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PARADIGMS OF MODELING AND IMPROVING THE RELIABILITY OF DATA TRANSMISSION IN VLC TECHNOLOGIES

Purpose. Development and improvement of data transmission process modeling methods in VLC systems to enhance their reliability, noise immunity, and ensure stable operation under external and internal uncertainties.

Methodology. The tasks set are realized on the basis of a comprehensive analysis of scientific literature and patent sources, as well as on analytical, experimental and modeling studies. Mathematical and simulation methods are applied to assess the impact of uncertainties and disturbances in VLC systems. In addition, correlation approaches for quantitative assessment of channel stability and transmission error risk prediction algorithms are applied, which allows identifying key reliability parameters under external and internal influences.

Findings. The paradigms of modeling of data transmission processes in VLC systems taking into account uncertainty and interference factors are developed. It is shown that high reliability of communication is achieved by integrating mathematical and simulation models for assessment of the risks of false and undetected defects. The key factors of stability are metrological support, control accuracy and reduction of design risks. The proposed models allow improving the systemic quality of design and operation of VLC-systems ensuring their performance under external and internal influences. The developed approaches are applicable to optimization of the architecture and technological solutions in reliable wireless optical networks.

Originality. A methodology has been developed for the quantitative assessment of risks of data transmission parameter control under conditions of uncertainty of normative values. A new paradigm for the robust design of VLC systems has been introduced, which takes into account the statistical characteristics of measurement errors and the influence of agent uncertainties. Algorithms for machine modeling of the probabilities of false and undetected defects under conditions of uncertainty in control standards have been proposed.

Practical value. Methods of quantitative assessment of control risks and improvement of data transmission reliability in VLC systems have been developed. Mathematical and simulation models allow one at the design stage to take into account more accurately the influence of metrological and operational factors on the quality of operation of optical data transmission channels. The algorithms are applicable for optimization of the element base, operation modes and channel condition monitoring. The results are relevant for reliable wireless networks in conditions of increased requirements to information security and for critical facilities.

Keywords: *VLC systems, process, model, probability, decision making, modeling, distribution law*

Introduction. Visible Light Communication (VLC) technology is rapidly evolving to offer innovative solutions for wireless communication. This technology is based on the use of light-emitting diodes (LEDs) to simultaneously illuminate and transmit information. One of the key advantages of VLC is high data transmission speed with minimal impact of electronic interference and a high degree of safety by limiting signal propagation within the illuminated space. Nevertheless, the stability and reliability of data transmission in VLC systems largely depend on many factors, including internal system noise, instability of electronic components parameters, the influence of external targeted electromagnetic influences, as well as metrological aspects of quality control of system elements [1–3]. This necessitates the development of new approaches to modeling data transmission processes and increasing the reliability of such systems operation. In the article under review, an important aspect of the research is the formation of a modeling paradigm aimed at improving the system quality of VLC system design and operation, taking into account uncertainties, risks and metrological features [4–6]. The methodology presented in this paper is focused on the complex solution of reliability and information security problems, which is important for the application of VLC in critical facilities that require high resistance to external influences.

Literature review. VLC technology started to be actively developed at the beginning of the *21*st century as an alternative to traditional RF data transmission systems. Studies conducted by H. Haas and his team [7] demonstrated the high potential throughput of VLC and its applicability in new generation wireless communication systems. The concept of Li-Fi, as a variation of VLC, immediately attracted attention due to its advantages: high data transmission rate, channel security and environmentally friendly use of visible light.

The fundamentals of data transmission in VLC are based on the possibility of high-frequency modulation of the intensity of light-emitting diodes (LEDs), which can simultaneously act as lighting devices [8]. In this case, the main technical challenge is efficient data encoding and decoding without compromising the quality of illumination.

Data transmission reliability. One of the fundamental challenges for VLC technologies is to ensure the reliability of data transmission under various external and internal influences. The work [9] emphasizes that unlike radio channels, VLC systems are more sensitive to such factors as light source instability, changes in lighting conditions, optical noise from extraneous sources, and degradation of LED parameters during operation. The authors of [10] emphasize metrological aspects as critical in ensuring the stability of transmission channels: the accuracy of control of component parameters, calibration of light and receiving elements, as well as consideration of temperature changes become the basis for maintaining system reliability.

Modeling of transmission processes in VLC. Modern research in the field of modeling VLC-systems is aimed at creating simulation and analytical models that consider both physical properties of the light propagation medium and stochastic parameters of perturbation. In [11], models based on radiative transfer equations and probability theory are proposed to account for noise, multipath, scattering, and attenuation of the optical signal.

