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DETECTION AND MITIGATION OF AI-DRIVEN ATTACKS

Abstract. *The paper summarizes the current state of the problem of attacks leveraging generative and large language models (LLMs), including personalized phishing, social engineering through deepfake technologies, prompt injection, and automated malware generation. Key approaches to detection and harm mitigation are analyzed: hybrid detectors based on stylometry and transformer architectures, adversarial training incorporating LLM-generated samples, prompt sandboxing and filtering for LLM protection, as well as measures aimed at reducing human-factor vulnerabilities. Practical recommendations are provided for the phased implementation of technical and organizational countermeasures, and the limitations of existing solutions and future research directions are outlined.*

Keywords. *AI-driven attacks, generative AI, phishing, prompt injection, adversarial training, explainability.*

Introduction. Modern generative models provide high-quality text generation and enable fine-grained message personalization, making phishing and social engineering attacks more effective and scalable [3, 7]. At the same time, new threat vectors have emerged, including prompt injection and jailbreak attacks on large language models (LLMs), data poisoning, and latent attacks targeting generative systems [2, 9]. Existing detectors and security policies developed for “traditional” spam and phishing are insufficiently resilient to these threats; moreover, standardized methods for robustness evaluation and unified response practices are still lacking [6, 4].

Literature review and problem statement. Modern studies of AI-driven attacks propose a variety of approaches; however, their effectiveness and adaptability to new data remain limited. Classical statistical and ML-based methods (e.g., TF-IDF and traditional classifiers) as well as transformer-based models perform well on known datasets but struggle to handle texts generated by large language models (LLMs). The main challenges of these systems include a high false positive rate and susceptibility to evasion attacks [6].

Adversarial approaches improve model robustness by training on attack samples, yet malicious actors can continuously adapt generative systems, meaning that effective defense requires regular updates and inclusion of new examples [2, 9].

To protect LLMs from prompt injection and jailbreak attacks, sandboxing techniques, content filters, and ensemble models are employed. These measures reduce the risk of malicious prompts but do not ensure complete security and require further refinement [10].

The human factor is also crucial. Users tend to trust personalized AI-generated messages more, which necessitates implementing educational programs and user-facing risk indicators to decrease the success rate of phishing attacks [3, 1].

Special attention is paid to deepfake-related threats, as audio and video forgeries significantly complicate identity verification. This calls for the development of dedicated multimodal content detectors and enhanced methods for detecting synthetic media [5].

A detailed comparison of different AI-driven threats, their characteristics, and the limitations of existing countermeasures is presented in Table 1.

Table 1. Consolidated Threat Control and Mitigation Measures

Type of Threat	Key Characteristic	Existing Measures	Limitations / Comments
Personalized Phishing (LLM)	Realistic, highly personalized text	Stylometry, ML classifiers, user training [6, 3]	Detectors require retraining with LLM-generated samples; false positive rate (FPR) remains an issue
Prompt Injection / Jailbreak	Manipulation of LLM context	Sandboxing, content filters, ensemble models [10]	Partially effective; challenging to balance restrictions with LLM usability
Adversarial Poisoning	Compromise of training data integrity	Data validation, robust training [9]	Difficult to fully eliminate; requires strict data source control
Deepfake (Audio/Video)	Fabrication of visual or audio content	Deepfake detection algorithms [5]	Detectors co-evolve with deepfake tools, requiring continuous updates

Research methods. Within a multi-layered system protection framework, several stages are defined in accordance with current literature recommendations, encompassing both organizational and technical measures.

At the Prevention level (policies and education), user awareness training and verification procedures are implemented [3].

The Detection level (technical tools) involves a hybrid detector that combines stylometric analysis, a fine-tuned transformer model, and network metadata provenance analysis [6], along with regular updates of training datasets using LLM-generated examples through adversarial training [2].

The Response level (remediation) includes automated blocking, quarantining, or escalation to human review in cases of uncertain outcomes [1].

The Model Security level encompasses sandboxing, prompt filtering, context control during LLM usage, and anomaly monitoring in user queries [10]. The overall system protection workflow is illustrated schematically in Figure 1.

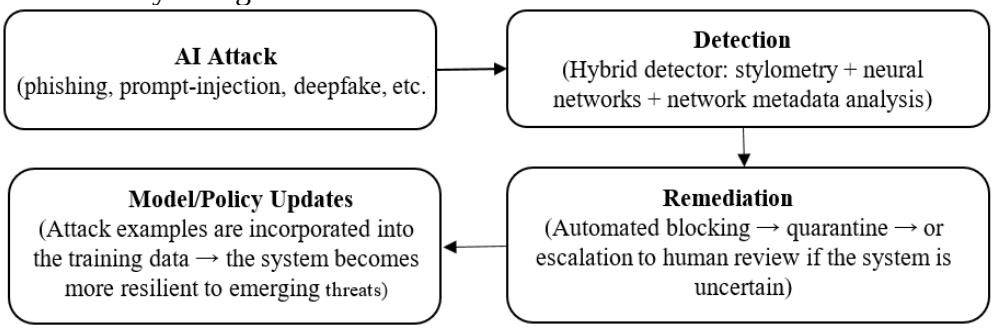

Fig.1. Multilayer Model for Countering AI-Driven Attacks

Discussion of Results. The analysis of results reveals several key aspects of defense against AI-driven attacks.

First, the dynamic nature of threats is significant: generative models and adversarial techniques evolve rapidly, while defense systems lag behind due to delays in updating data and model parameters [6].

Second, balancing utility and security remains a major challenge, as strict LLM restrictions - such as aggressive filtering - can reduce their usefulness in legitimate scenarios, leading organizations to hesitate between these competing priorities [10].

Third, the human factor plays a crucial role: although technologies can detect suspicious patterns, final decisions often depend on human judgment, and user education initiatives tend to change behavior slowly [3].

Finally, the lack of standards and benchmarks complicates the comparison of defensive solutions, as no unified tests or reproducible benchmarks currently exist for LLM-based phishing and other AI-driven attacks [4].

