizes an aggregate as a system containing uncertainty, which is distributed over all structural elements of the aggregate. The task of constructing a diagnostic model is theoretically aimed at revealing the uncertainty of the state of the model [17].

As information is obtained during diagnostics, the level of uncertainty decreases by the value of excluding the number of certain states of the model elements. Knowledge of the distribution mechanism of uncertainty over structural elements can be used to evaluate various ways to find a defect [18].

This mechanism is mathematically described by the following expressions:

- complete system uncertainty:

$$Z \log_2 \sum_1^n f_{\text{max}}, \text{bit}$$

where $\sum_1^n f$ - total number of items $f$ of lower level model including $n$ levels.
- The probability of finding the system in a state \( D_0 \xrightarrow{i} D_1 \) system in R-state, included in the group of state transition events \( i \) from the normalized value to the pre-failure value is represented by the expression:

\[
P_{D_{0 \xrightarrow{i} 1}} = \sum_j^R P_{D_j}
\]

(4)

- Uncertainty of unit element \( f \):

\[
Z_f = -P_{D_0} \log_2 \frac{P_{D_0}}{P_{R_{a=D_1}}},
\]

(5)

where \( P_{D_0} \) - probability of finding the system in a normalized state;

\( P_{R_{a=D_1}} \) - the probability of the system being in the R-state at the pre-failure level.

- Total uncertainty level:

\[
Z_n = \sum_{i=1}^R Z_i, \text{ bit}
\]

(6)

- Total uncertainty of elements:

\[
Z_m = \sum_{i=1}^{R} \Sigma_{n=1}^n Z_i, \text{ bit}
\]

(7)

Informative value of the diagnostic parameter \( X \), which determines the uncertainty:

\[
J_X = \sum_{i=1}^n Z_i
\]

(8)

Informative value of the diagnostic parameter \( X \), at \( n \) level characterizing \( R \) states of \( f \) elements:

\[
J_f = \sum_{i=1}^n Z_i^R
\]

(9)

The diagnostic model consists of:

- \( n \) model levels;

- \( R \)-state of mating elements \( f_j \) of functioning (intermediate levels following the integral parameter), for example, oil pressure, coolant temperature, cylinder compression ratio, etc.);

- \( f_j \) system elements that describe functional interfaces at the lower level, physically implemented by interconnected parts, quantitatively - geometric parameters, (for example: tolerances, fits, clearances).

Complete control of the entire system by \( X \)-th diagnostic parameter

\[
\Pi_x = \frac{J_X}{Z_i^f}
\]

(10)

Information retrieval rate of \( f \)-th element status

\[
\tau = \frac{J_f}{t_f}, \text{ bit/c}
\]

(11)

where \( J_f \) and \( t_f \) – amount of information and the time spent on diagnosing the element, respectively.

Special equipment, in terms of its structural characteristics, is a combination of complex technical systems characterized by geometric, structural and functional.

2.2. Digital description of the criteria for recognizing the state of a technical system

Digital systems make it possible to create an algorithm for searching for a defect (risk-failure) by providing a recognition criterion. Graphically, the options for obtaining a statistical solution in the presence of a zone of uncertainty are presented in Figure 1 [15].
**Figure 1.** Area of displacement of the zone of uncertainty.

The algorithm for the recognition rule for the area of displacement of uncertainty zones takes the form:

\[
\begin{align*}
\text{if } x \leq x_a & \Rightarrow x \in D_0 \\
\text{if } x \geq x_a & \Rightarrow x \in D_1 \\
\text{if } x_a \leq x \leq x_b & \Rightarrow H \in D_0 \Rightarrow H \in D_1,
\end{align*}
\]

where $H$ – uncertainty function, which for a digital control module is a signal for refusal to recognize a system:
- in good condition – $H_{D_0}$;
- in failure state – $H_{D_1}$

\[
P(H_{D_k}) = P_{D_k} \int_{x_a}^{x_b} f\left(\frac{x}{D_k}\right)dx,
\]

\[
P(H_{D_1}) = P_{D_1} \int_{x_a}^{x_b} f\left(\frac{x}{D_1}\right)dx.
\]