Emphasis is placed on the development of robust transmission methods that are robust to internal fluctuations of system parameters and intentional external influences [12]. These methods include adaptive modulation, error correction at the physical and link layers, and the use of multi-agent approaches to predict the risk of failures.

Reliability assessment and risk management. The topic of risks in the design and operation of VLC systems is deeply elaborated in several studies [13]. Channel reliability is assessed not only by the probability of transmission errors (BER – Bit Error Rate), but also through integral stability indices including metrological control errors, risks of false and undetected defects (“false defect” and “undetected defect”, respectively). Special attention is paid to the development of quantitative risk assessment models based on statistical characteristics of measurement and quality management processes [14]. In the study [15], the Monte Carlo method for simulation analysis and prediction of failures in systems with parametric uncertainty is applied.

Problematics of internal and external resilience. Works in the field of VLC channel robustness [16] separate internal disturbances (measurement errors, component noise) and external intentional influences (e.g., attacks using powerful light sources or electromagnetic interference). Methods to improve the robustness of systems through the introduction of adaptive link recovery algorithms, channel redundancy and intelligent network resource management are investigated.

Standardization and regulatory requirements. An important area of VLC technology development is the creation of standards and regulations to ensure system compatibility and security. IEEE organizations (e.g., IEEE 802.15.7 standard) have established basic requirements for physical and link layers of VLC networks [17]. Nevertheless, as noted in [11, 18], in terms of metrological support and reliability modeling there is still a lack of universal techniques, which stimulate further research in this area.

Unsolved aspects of the problem. Despite the active development of wireless data transmission technologies and considerable attention to modeling of VLC systems, the issues of reliability and stability of such systems under conditions of external and internal uncertainties remain insufficiently studied. In particular, the influence of metrological factors, unstable parameters of hardware components and uncontrolled interference on the functional characteristics of VLC-channels is insufficiently investigated. The existing works, as a rule, do not take into account the complex risks associated with false and undetected data transmission errors, which limits the practical application of models in critical tasks. The present study aims to fill these gaps by developing an integrated modeling approach that takes into account metrological, operational, and stochastic parameters. This makes it possible to reasonably assess the reliability of VLC systems and form forecasts of their operation under unstable environment conditions, which is especially important for application in systems with increased requirements to information security and communication stability.

The purpose of this article is to theoretically investigate the impact of statistical properties of instrumentation on the quality of transmission in the VLC system. The quality of control in this system is evaluated taking into account the magnitude of control errors, or risks. To solve this problem, a formal apparatus is used, including mathematical and simulation modeling, which allows one to analyze and evaluate more accurately the impact of various factors on the efficiency of transmission in the VLC system.

Methodological aspects of the research. The object of research is data transmission systems based on VLC technologies using visible light sources to organize wireless communication channels. The subject of the study is the processes of modeling, evaluating and improving the reliability of data transmission under conditions of stochastic perturbations and metrological uncertainties of VLC system components.

The baseline used is:

1. VLC transmission standards (e.g., IEEE 802.15.7, ITU-T G.VLC).
2. Indoor and outdoor light propagation models [19].
3. Experimental characteristics of light-emitting diodes (LEDs) and photo detectors: spectral efficiency, emission stability, temperature dependencies [20].
4. Statistical data on typical measurement errors of VLC components [21].
5. Basic models of data transmission errors: additive white Gaussian noise (AWGN) models, multipath models and attenuation models.

The general concept of the research methodology is summarized below according to Fig. 1.

According to Fig. 1, the overall concept of research methods is organized into several sequential steps. Let us give a more detailed description of these stages:

Mathematical modeling of transmission processes:

- construction of an optical channel model that considers attenuation, scattering, illumination noise and multipath;