Among the concrete short-term steps that can be implemented immediately are the use of a hybrid detector combining stylometric analysis and a fine-tuned transformer model, with regular updates to the training dataset using LLM-generated examples [6, 8].

Additionally, configuring sandboxing and prompt filters for model interactions and restricting critical actions without additional verification are advisable [10].

The integration of explainability mechanisms, which provide concise justifications for blocking decisions to both operators and users, is also essential [1].

It is further recommended to develop internal benchmarks and test corpora for LLM-based phishing to support regular evaluation of defense effectiveness [8, 4].

Conclusions. Attacks based on generative artificial intelligence pose a significant challenge to information security: they combine technological power with exploitation of human vulnerabilities. A complete, definitive solution does not yet exist; however, a combination of technical mechanisms (hybrid detectors, adversarial training, and sandboxing for LLMs) and organizational measures (training, verification procedures, and internal benchmarks) can substantially reduce risk and markedly degrade attack effectiveness. Future research should focus on standardizing evaluation methodologies and creating reproducible experimental benchmarks.

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RESEARCH OF THE INERTIAL NAVIGATION SYSTEM

Abstract. *The purpose of this work is to study methods and algorithms for improving the accuracy of a strapdown inertial navigation system (SINS) by correcting it using an optoelectronic system for orientation and navigation (OESON). Although SINS are fully autonomous systems, their main disadvantage is the accumulation of errors in determining coordinates and orientation over time. This research focuses on analyzing SINS error models and the mathematical foundations of OESON operation, which are based on LiDAR survey and "machine vision" methods. An increase in the accuracy of the navigation complex is achieved by synthesizing a compensation scheme based on a Kalman filter (KF), which processes the difference in the output data of both systems.*

Key words: *strapdown inertial navigation system (SINS), optoelectronic system for orientation and navigation (OESON), correction, Kalman filter (KF), SINS errors, systems integration, LiDAR survey, machine vision.*

Introduction. Modern requirements for navigation systems demand high accuracy, reliability, and continuity in determining an object's motion parameters. Strapdown inertial navigation systems (SINS) are widely used due to their autonomy. However, their fundamental problem is the accumulation of errors over time, primarily caused by gyroscope drift and accelerometer zero-bias. This necessitates the integration of SINS with navigation systems based on non-inertial principles. While integration with satellite navigation systems (SNS) is common, SNS are vulnerable to interference and signal loss. Therefore, a relevant task is to study SINS correction methods using optoelectronic orientation and navigation systems (OESON), which do not exhibit temporal error accumulation. The goal of this work is to investigate and develop algorithms for such integration and to evaluate their effectiveness.

Methods and Materials. This paper analyzes the mathematical model of a SINS, which includes two main modes: initial alignment and navigation. The initial alignment process allows for the autonomous determination of the initial orientation angles (roll, pitch, yaw) using accelerometers and gyroscopes on a stationary base. The main operational mode consists of an orientation channel (integrating kinematic equations, e.g., Poisson's equations) and a navigation channel (double integration of measured accelerations) [3, 4]. The sources of SINS errors are analyzed in detail. It is shown that accelerometer zero-bias leads to a quadratic error in position determination, whereas gyroscope drift leads to a cubic dependence of the error on time [3]. The operating principles of OESON, based on "machine vision" technologies, are investigated. These systems determine position by comparing the current terrain image with a reference, which can be a digital elevation model (DEM). The LiDAR (Light Detection and Ranging) survey method is considered as a means of forming such reference 3D models [2]. A compensation scheme is used for SINS correction from OESON (Fig. 1).

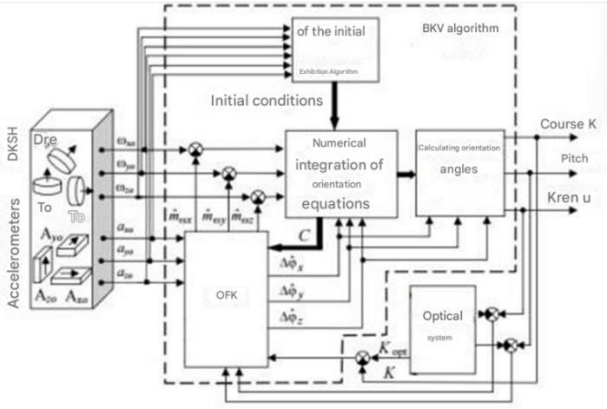

Fig. 1. Functional diagram of SINS and OESON integration

An integration algorithm based on the Kalman filter (KF) is synthesized [1, 2]. The SINS error model is represented in state-space form, and the data from OESON is used as the measurement vector [2]. The Kalman filter recursively estimates the SINS error vector [1], which is then subtracted from the system's current calculations, providing correction of the output navigation parameters. The effectiveness of the method is shown in Fig. 2.

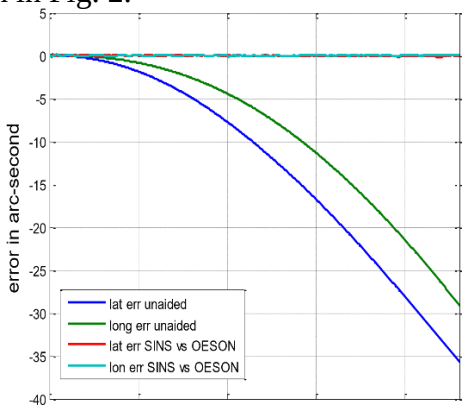

Fig. 2. Latitude and longitude errors
(blue/green – uncorrected, red/turquoise – corrected)

Conclusions. During the master's work, SINS models and their error sources were analyzed, and the principles of OESON construction were reviewed. An algorithm for SINS and OESON integration based on the Kalman filter was substantiated and synthesized. Simulation modeling was carried out in the MatLAB environment, which confirmed the correctness and effectiveness of the proposed algorithm. The simulation results (see Fig. 2) demonstrate that correction from OESON significantly reduces the accumulated errors of the SINS. Over a simulated period of 20-25 minutes, the object's position determination errors were reduced to 2–10 meters, velocity errors to 4 m/s, and orientation angle estimation errors did not exceed 180 arcseconds.