The condition for the minimum average risk is the expression:

\[
\begin{align*}
\frac{f^j\left(\frac{x_a}{D_0}\right)}{f^j\left(\frac{x_a}{D_1}\right)} \leq \frac{P_{D_1}}{P_{D_0}}, & \quad \frac{f^j\left(\frac{x_b}{D_0}\right)}{f^j\left(\frac{x_b}{D_1}\right)} \leq \frac{P_{D_1}}{P_{D_0}}
\end{align*}
\]

The conceptual apparatus for digitalization of the information base of the technical state of special equipment systems is presented by an algorithm in a symbolic format in Figure 2, a description of the compilation and the implementation mechanism are proposed in the previous studies of the authors [18].
3. Results and discussion

3.1. Simulation modeling of a change in the technical system state using the example of a universal joint

The system for maintaining the operability of the structural element of the machine is standardized by the manufacturer in the format of proactive measures of service impact and technology for carrying out repair work as needed. The implementation of these measures makes it possible to eliminate the risks of system failures during the operation of machines at technological facilities, which is important for performing land reclamation work at a distance from the base of maintenance infrastructures.

Structurally, the technical system - cardan joint, is represented by a typical set of interconnected elements with a series connection. In the hierarchical structure, a subsystem of the I level of complexity is distinguished, which includes 6 elements: 1 - cross spikes, 2 - needle rollers, 3 - bearing cups, 4 - radial seals, 5 - axial seals and 6 - lubricant. The calculation of the reliability of the cardan joint is presented by structuring according to the method of connecting assembly elements with a theoretically specified, 99% level of probability of no-failure operation:

\[ P_γ = \prod_{i=1}^{6} P_i = 0.99^6 = 0.941, \]  
(15)

In this case, this is an idealized case of setting the level of the probability of no-failure operation, which in mass production leads to an unreasonable overestimation of the product's cost.

Further calculations are reduced to obtain an economically justified value of the probability of failure-free operation of the universal joint.

Omitting intermediate calculations, the result is presented:

\[ P_γ = \prod_{i=1}^{6} P_i = P_1 \cdot P_2 \cdot P_3 \cdot P_4 \cdot P_5 \cdot P_6 \]

\[ P_γ = 0.949 \cdot 0.932 \cdot 0.964 \cdot 0.949 \cdot 0.949 \cdot 0.949 = 0.729. \]

In the transmission of technological machines performing reclamation work, a large number of cardan joints are used, so if there are 3 cardan shafts, the number of joints increases to 6, and bearing assemblies up to 24 units. At the same time, the probability of failure-free operation with various redundancy options leads to a level change from 0.729 (without redundancy), 0.898 (single redundancy) to 0.937 (double redundancy).

Calculations show that by putting in the model the uncertainty of the intensity of changes in
parameters that reduce the level of no-failure operation, it is possible to reduce the variability of recognition of the probability of a risk-failure of an element already at the level of simulation modeling, setting a theoretically justified range of the parameter of the functional structure as a whole. For clarity, simulation of the cardan joint elements was performed with the imposition of deformation loads and the display of the fields most susceptible to wear, allowing to establish the zones of surfaces prone to risk-failures (Figure 3).

![Crosspiece](image1.png) ![Thorn pressure](image2.png) ![Deformation model](image3.png)

**Figure 3.** Computer model of the gimbal.

With a priori information about the rate of change in the state of each part of the universal joint, a logical analysis of possible failures is carried out. In particular, it was found that the working surface of the bearing unit is exposed to the greatest intensity of wear; to reduce the risks of its failure, preventive work is carried out to flush the joint and replace the lubricant as a preventive operation, these actions can be qualified as a one-time light redundancy.