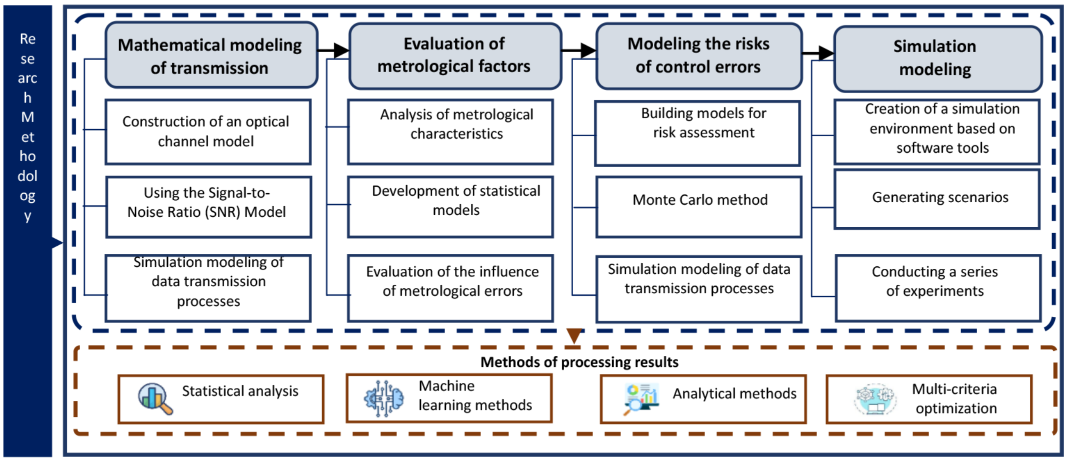

Fig. 1. General concept of research methodology

- use of signal-to-noise (SNR) model based on source and receiver parameters;
- simulation modeling of data transmission processes under different levels of background illumination and disturbances.

Evaluation of metrological factors:
- analysis of metrological characteristics of measuring devices and components of VLC-systems (errors of amplitude, frequency, temperature fluctuations);
- development of statistical models of control and measurement errors;
- evaluation of the influence of metrological errors on the transmission error probability (BER) [22].

Modeling of risks of control errors:
- building models to estimate false defect risks (R_{FD}) and undetected defect risks (R_{UD}) in the presence of uncertainties in normative values;
- application of the Monte Carlo method to model the probability distribution of measurement errors and their impact on decision-making processes in quality control.

Simulation modeling:
- creation of simulation environment based on software tools for generating data samples;
- generation of system operation scenarios with different levels of internal and external disturbances;
- conducting a series of experiments to assess the impact of system parameters on the reliability of data transmission.

Methods for processing results:
- statistical analysis: calculation of confidence intervals, standard deviations, correlation coefficients;
- machine learning methods: construction of predictive models for failure prediction based on data on system parameters;
- analytical methods: estimation of functional dependencies of error probabilities on the characteristics of system components;
- multicriteria optimization methods: search for trade-offs between transmission speed, energy efficiency and reliability [23].

The developed methodology allows us to comprehensively investigate the paradigms of improving the reliability of data transmission in VLC systems, to consider the influence of metrological factors, stochastic perturbations and uncertainties, as well as to create quantitative risk assessments and predict the behavior of the system in real operating conditions.

Research results and discussion. Among the metrological indicators that are integrated into the system of quality control, assessment reliability is the most important. This indicator includes the following components, namely (P_{FD}) – probability of false rejection, (P_{UD}) – probability of undetected defect. It is important to note that in our case the term "false defect" is interpreted in metrology as "manufacturer's risk" and "consumer's risk", as well as "false failure" and "undetected defect" in reliability theory. This approach allows for a more accurate assessment and management of risk in quality control and quality assurance systems.

The control process includes the following stages: at the initial stage the conditional parameter S_i is measured, further the obtained value will be compared with the established standards, lower or upper limit of the permissible value. In case of deviation of the measured value from the permissible limits, the decision-making system initiates corrective actions aimed at restoring the operability of the object. In applied practice it is considered that the main source of errors in observations are measurement errors, which emphasizes the importance of accuracy and reliability of metrological support.

It is required to create mathematical or simulation models capable of providing a quantitative assessment of potential errors, as well as to predict their level depending on the statistical characteristics of the agents involved in the measurement process. This defines the general task of developing models that allow us to formalize and compute the risks arising in control systems. Such risks are functions that depend on a set of statistical parameters of the components of a multi-agent measurement system, including measurement errors, normative tolerances and decision-making algorithms.

At the first stage of modeling, the values are assumed to be deterministic. The first version of the model considers the case of a single-bound constraint on a parameter that is controlled with a lower bound norm S_n (Fig. 2). Two types of errors are analyzed in terms of probability.

1. The actual value of the parameter exceeds the norm ($S_i > S_n$), which means that the controlled parameter is in the "permissible" zone. However, the measured value of S_m is accidentally fixed below the norm ($S_{mi} < S_n$)

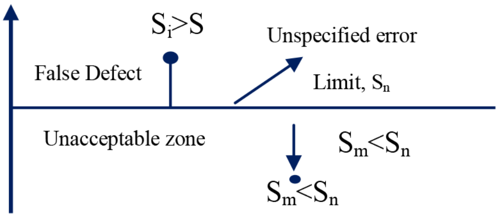

Fig. 2. Scheme for generating lower limit control errors

due to an error, which places it in the "unacceptable" zone. This is an error that results in a false defect.