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FEATURES OF RESEARCH ON OZONE PROCESSES FOR ABSORPTION PURIFICATION OF GASES FROM NITROGEN OXIDES

Abstract. *The mechanisms of ozone decomposition in aqueous solutions are considered. It is proved that the mechanism proposed by G.S. Stolyarenko more realistically reflects the process under study. Based on this, studies were conducted on the absorption ozone-radical cleaning of gases from nitrogen oxides.*

Key words: *ozone, radicals, S.D. Razumovsky, G.S. Stolyarenko.*

Introduction. In recent years, in the study of many chemical processes, a large role has been given to oxygen-containing radicals $HO^{\bullet}$ and $HO_2^{\bullet}$. One of the common sources of oxygen-containing radicals is ozonated aqueous solutions. And this process is very common for absorption purification of gas streams, for example, from nitrogen oxides. The decomposition of ozone in aqueous environments has been studied for ninety years, and already in early works attempts were made to explain its kinetics and mechanism.

Theoretical part. For the first time, the radical mechanism of ozone decomposition in aqueous environments was proposed by D. Weiss in 1935. In this mechanism, D. Weiss first noted the existence of a superoxide radical in the $H_2O - O_3$ system, and showed the ion-radical mechanism of ozone decomposition and spontaneous interaction of radicals after their occurrence in solution. The main role in this is assigned to the radical $HO_2^{\bullet}$. In the mechanism proposed by E. Abel in 1955, the author tries to take into account all the intermediate complex compounds that are formed by this mechanism and are determined spectrally. In E. Abel's mechanism, the formation of an intermediate particle $O^{\bullet -}O^{\bullet}O^{\bullet}$ was first proposed, which is essentially an ion-ozonide radical $O_3^{\bullet -}$ with an electron localized on a certain oxygen atom. In 1972, Yu.I.Ivanov and his colleagues first analyzed from a thermodynamic standpoint the individual possible stages that initiate, carry, and terminate the chain.

S.D. Razumovsky proposed his mechanism for the decomposition of ozone in aqueous solutions:

$$O_3 + OH^- \rightarrow O_3^{\bullet -} + HO^{\bullet}, \quad (1)$$

$$O_3^{\bullet -} + H^+ \rightarrow HO_3^{\bullet}, \quad (2)$$

$$HO_3^{\bullet} \rightarrow HO^{\bullet} + O_2, \quad (3)$$

$$O_3 + HO^{\bullet} \rightarrow HO_2^{\bullet} + O_2, \quad (4)$$

$$HO^{\bullet} + OH^- \rightarrow O^- + H_2O, \quad (5)$$

$$O^- + O_3 \rightarrow O_2 + O_2^{\bullet -}, \quad (6)$$

$$O_2^{\bullet -} + O_3 \rightarrow O_2 + O_3^{\bullet -}, \quad (7)$$

$$2\,HO^{\bullet} \rightarrow \text{products}, \quad (8)$$

$$2\,HO_2^{\bullet} \rightarrow \text{products}, \quad (9)$$

$$HO_2^{\bullet} + HO^{\bullet} \rightarrow \text{products}. \quad (10)$$

In this mechanism, reaction (1), according to the author, is the limiting stage of the process of ozone decomposition in aqueous solutions. The author, analyzing the process of interaction of ozone with intermediate particles (reactions (4-10)), derived the dependence of the concentrations of these intermediate particles on the concentration of ozone and the pH of the solution.

A similar mechanism of ozone decomposition in jet streams of aqueous solutions was proposed by G.S. Stolyarenko:

$$O_3+OH^- \rightarrow O_3^{\bullet -} + HO^{\bullet}, \quad (11)$$

$$O_3+OH^- \rightarrow O_2^{\bullet -} + HO_2^{\bullet}, \quad (12)$$

$$O_2^{\bullet -} + H_2O \rightarrow HO_2^{\bullet} + OH^-, \quad (13)$$

$$O_3^{\bullet -} + H_2O \rightarrow HO^{\bullet} + OH^- + O_2, \quad (14)$$

$$O_3+HO_2^{\bullet} \rightarrow HO^{\bullet} + 2\,O_2, \quad (15)$$

$$O_3+HO^{\bullet} \rightarrow HO_2^{\bullet} + O_2, \quad (16)$$

$$HO_2^{\bullet} + HO^{\bullet} \rightarrow H_2O+O_2. \quad (17)$$

According to the author, reactions (14) and (15) proceed in parallel, which leads to the simultaneous synthesis of $O_3^{\bullet -}$, $O_2^{\bullet -}$, $HO^{\bullet}$, $HO_2^{\bullet}$. When the pH increases, the rate of reaction (15) with increasing pH increases faster than the rate of reaction (16), and the primary acts of interaction of ozone and hydroxyl ion shift to the region of synthesis of the radical ion $O_3^{\bullet -}$.

As we can see, these mechanisms differ significantly from each other. Some mechanisms even take into account different conditions of implementation. Thus, the mechanism of S.D. Razumovsky describes the decomposition of ozone in stationary environments. Which is not possible during absorption. Then the mechanism of G.S. Stolyarenko, on the contrary, investigated the process of decomposition of ozone in moving flows, namely during absorption by ozonized solutions of nitrogen oxides. But the mechanism itself, due to the rather short existence time of oxygen-containing radicals and other compounds (it is thousandths of a second), was not confirmed experimentally. Therefore, to confirm this mechanism, studies were conducted on the suppression of the formation of nitrogen oxides during the combustion of gaseous fuel. Two mechanisms were compared. This is the mechanism of S.D. Razumovsky and the mechanism of G.S. Stolyarenko. Since they most fully reflect the processes under study. Mathematical models were developed and solved that describe the suppression of the formation of nitrogen oxides during the combustion of gaseous fuel. As a result of the study, it was proven that the G.S. Stolyarenko mechanism more accurately and completely describes the process of ozone destruction in some solutions. And therefore, it can be used for further research into the processes of absorption purification of gas streams.