4. Discussion

In practice, it is laborious to carry out such calculations, it is also economically unjustified to increase the frequency of service actions in a preventive manner, which logically leads to the conclusion that a digital module for monitoring the technical state of the cardan joint as a whole, equipped with a calculation algorithm for evaluating parametric changes with an interface predictive notification of risk failure, is included in the design and planning of service actions by condition.

Technically, such concepts are feasible, since the control systems available in free circulation allow reprogramming control units for specific algorithms, the construction mechanism of which with the logical apparatus of mathematical and model support is presented in these studies. At the same time, the authors of the article propose to systematically expand the scope of innovative technologies, bringing them to the dual-use level, which is noted in previous scientific works [16-18].

It should be noted that such developments should be implemented by specialists in the field of technical operation of transport and transport-technological machines, and IT specialists should convert these algorithms into digital control modules.

As for example, in the work of groups of authors:

- offered (Bouziane Brik, Belgacem Bettayeb, M'hammedSahnoun, FabriceDuval) an Industry 4.0 system crash monitoring tool that focuses on system crashes related to resource localization. [19].
- offered (Ado Adamou Abba Ari, Abdelhak Gueroui, Chafiq Titouna, Ousmane Thiare, Zibouda Aliouat) use a fifth generation (5G) system providing a coherent mapping between user equipment (UE) and remote radio point (RRH) and between RRHs and baseband processing unit (BBU). The calculation results show that the proposed scheme Bee-Ant-CRAN to solve the problem of resource allocation: UE-rrh association and rrh-BBU mapping, (clustering) RRH-BBU reduces resource losses and significantly increases spectral efficiency [20].
Currently, with a high intensity of innovative proposals, the theory of "technological parasites" is being developed (Mario Coccia, Joshua Watts) based on the idea of accelerating the evolution of parasitic-economic relations between technologies aimed at maintaining the competitive advantages of firms and nations. This theory offers a new direction for developing more sophisticated concepts and theoretical foundations to explain technological and industrial changes in economic systems. [21].

Researches (Frans Prenkert, Nina Hasche, Gabriel Linton) highlight the consistency of the analytical structure, recognizing the empirical variability of resource interfaces along with a consistent conceptualization of resources [22], which is consistent with the work of leading Russian scientists V.A. Zorina and N.I. Baurova, who introduce the basic provisions of the theory of catastrophes into the analytical apparatus for assessing the resource of a technical system [23].

5. Conclusions

Special equipment, in terms of its design characteristics, is a combination of complex ones. It is substantiated that, in accordance with the theory of probability, there can be only one failure in a unit at a time, even if several damages are diagnosed, and then there is always a single cause, i.e. failure that caused a chain reaction of damage.

It has been established that the mechanism for recognizing the uncertainty of the state of the system is based on functional and structural multi-parameter relationships, in connection with which the concept of an integrated parameter is introduced, largely characterizing the state of the unit.

The construction of a diagnostic model by using the basic provisions of information theory made it possible to represent the unit as a system containing the risk of uncertainty based on the sign of failure, which is distributed over all structural elements of the unit.

An algorithm for the recognition rule for the area of displacement of uncertainty zones has been developed, the translation of which into a digital format with the introduction of a recognition criterion will provide a search for a defect (risk-failure).

Simulation modeling has been performed as a practical implementation of the risk-failure recognition mechanism when the state of a technical system changes, using the example of a cardan joint of a technological machine, which is in severe operating conditions during reclamation work.

It is proposed to include in the design of technological machines a digital module for monitoring the technical state of the unit, including: a module for recognizing the elemental structure; a software shell with a calculation algorithm for evaluating parametric changes; module of interface predictive notification of risk-failure; service control module by state.