2. The true value of the parameter is below the norm ($S_i < S_n$), which means that the controlled parameter is in the "inadmissible" zone. However, the measured value happens to be higher than normal ($S_{mi} > S_n$) due to an error, which places it in the "allowable" zone. This is an error that results in an unspecified error.

The scheme of formation of control errors by the lower limit for the controlled parameter can be represented as follows:

1. Actual value of the parameter (S_i): This actual value of the parameter may take a high or low value of the norm.

2. Standard value (S_n): The lower limit is the minimum acceptable value for monitoring the parameter. The parameter must meet this value, i.e. not be lower than this, to be within the permissible limits.

3. Measured value (S_{mi}): A given value obtained by measurement, which may deviate from the actual value due to random errors.

4. Control errors:

- *false defect*: the actual value of a parameter (S_i) is higher than the normal value (S_n). However, due to random errors, the measured value (S_{mi}) will be lower than normal. In this situation, this may lead to an error, since such a parameter is acceptable, but in fact it will be erroneous and classified as invalid;

- *undetected defect*: in a situation where the actual value of a parameter (S_i) is lower than the specified standard (S_n), but due to random error the measured value (S_{mi}) may be higher than the standard. This leads to an error where a parameter is unacceptable but is erroneously categorized as acceptable.

Visually, this can be represented as a graph where:

1. The lower limit of norms (S_n) is the boundary for acceptable values of the parameter.

2. False defect errors occur when a measurement falls below the norm, even though the actual value is within the acceptable range.

It is important to develop mathematical models to estimate the probabilities P_f and P_u, which will depend on the statistical characteristics of the model agents. Thus, we can stop on the assumption where $F(S)$ (statistical distributions of the observed parameter) and $j(y)$ (of the random error) follow Gaussian laws. The distribution density and error (uncertainty) functions of the observed parameter are as follows

$$f(S)=\frac{1}{\sigma_s\sqrt{2\pi}}\cdot e^{-\frac{(S_i-S_{avg})^2}{2}};$$

$$\varphi(Y)=\frac{1}{\sigma_s\sqrt{2\pi}}\cdot e^{-\frac{Y^2}{2}}, \qquad (1)$$

where the parameter S_{avg} is the mean value of the observed parameter; σ_S and σ_j are the standard deviations and measurement errors of the distribution density functions of the observed parameter.

According to the weighted recommendations of the standard (Type A), uncertainties are measured through standard deviations. If event A occurs when the value of parameter S falls within the interval $[S_{i+1}]$ and event S occurs when the value of parameter S is below the threshold level S_n, a situation denoted as a false defect occurs. The index of the Weibull distribution shape – B, determines the nature of change in the probability of deviations or errors.

$$P_i(A)=\int_{S_i}^{S_{i+1}} f(S)dS, \quad P_i(B)=\int_{-\infty}^{S_i-S_n}\varphi(Y)dY; \qquad (2)$$

$$P_{FD}=\sum_{t=1}^{n}\frac{1}{\sqrt{2\pi}}\int_{t_i}^{t_{i+1}} e^{-\frac{t^2}{2}}dt\cdot\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{z_i} e^{-\frac{z^2}{2}}dz. \qquad (3)$$

The expression for estimating the probability of undetected defect P_{UD} has the following form

$$P_{UD}=\sum_{t=1}^{n}\frac{1}{\sqrt{2\pi}}\int_{t_i}^{t_{i+1}} e^{-\frac{t^2}{2}}dt\cdot\frac{1}{\sqrt{2\pi}}\int_{z_i}^{+\infty} e^{-\frac{z^2}{2}}dz. \qquad (4)$$

The parameter T is calculated by replacing the integration variable S by t, where $t = (S_i - S_{avg})$. A similar replacement is also applied to the variable Y. Thus, the analytical models (1) and (2) provide a quantitative assessment and analysis of the impact of all statistical characteristics of the control system on the levels of risk P_{FD} and P_{UD}. Similarly, the problem is solved for the case when the parameter is limited both from below and from above simultaneously.