Research results. The studies were conducted on a laboratory installation, which consisted of a unit for obtaining an ozone-air mixture, a unit for absorbing ozone with water and a unit for cleaning gas from nitrogen oxides. The concentration of nitrogen oxides in the simulated gas was maintained within the following limits: nitrogen oxide (II) from 16 to 60 ppm, nitrogen oxide (IV) from 2 to 15 ppm. The concentration of ozone in the liquid phase was approximately 0.0002±0.000005 mol/dm^3.

Fig. 1 and table 1 show the average results of several series of studies on cleaning gases from nitrogen oxides. It should be noted that these concentrations are minimal for real flue gases.

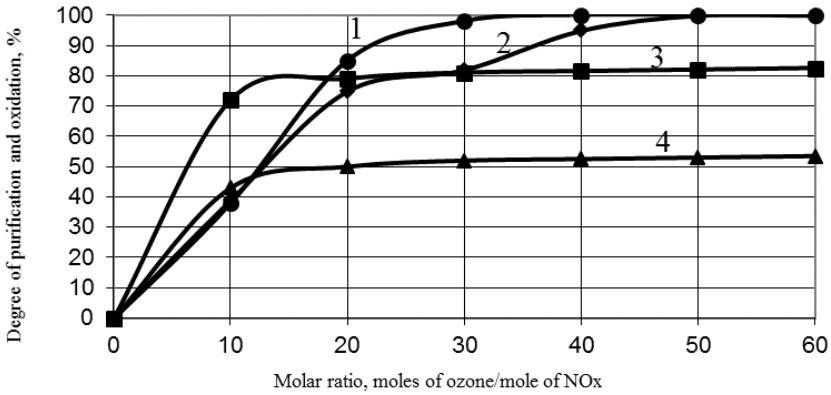

Fig. 1. Dependence of the degree of purification and oxidation on the molar ratio:
1 – pH=9 – purification; 2 – pH=9 – oxidation; 3 – pH=2.5 – purification; 4 – pH=2.5 - oxidation

However, as the concentration of nitrogen oxides increases, the studies have shown that the degree of gas cleaning increases to 90-92% with a sufficient amount of ozone in the liquid phase. Thus, the selected concentrations of nitrogen oxides can be considered limiting for this method.

Table 1. Results of studies on the purification of gases from nitrogen oxides

Experiment time, s	Volume of the cube, cm^3	pH	NO concentration at the inlet, ppm	NO_2 concentration at the inlet, ppm	NO concentration at the outlet, ppm	NO_2 concentration at the outlet, ppm	Degree of purification from NO, %	Degree of purification from NO_2, %	Total degree of purification, %
255	570	6,7	27,52	7,6	16,7	0,43	39,31	94,34	51,22
240	500	11,19	27,52	7,68	16,68	1,18	39,38	84,47	49,15
120	240	11,34	27,52	7,6	11,3	1,67	58,93	78,02	63,07
180	200	6,7	16,9	2,43	11,79	7,01	30,41	58,43	33,94
265	310	11,27	16,9	2,43	11,03	0,68	34,731	72,01	39,42
160	180	11,34	16,9	2,43	9,03	0,39	46,56	83,95	51,27
285	500	11,25	29,999	10,25	22,7	1,64	24,30	84	39,51
150	255	11,34	29,99	10,25	25,11	2,33	16,27	77,26	31,81
265	270	6,7	58,6	14,86	34,85	7,9	40,52	93,74	51,29
245	230	10,74	58,6	14,86	31,06	6,2	46,99	58,27	49,28
185	150	11,34	58,6	14,86	40,04	13,14	30,13	11,57	26,38

As can be seen from table 1, the pH of the solution significantly affects the degree of gas purification from nitrogen oxide. Thus, at a pH value of 6.7 (distilled water without the addition of alkali), the degree of purification from nitrogen oxide (II) is very small and is approximately 40%, which is achieved by further oxidation of nitrogen oxide (II) with the remaining ozone and its dissolution in water. Analyzing the dependence of gas purification from nitrogen oxides on the molar ratio O_3/NO (Fig. 1), it is seen that the highest degree of purification is achieved at molar ratios within 20-30 at a pH value of 9. At other pH values and molar ratios, the degree of purification is much lower.

Conclusions. There are many mechanisms for the decomposition of ozone in aqueous solutions. In all of them, radicals $HO^{\bullet}$ and $HO_2^{\bullet}$ are present, but in each mechanism a different role is assigned. In all radicals $HO^{\bullet}$ and $HO_2^{\bullet}$ are present, but each mechanism plays a different role. The mechanism of G.S. Stolyarenko more accurately and completely describes the process of ozone destruction in some solutions. And therefore it can be used for further research into the processes of absorption purification of gas streams; the greatest purification of gases from nitrogen oxides during the experiments was observed at pH=11.67, and the least at pH=6.7 (distilled water).

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AUTOMATIC PUMP SPEED CONTROL SYSTEM FOR ACCURATE AND SAFE LIQUID FILLING

Abstract. *This work presents an automatic pump speed control system designed for precise and safe liquid filling in industrial processes. The main goal is to ensure high dosing accuracy (±0.5 %), stable flow, and minimal foam formation and oxygen saturation of the product. The system monitors product quantity using Coriolis flow meters or inductive flow meters, allowing adaptive pump operation depending on liquid characteristics and process conditions.*

Key words: *automation, pump, liquid filling, speed control, Coriolis flow meter, inductive flow meter, dosing accuracy, industrial automation.*

Introduction. Modern food, chemical, and pharmaceutical production requires high accuracy and quality in technological processes. One of the critical stages is liquid filling, which must be performed without product loss, foam formation, or quality degradation.

Conventional fixed-speed pumping systems often fail to account for changes in viscosity, temperature, or tank level, leading to flow fluctuations, product loss, and increased foam formation.

The relevance of this study lies in implementing intelligent solutions for adaptive pump speed control in real time, ensuring stable and precise filling under varying process conditions.