References

[1] Grib V V, Zorin V A and Shchukov R V 2016 J. Repair. Restore. Modernization 6 pp19-22
[2] Sevryugina N S and Stepanov M A 2017 J. Magazine of Civil Eng. 7(75) pp.23-36. DOI: 10.18720/MCE.75.3
[3] Sevryugina Nadezhda 2017 Inter. scien. conf., EMMFT 2017: Advances in Intelligent Systems and Computing 692 pp 273-281. DOI:10.1007/978-3-319-70987-1_29
[4] Zorin V A et al 2019 Russian Engineering Research 8(39) pp 680-682 DOI: 10.3103/S1068798X19080227
[5] Sevryugina N and Kapyrin P 2018 MATEC Web of Conf. 178 06017 https://doi.org/10.1051/mateconf/201817806017
[6] A P Kuznetsov et al 2016 Procedia CIRP 46 pp. 340-343 https://doi.org/10.1016/j.procir.2016.04.002
[7] Hsin-Hui Chou and Judy Zolkiewski 2012 J. of Business Research 2(65) pp. 188-195, ISSN 0148-2963, https://doi.org/10.1016/j.jbusres.2011.05.021
[8] Niko Siltala, Eeva Järvenpää and Minna Lanz 2018 IFAC-Papers On Line ReCaM 11(51) pp 102-107, ISSN 2405-8963, https://doi.org/10.1016/j.ifacol.2018.08.242
[9] S I Chalaganidze, J B Katsitadz and G G Kutelia 2017 J. Annals of Agrarian Science 3(15) pp 329-331, https://doi.org/10.1016/j.aasci.2017.05.024
[10] Valerie C Y Zhu et al 2010 *J. Comp. & Ind. Engin.* 1(58) pp 84-87, https://doi.org/10.1016/j.cie.2009.08.006
[11] S Berg, M Wustmans and S Bröring 2019 *J. Tech. For. and Soc. Change* 146 pp. 706-722, https://doi.org/10.1016/j.techfore.2018.07.046
[12] Xiangxiang Sun at al 2020 *J. Science of The Total Envir.* 706 135749, https://doi.org/10.1016/j.scitotenv.2019.135749
[13] Hung-Chun Huang and Hsin-Ning Su 2019 *J. Technovation* 84–85 pp 59-70, ISSN 0166-4972, https://doi.org/10.1016/j.technovation.2018.12.003
[14] Delu Wang, Xian Tong and Yadong Wang 2020 *J. Resources Policy* 66 101593, ISSN 0301-4207, https://doi.org/10.1016/j.resourpol.2020.101593
[15] Zorin V A, Baurova N I and Pegachkov A A 2019 *J. Period. of Eng. and Nat. Sci.* 1(7) pp 287-293. DOI: 10.21533/pen.v7i1.391
[16] Sevryugina N and Apatenko A 2020 *J. Eng. for Rural Devel.* 19 pp 591-597. DOI: 10.22616/ERDev2020.19.TF132
[17] Apatenko A and Sevryugina N 2019 *IOP Conf. Ser.: Mater. Sci. and Eng. ISM – 2019* 786 012037 https://doi.org/10.1088/1757-899X/786/1/012037
[18] Apatenko A and Sevryugina N 2020 *E3S Web Conf.* 175 https://doi.org/10.1051/e3sconf/202017505011
[19] Bouziane Brik et al 2019 *J. Proc. Comp. Sci.* 151 pp 667-674 https://doi.org/10.1016/j.procs.2019.04.089.
[20] Ado Adamou Abba Ari et al 2019, *J. Comp. Networks* 165 106957, https://doi.org/10.1016/j.comnet.2019.106957
[21] Mario Coccia and Joshua Watts 2020 *J. of Eng. and Tech. Management* 55 101552, ISSN 0923-4748, https://doi.org/10.1016/j.jenteman.2019.11.003
[22] Frans Prenkert, Nina Hasche and Gabriel Linton 2019 *J. of Bus. Res.* 100 pp 139-149, ISSN 0148-2963, https://doi.org/10.1016/j.jbusres.2019.03.027
[23] Zorin V and Baurova N 2018 MATEC Web of Conf. IPICSE-2018 251 https://doi.org/10.1051/matecconf/201825103008