In mathematical models of limit constraints, it is usually assumed that the limits S_n and S_u are symmetric with respect to the mean value of the observed parameter, but in practice this condition is not always met. In this connection, it is necessary to consider the hypothesis of arbitrary location of norms relative to the mean value of the observed parameter and the case when the distribution function of the observed parameter obeys the Weibull law, which significantly expands the practical application of the developed model. Universality is provided by the properties of the Weibull law. In the context of reliability theory research, it was revealed that the Weibull law describes about 60 % of all statistical data. Also, most of the laws can be considered as special cases of the Weibull law. Thus, at $B = 0.5$ the value will be close to the exponential law, for $B = 2.5$ corresponds to the Rayleigh law, and at the value of $B = 3.25$ the form of the Weibull distribution corresponds to the normal law. The distribution density function of the Weibull law has the following form

$$f(S,\alpha,\beta,\gamma)=\frac{\beta}{\alpha}(S-\gamma)^{\beta-1}\cdot e^{-\frac{(S-\gamma)\beta}{\alpha}}, \quad S\ge\gamma, \qquad (5)$$

where α is the scale parameter; b is the shape parameter; g is the position parameter. Fig. 3 presents a graphical diagram explaining the development of the required models.

Let us analyze the case when the true value of the parameter S is greater than S_u, while remaining less than

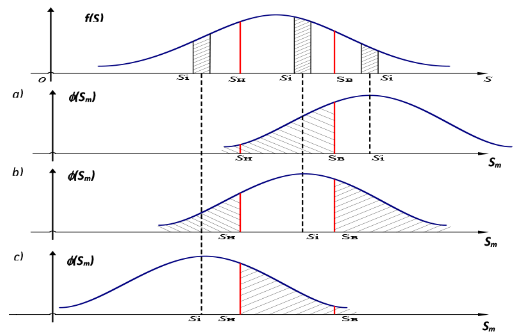

Fig. 3. Formation of control errors at arbitrary placement of standards around controlled parameters

S_n. The threshold values S_n and S_u can be set arbitrarily, as it is convenient for the researcher. Unlike normal distributions, the Weibull distribution has the property of having an analytically expressed integrable function.

$$F(S) = 1 - e^{-\frac{(S-\gamma)\beta}{\alpha}}, \tag{6}$$

where $F(S)$ is used to integrate the Weibull's law function, and we find the final expression to calculate the probability of P_{FD}

$$\begin{aligned} P_{FD} = \sum_{i=1}^{k} \left(e^{-\frac{S_i^{\beta}}{\alpha}} - e^{-\frac{S_{i+1}^{\beta}}{\alpha}}\right) \cdot \Bigg[\frac{1}{\sigma_y \sqrt{2\pi}} \int_{S_n}^{S_i - 3\sigma_y} e^{-\frac{y^2}{2}} dy + \\ + \frac{1}{\sigma_y \sqrt{2\pi}} \int_{S_B}^{S_i + 3\sigma_y} e^{-\frac{y^2}{2}} dy \Bigg]. \end{aligned} \tag{7}$$

The calculated expression for P_{UD} will be as follows with two components

$$\begin{aligned} P_{UD} = \sum_{i=1}^{k} \left(e^{-\frac{S_i^{\beta}}{\alpha}} - e^{-\frac{S_{i+1}^{\beta}}{\alpha}}\right) \cdot \frac{1}{\sigma_y \sqrt{2\pi}} \int_{S_n}^{S_i - 3\sigma_y} e^{-\frac{y^2}{2\sigma_y^2}} dy + \\ + \sum_{i=1}^{k} \left(e^{-\frac{S_i^{\beta}}{\alpha}} - e^{-\frac{S_{i+1}^{\beta}}{\alpha}}\right) \cdot \frac{1}{\sigma_y \sqrt{2\pi}} \int_{S_B}^{S_i + 3\sigma_y} e^{-\frac{y^2}{2\sigma_y^2}} dy. \end{aligned} \tag{8}$$

Under the above conditions, the tolerances for the observed parameter were treated as deterministic quantities. However, in practice, standards are often accompanied by a significant degree of uncertainty for a variety of reasons. This fact is regularly confirmed by a variety of examples covering a wide range of human activities.

The development of optimal standards in each specific area has become one of the key scientific and technical tasks, which not only remains relevant, but is becoming increasingly important.

In modern design practice fundamentally new and, as a rule, insufficiently developed tools or technologies are introduced. In this case, in the presence of statistical uncertainty of standards, the task of further control numerically and error estimation becomes especially important. It is logical to assume that the quantities whose limit values have control parameters are random variables, which in each case, both at the beginning and subsequently have statistically defined distribution laws. The boundary value problem for the system is established.