Objectives. The purpose of this work is to develop an automatic pump speed control system to achieve the most efficient and high-quality liquid filling.

Research tasks:

- analyze existing pump speed control methods in industrial processes;
- develop an adaptive speed control algorithm to minimize foam formation;
- implement real-time flow monitoring using Coriolis or inductive flow meters;
- improve system energy efficiency and reduce product losses;
- ensure high dosing accuracy (±0.5 %) for various liquids.

Methods and System Structure. The automatic control system consists of the following main components:

1. Coriolis or inductive flow meters for precise flow measurement, providing high accuracy under varying process conditions.
2. Level sensors (ultrasonic or capacitive) to monitor tank filling and safely terminate the filling cycle.
3. Controller with an adaptive PID pump speed regulator to adjust pump operation in real time.
4. Variable frequency drive (VFD) for smooth pump speed adjustment, preventing hydraulic shocks and foam formation.
5. Operator interface (HMI) for process monitoring, displaying flow, tank level, and pump speed, and allowing parameter configuration.

The system not only maintains stable flow but also adapts pump speed based on actual process conditions, which is particularly important for liquids of varying viscosity, temperature, or changing tank levels.

Pump Speed Control Algorithm. The system algorithm is based on comparing the actual flow with the setpoint value from the HMI, followed by adaptive pump speed adjustment considering real flow and operating conditions.

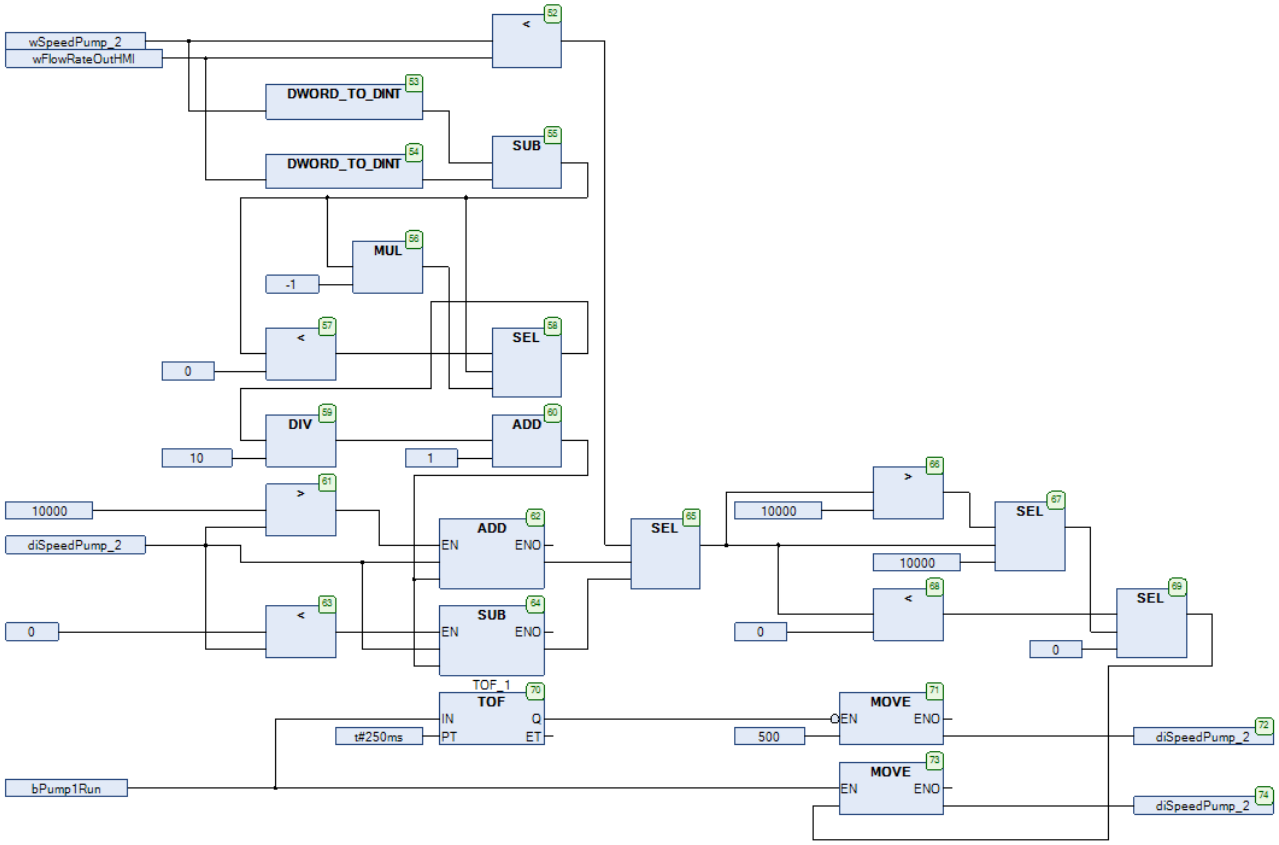

Fig. 1. Logic of the automatic pump speed control system

The diagram should illustrate the main algorithm steps: flow difference calculation, scaling, new speed formation, speed limits, startup speed, and smooth deceleration when the pump is turned off.

Conclusions. The developed automatic pump speed control system ensures precise and safe liquid filling. Product quantity is controlled via Coriolis or inductive flow meters, enhancing process reliability. Adaptive pump speed regulation minimizes foam formation and oxygen saturation. Smooth pump speed control maintains process stability under variable conditions. The proposed approach can serve as a basis for further development of intelligent liquid filling systems.

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ANALYSIS OF DOMINANT FACTORS AND PHYSICAL MECHANISMS OF INTERLAYER ADHESION IN FDM 3D PRINTING

Abstract. *The purpose of this work is to analyze and systematize the key technological parameters that determine the quality of interlayer adhesion in Fused Deposition Modeling (FDM/FFF). This is stipulated by the fact that the bond strength between layers is a critical factor directly impacting the mechanical properties, anisotropy, and durability of the finished products. The study, based on a review of existing works focuses on the physical mechanisms of sintering and polymer chain diffusion at the contact interface. The influence of key parameters is analyzed: layer height and environment temperature, which are identified as the main drivers of mechanical properties. The influence of nozzle temperature and print speed on the overall thermal history and the time available for bond formation is also discussed in detail.*

Key words: *3D printing, FDM, FFF, interlayer adhesion, sintering, mechanical properties, layer height, environment temperature, nozzle temperature, anisotropy.*

Introduction. The technology of additive manufacturing by fused deposition modeling (FDM) remains limited due to significant anisotropy of mechanical properties. Parts printed by this method exhibit much lower strength in the Z-axis direction (perpendicular to the layers) compared to the X and Y directions. This phenomenon is directly related to insufficient bonding strength (adhesion) between successive layers. The physical basis of this bond is the process of sintering and mutual diffusion of polymer chains, which can only occur when the interface between the layers is above the glass transition temperature (Tg) for a sufficient time. Controlling this process through printing parameters is a relevant task for obtaining functional products.

Methods and Materials. The analysis uses a theoretical model describing heat transfer and the sintering process at the layer contact interface. The bond strength (degree of sintering) is a function of the thermal history (temperature and time). It has been determined that printing parameters control this thermal history.

The structural diagram in Fig. 1 illustrates the cause-and-effect chain of the process. The input technological parameters, selected by the operator, directly determine the physical conditions in the contact zone. These conditions (thermal history and time) enable the physical processes of sintering and diffusion, which form the bond microstructure. The quality of this microstructure (contact area, absence of pores) directly determines the final mechanical property – interlayer adhesion.

According to current scientific data, the studied parameters are hierarchically divided into:

1. Dominant Factors:

Layer Height: Identified as one of the main drivers of mechanical properties. A smaller layer height (e.g., 0.1-0.2 mm) ensures better heat transfer from the new layer to the previous one, heating it more deeply. This also increases the contact pressure during extrusion, improving wetting and initial bonding. Studies show that reducing the layer height from 0.4 mm to 0.2 mm can increase strength by 12% or more.

Environment Temperature: The second key driver. Printing in an enclosed, heated chamber maintains the part's temperature above or near Tg. This radically reduces the cooling rate, relieves internal stresses from thermal shrinkage, and gives the layers significantly more time for full diffusion and sintering.

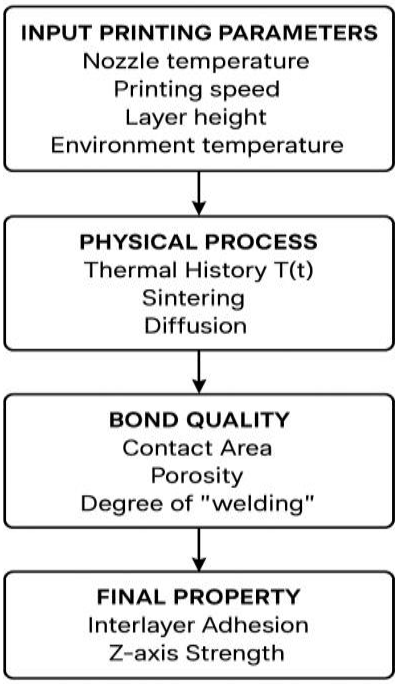

Fig. 1. Simplified structural diagram of interlayer adhesion formation

2. Critical Control Parameters:

Nozzle Temperature: Determines the initial thermal energy introduced into the system. A higher temperature (within limits that do not cause material degradation) activates diffusion processes. Increasing the nozzle temperature (e.g., for PLA from 200°C to 220°C) can improve strength by 10%.

Print Speed (Feed Rate): Inversely related to contact time. A lower print speed (e.g., 40 mm/s instead of 60 mm/s) increases the time during which the hot nozzle and extruded material transfer heat to the previous layer, which positively affects adhesion.

3. Secondary Factors:

Cooling (Part Fan): Excessive cooling acts contrary to a heated chamber – it rapidly cools the layer, stopping the diffusion process.

Filament Moisture: The presence of moisture leads to the formation of pores at the layer interface, which reduces the effective contact area and strength.

Conclusions. It has been established that controlling only the nozzle temperature is insufficient to achieve maximum interlayer adhesion. The dominant factors controlling the final mechanical properties of FDM-produced parts are layer height and environment temperature, as they directly determine the thermal conditions and the degree of sintering between layers. The physical basis of a strong bond is this sintering process, which requires sufficient time and maintaining a temperature above the material's glass transition temperature (Tg). Therefore, the optimal strategy for maximizing adhesion is to use the minimum possible layer height in combination with the maximum possible environment temperature, ideally utilizing a heated chamber.

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COMPARATIVE ANALYSIS OF CLASSICAL AND QUANTUM ENCRYPTION METHODS FOR SECURE MILITARY COMMUNICATIONS

Abstract. *This paper provides a structured comparison of classical cryptosystems (symmetric and public-key), post-quantum cryptography (PQC), and quantum key distribution (QKD) with respect to their suitability for secure military communications. We analyze threat models (classical supercomputer vs. quantum-capable adversary), secrecy properties, channel requirements (fiber-optic and free-space optics), and the impact on latency, throughput, and key-lifecycle management. We show that AES-256 in authenticated modes remains the foundation for bulk traffic, while public-key schemes based on factorization/discrete logarithms require migration to PQC standards. QKD delivers physics-grounded key establishment for critical routes but requires specialized infrastructure and careful integration with key management systems (KMS). We propose a phased hybrid architecture (QKD+PQC+AES) and outline a deployment roadmap for Ukraine's security and defense sector.*

Keywords: *military communications, quantum key distribution, post-quantum cryptography, AES-256-GCM, ML-KEM, ML-DSA, SLH-DSA, MACsec/IPsec, fiber-optic and FSO links.*

Introduction and Motivation. Resilience of secure communications amid long-term warfare and increasingly sophisticated cyber operations is a national priority. Classical symmetric ciphers (AES) provide high-throughput confidentiality, while public-key schemes (RSA/ECC) support key establishment and digital signatures. Large-scale quantum computing undermines trust in many public-key algorithms (Shor's algorithm) and moderately affects symmetric ciphers (Grover's algorithm), which can be countered by parameter increases. Two complementary lines of response are emerging: post-quantum cryptography (PQC) – standardized, quantum-resistant algorithms deployable without changing the physical medium [2]; and quantum key distribution (QKD) – a physical-layer method for establishing keys with security guaranteed by quantum mechanics [3].