It is also assumed that the distributions of random errors of the observed parameter, as well as of the normative values, have a normal distribution. For the upper and lower baseline constraints, assume that the shape of the density distribution for the corresponding ones is as follows

$$\Theta_1(S_n) = \frac{1}{\sqrt{2\pi}\sigma_n} e^{-\frac{(S_n - S_{navg})^2}{2\sigma_n^2}}; \tag{9}$$

$$\Theta_2(S_b) = \frac{1}{\sqrt{2\pi} \cdot \sigma_b} e^{-\frac{(S_b - Sbavg)^2}{2\sigma_b^2}}, \tag{10}$$

where S_n and S_u are the mean square deviation of the lower and upper normative values; S_{navg} and S_{uavg} are the average values of the lower and upper norms.

When considering this task, attention should be paid to the method of simulation modeling, which will allow us to reproduce the dynamics of false defect probabilities of the upper (P_{FD}) and lower (P_{UD}) levels depending on all the involved statistical factors. This approach provides a more realistic and flexible representation of the uncertainty's characteristic of the processes of control and compliance assessment.

When controlling the state of the object by a conditional parameter S, it is assumed that this parameter has a current real value S_i, which is formed (or "reproduced") in the simulation model using a special generator program in accordance with a given distribution law. This approach allows us to consider the stochastic nature of the parameter and to carry out realistic modeling of control processes.

In all the cases considered in this example, it is assumed that the distributions of parameters obey the normal law. However, in real practice, the distributions for each model parameter are usually experimental and determined from empirical data. Therefore, it is necessary to develop customized random number generators corresponding to each specific distribution law. In addition, the measurement process is accompanied by random error, because of which the measured value of the parameter S_{mi} randomly deviates from its true value S_i.

The modeling algorithm presented in Fig. 4 functions as follows. At the first stage of the program operation, in block 1, all initial parameters of the model are entered, including the value N, which determines the number of simulation cycles.

Within the simulation model, $F(s)$ remains the density function of the distribution of the observed parameter. The distribution density function of the lower norm is denoted as $\theta_1(S_n)$. Further stages of the algorithm include generation of random values based on the specified distributions and calculation of various characteristics associated with the monitored parameter and its deviations from the normative values.

The algorithm presented in Fig. 4 serves for simulation modeling of the process of control of parameter S in conditions of uncertainty of normative limits. The purpose of the algorithm is to quantify the risks of false defect resulting from statistical deviations of parameters and measurement errors.

The stages of the algorithm are:

1. Input of initial data (block 1):

The user sets the model parameters, including the distribution law of the observed parameter $F(s)$, the nor-

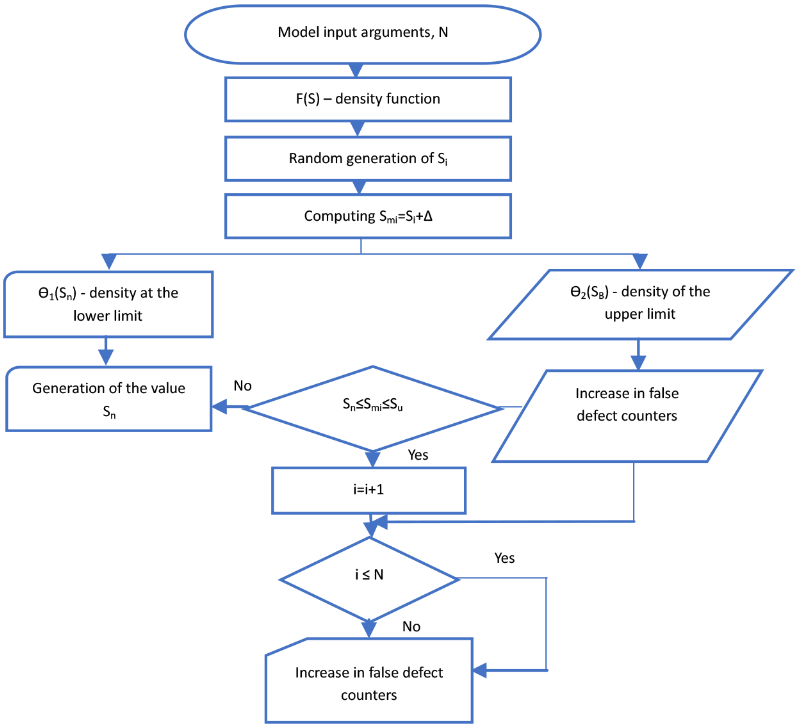

Fig. 4. Algorithm for modeling control risk assessment in case of uncertainty of normative values

mality densities $\theta_1(S_n)$ and $\theta_2(S_u)$, and the number of simulated cycles.

2. Generating the true value of the parameter S_i:

Using the density function $F(s)$, the random value of the object parameter is generated.

3. Accounting for measurement error:

The measured value $S_{mi} = S_i + \Delta$ is calculated, where Δ is the random measurement error.