Objective. To justify the cryptographic choices for military communications by comparing classical, post-quantum, and quantum approaches and proposing a viable model for their combined use55.

Methodology and Comparison Criteria. We evaluate along: (i) security model (classical/quantum adversary, forward/backward secrecy, resistance to "record-now-decrypt-later"), (ii) key establishment mechanisms and refresh rates, (iii) latency/throughput and hardware acceleration, (iv) channel requirements and delivery reliability (BER, atmospheric effects for FSO), (v) compatibility with existing MACsec/IPsec and KMS, (vi) CAPEX/OPEX and lifecycle assurance, (vii) alignment with standards and security policies.

Technical Overview.

1. Symmetric cryptography. AES-256-GCM/CTR as the baseline for bulk data encryption; low latency, broad hardware support, and manageable "quantum overhead" via parameter scaling.

2. Public-key / post-quantum cryptography. Traditional RSA/ECC are vulnerable to Shor's algorithm; migration to standardized PQC KEMs/signatures (e.g., ML-KEM, ML-DSA, SLH-DSA) is recommended. Their advantages include software compatibility and scalability across existing networks [2, 3].

3. Quantum key distribution (QKD) Protocols BB84/E91/MDI-QKD; channels include optical fiber and free-space/satellite; required components are single-photon sources/detectors, QRNG, synchronization, and error-correction/privacy-amplification stacks [3]. QKD feeds fresh key material into the KMS for use by symmetric protocols (IPsec/MACsec/one-time pad on critical routes).

Comparative Analysis

Table 1. Comparative analysis of cryptographic approaches for military communications

Criterion	AES-256 (symmetric)	RSA/ECC (classical PK)	PQC (ML-KEM / ML-DSA / SLH-DSA)	QKD
Security basis	Computational hardness; Grover mitigated via larger parameters.	Computational hardness; vulnerable to Shor's algorithm.	New hardness assumptions (lattices / hashes) designed to resist quantum attacks.	Laws of quantum physics (no-cloning, measurement disturbance).
Role in system	Bulk encryption + authentication.	Key exchange/signatures (legacy paradigm).	Key exchange/signatures (soft-rollout migration).	Supplies keys to KMS/OTP.
Performance	Very high; low latency.	Moderate/high with acceleration.	Better than RSA at comparable security; larger keys/sigs.	Channel-limited; key rates are distance-/loss-limited.
Infrastructure	Existing.	Existing.	Existing (SW/FPGA/NIC updates).	Quantum modules, fiber/FSO, trusted nodes required.
Best use	Any links and storage.	Legacy/transition.	Broad interagency use.	Highest-value corridors (HQ↔DC, government backbone).

Note: "PQC standards used: FIPS 203/204/205; QKD profiles/interfaces: ITU-T Y.3800 series, ETSI GS QKD. [2] Threat model includes harvest-now-decrypt-later; QKD keys consumed by MACsec/IPsec via KMS [3]."

Regulatory and Standards Context (Ukraine/International).

• National cybersecurity policy and requirements for cryptographic protection in the public sector; current orders and message-format requirements for cryptographic tools.

• National encryption standards (including the Ukrainian block cipher "Kalyna"), algorithm identifiers, integration with trust services.

• International standards: profiles and interfaces for QKD networks (ETSI/ITU-T); PQC standards (FIPS) for KEM and signatures [2, 3]. *Note.* QKD deployment must be aligned with existing KMS (REST key delivery, key-lifecycle policies, audit).

Architecture and Roadmap for Ukraine's Security and Defense Sector.

1. Architectural principles. Trust-domain segmentation; attack-surface minimization; separation of quantum and classical channels. QKD-KMS integration with MACsec/IPsec (fresh key delivery, accounting, rotation). PQC for all interagency transits and signatures, with protocol compatibility.

2. Roadmap (phases). 1) PQC migration—transition to ML-KEM/ML-DSA/SLH-DSA and upgrade of cryptomodules and certification chains; 2) QKD pilot—link between two strategic facilities (dark fiber with FSO backup) integrated with departmental KMS; 3) Trusted-node network—backbone scaling and key-lifecycle policy alignment; 4) Expansion—evaluate satellite segments and ensure multi-vendor interoperability via open profiles.

Practical Significance and Novelty. We propose a unified model for cryptographic transformation of defense networks that combines the strengths of QKD and PQC while remaining deployable on existing infrastructure. The novelty lies in an applied focus on key lifecycle, integration interfaces, and phased implementation aligned with Ukraine's regulatory environment.

Conclusions. In the course of this work, classical (AES/RSA/ECC), post-quantum (ML-KEM/ML-DSA/SLH-DSA), and quantum (QKD) approaches for defense-grade communications were assessed. We conclude that AES-256 (authenticated modes) is optimal for bulk traffic, public-

key functions should migrate to standardized PQC, and QKD should be applied selectively on the most sensitive fixed routes to supply physics-grounded keys. The roadmap is: PQC migration across PKI/gateways → a dark-fiber QKD pilot with KMS integration and FSO backup → expansion to a trusted-node backbone with strict key-lifecycle governance. This hybrid posture strengthens forward secrecy, lowers record-now-decrypt-later risk, and scales on existing MACsec/IPsec networks.