4. Formation of regulatory limits:

The control limits S_n and S_u are modeled using appropriate densities θ_1 and θ_2 that account for regulatory uncertainty.

5. Verification of compliance condition:

The measured value of S_{mi} is compared with the limits of S_n and S_u. If it does not fall within the acceptable interval, a false defect case is recorded.

6. Counter and cycle completion:

After each cycle, the counter value is increased. When $i > N$ is reached, the simulation is terminated.

The purpose of the algorithm is:

The algorithm allows us to quantify the influence of random factors on the reliability of the control and the probability of false defects, as well as to study the sensitivity of the control system to changes in the normative and measuring. This is especially true when standards are not precisely set or are experimental in nature.

In the simulation process, given a set number of simulations, given a value of N, the probability of false defects and uncertain defects can be calculated using the following formulas (probable observation errors)

$$P_{FD} = N_{FD}/N; \quad P_{UD} = N_{UD}/N,$$

where N_{FD} is the value of the false defect counter; N_{UD} is the value of the undetected defect counter; N is the number of all simulated repetitions.

Calculations of this kind can also be performed for different combinations of distribution laws, which makes it possible to evaluate and compare their impact on the risks that arise in the management using distributions of modeling parameters. A graphical representation of the results of the computer experiment is given in Figs. 5 and 6.

The graph illustrates the results of modeling the probability of false defect P_{FD}, provided that the normative values are set as deterministic, that is, not subject to random fluctuations. The calculations are performed

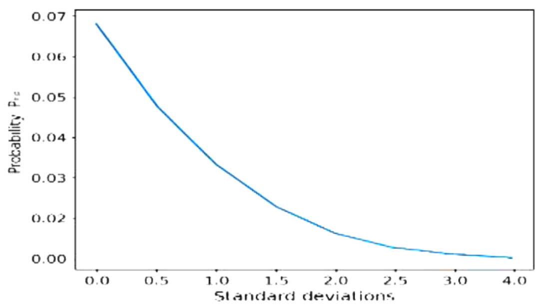

Fig. 5. Results of machine modeling for deterministic standards (probability P_{FD})

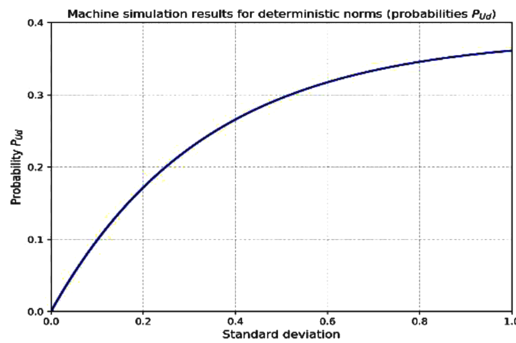

Fig. 6. Results of machine modeling for deterministic norms (probability P_{UD})

using the influence of random measurement errors and variability of the parameter *S*.

Key Points:

1. On the abscissa axis (*X*) the standard deviation values are plotted reflecting the level of variability of the measured parameter.
2. On the ordinate axis (*Y*) is the probability of false defect P_{FD}, which occurs when the measured value deviates from the true value, despite the compliance of the object with the established norms.

Analysis of results:

1. There is a clear tendency for the false defect probability to decrease with increasing standard deviation, which is due to an increase in the variation of the parameter and, consequently, a decrease in the density of getting into the critical zone of misclassification.
2. At zero deviation the probability of false defect is maximum, which corresponds to the highest sensitivity of the system to even insignificant measurement errors.
3. As P_{FD} decreases, the reliability of decision making in the quality control system increases.

The graph confirms that even with deterministic normative boundaries, the level of measurement uncertainty has a significant impact on the probability of false defects. These results emphasize the need to consider the statistical nature of errors and parameters in the tasks of quality control and management.

The graph shows the dependence of the probability of non-compliance $P_{UD}\{ud\}$ on the value of the standard deviation of the observed parameter, provided that the normative limits are set to fixed (deterministic) values. This probability reflects the cases when an object that does not meet the established requirements is erroneously recognized as good due to the influence of random factors, primarily measurement errors and scatter of characteristics.

Analysis of results:

1. As the standard deviation increases, the probability of P_{UD} also increases. This indicates that the sensitivity of the control system decreases as the variability of the parameter increases.
2. The minimum values of P_{UD} are observed at deviations close to zero, which is logical, because in this case the measurements reflect the true value of the parameter as accurately as possible.
3. The increase in the probability of defect indicates high risks when making decisions under conditions of considerable uncertainty, especially when there is no adjustment of standards or adaptive control methods. Modeling demonstrates that the use of deterministic norms under conditions of high statistical uncertainty can lead to underestimation of the proportion of unfit products. This emphasizes the need to use adaptive or probabilistic approaches in quality control systems. The purpose of the computer experiment was to investigate the influence of errors of the measuring instrument and the controlled parameter on the control result depending on the ratio $\sigma_\varphi/\sigma_{si}$, where σ_φ is the standard deviation of the measuring instrument and σ_s is the standard deviation of the parameter. During the experiment, this ratio varied from 0.1 to 1.0 for different given values of the normal of the parameter *S*. The analysis of the graphs shows that in both cases the numerical values of the control errors show a clearly expressed nonlinear dependence and depend significantly both on the structure of the error system and on the set pores.

Conclusions. The development of a general concept of methodological approaches to modeling data transmission processes in VLC systems to improve reliability and robustness to both internal and external disturbing factors demonstrated the levels of uncertainty of the measuring instrument σ_φ compared to the deviation of the controlled parameter σ_s because of modeling the risk of failure within 25 %. As the graphs show, the effect of varying the ratio σ_φ/σ_s far outweighs the effect caused by measurement errors alone. The results demonstrate the potential of using simulation data for risk prediction in automated design systems. The research confirms that control risks can serve as a quantitative indicator of the vulnerability of the technical systems under study. In this case, traditional metrological methods for assessing the accuracy of measuring instruments become ineffective due to the high degree of uncertainty inherent in the agents involved in controlling the system. The overall result of the work is to further develop the theory of reliability management through the concept of metrological reliability of management processes in technical policy, system design methodology, as well as metrological reliability (stability) of data transmission systems using optoelectronic technologies utilizing VLC principles. Future work will investigate the development of models that account for dynamically changing operating conditions and the integration of artificial intelligence-based adaptive control algorithms.

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Парадигми моделювання та підвищення надійності передачі даних у VLC технологій

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Мета. Розробка та вдосконалення методів моделювання процесів передачі даних у системах VLC із метою підвищення їх надійності, стійкості до перешкод і забезпечення стабільності функціонування в умовах зовнішніх і внутрішніх невизначеностей.

Методика. Поставлені завдання реалізовані на основі комплексного аналізу наукової літератури й патентних джерел, а також на проведенні аналітичних, експериментальних і моделюючих досліджень. Застосовуються математичні й імітаційні методи для оцінки впливу невизначеностей і перешкод у системах VLC. Крім цього, застосовані кореляційні підходи для кількісної оцінки стійкості каналу та алгоритми прогнозування ризиків помилок передачі, що дає змогу виявити ключові параметри надійності в умовах зовнішніх і внутрішніх впливів.

Результати. У результаті проведеного дослідження розроблені парадигми моделювання процесів передачі даних у системах VLC з урахуванням факторів невизначеності й перешкод. Показано, що забезпечення високої надійності зв'язку потребує інтеграції математичних та імітаційних моделей для кількісної оцінки ризиків помилкового й невиявленого браку. Виявлено, що ключовими факторами стійкості є якість метрологічного забезпечення, точність контролю параметрів і мінімізація проєктних ризиків. Застосування запропонованих моделей дозволяє підвищити системну якість проєктування та експлуатації VLC систем, забезпечуючи їхню працездатність в умовах зовнішніх і внутрішніх впливів. Розроблені підходи можуть бути використані для оптимізації архітектури й технологічних рішень у перспективних бездротових оптичних мережах.

Наукова новизна. Розроблена методологія кількісної оцінки ризиків контролю параметрів передачі даних при невизначеності нормативних значень. Введена нова парадигма робастного проєктування VLC систем, що враховує статистичні характеристики помилок вимірювань і вплив агентських невизначеностей. Запропоновані алгоритми машинного моделювання ймовірностей помилкового й невиявленого браку в умовах невизначеності стандартів контролю.

Практична значимість. Розроблені методики кількісної оцінки контролю ризиків і підвищення надійності передачі даних у системах VLC. Математичні й імітаційні моделі дозволяють на етапі проєктування більш точно враховувати вплив метрологічних та експлуатаційних факторів на якість функціонування оптичних каналів передачі даних. Алгоритми застосовні для оптимізації елементної бази, режимів експлуатації й моніторингу стану каналів. Результати актуальні для надійних бездротових мереж в умовах підвищених вимог до інформаційної безпеки й для критично важливих об'єктів.

Ключові слова: *системи VLC, процес, модель, ймовірність, ухвалення рішень, моделювання, закон розподілу*

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