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DEVELOPMENT OF A RISK ASSESSMENT SYSTEM AND METHODS FOR MINIMIZING THE IMPACT OF CYBER THREATS IN A REMOTE OFFICE

Abstract. *The study examines the issue of ensuring cybersecurity for organizations operating in remote or hybrid formats. Modern cyber threats typical for remote environments are analyzed, including credential compromise risks, phishing, malware, and unauthorized access to corporate resources. An algorithm for building a risk assessment system and selecting methods to minimize the impact of cyber threats is proposed. The developed methodology is based on a systematic approach to risk management and takes into account international standards such as ISO/IEC 27005, NIST SP 800-30, and GDPR. The economic feasibility of implementing a set of protective measures has been substantiated.*

Key words: risk assessment, cyber threats, remote work, data security, Python, economic efficiency.

Introduction. The remote work format, which has become widespread after 2020, creates new challenges for the information security of enterprises. The use of personal devices, connections through public Wi-Fi networks, and the application of cloud services without proper protection increase the likelihood of attacks such as phishing, man-in-the-middle, ransomware, or data leakage. According to the ENISA Threat Landscape 2024, over 60% of incidents in remote environments are related to human factors or vulnerable access channels [1].

In this regard, there is a need to create a comprehensive system for risk assessment and minimization of cyber threat impact, which will allow organizations to reduce financial, reputational, and operational losses.

The aim of the work is to develop a risk assessment system and to build a strategy for minimizing the impact of cyber threats for organizations operating remotely.

Objectives of the study:

- Analyze key information security threats during remote work.
- Classify risks and develop a combined assessment model (qualitative and quantitative).
- Implement a risk assessment algorithm and develop a mitigation strategy.
- Perform practical calculations using Python to construct a risk matrix.
- Assess the economic feasibility of implementing cybersecurity measures.

The developed system is based on a systematic approach to risk management and includes five main stages (Fig. 1):

1. Asset identification – determining the objects that require protection.
2. Threat and vulnerability detection – analyzing technical, organizational, and human factors.
3. Risk assessment ($R = P \times I$), where P is the probability of a threat and I is the potential loss [3].
4. Development and selection of security measures – both technical (MFA, VPN, SIEM, IDS/IPS) and organizational (staff training, access policies).

Monitoring and re-evaluation of risks – continuous improvement of the system [2].

Qualitative and quantitative methods were used to assess the level of risk, which made it possible to construct an impact matrix (Fig. 2) [6].

To automate the process, a Python script was developed to calculate the risk level according to specified criteria and visualize the results in the form of tables and graphs.

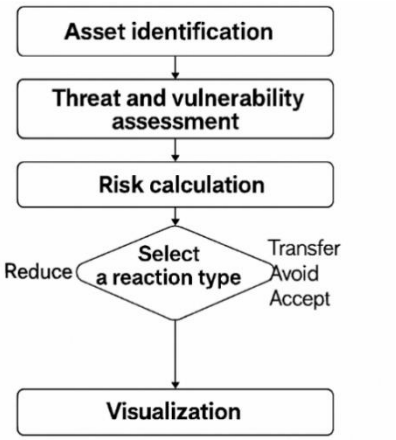

Fig. 1. Algorithm for building a confidential data protection system

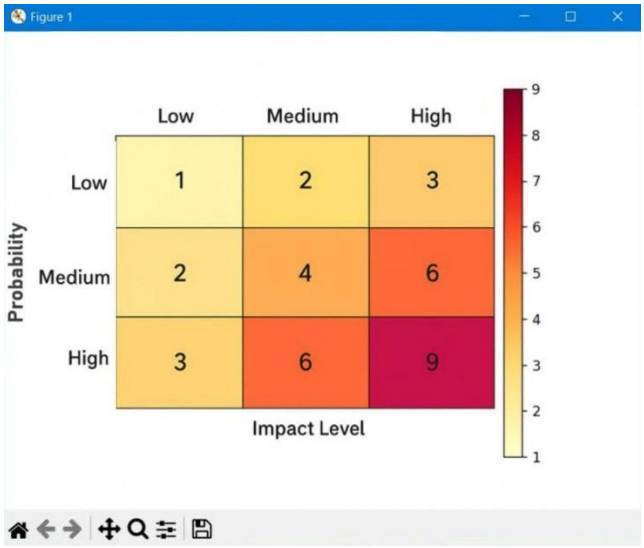

Fig. 2. Risk matrix

The practical implementation was carried out using the example of InfoService LLC, a company that operates entirely in a remote format. The calculations showed that after implementing a set of measures — including a VPN with two-factor authentication, network segmentation, regular updates, SIEM monitoring, and employee training — the overall risk level decreased by more than 60% [4].

According to the economic analysis, the implementation costs amounted to approximately 150,000 UAH, while potential losses from incidents could exceed 600,000 UAH. The payback period of cybersecurity investments is about 8 months, which is confirmed by the results presented in (Fig. 3) [5].

In addition, an analysis of the benefits of system implementation was conducted, as shown in (Fig. 4).

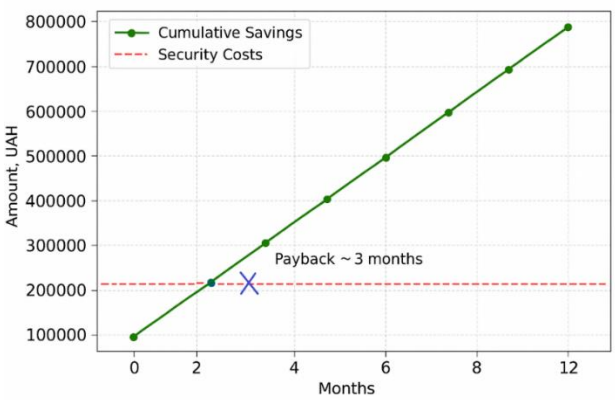

Fig. 3. Dynamics of investment payback in security measures

Fig. 4. Implementation benefits

The results demonstrate that the introduction of the proposed system has increased the company's cyber resilience, optimized information security expenditures, and improved the efficiency of business processes.

Conclusions. Thus, a risk assessment system was developed, and methods for minimizing the impact of cyber threats on a remote office were identified. An algorithm for building a protection strategy was proposed, allowing for the identification of assets, assessment of risk levels, and selection of effective security measures. The practical results confirmed the system's effectiveness: a 60% reduction in the overall risk level and a threefold decrease in potential financial losses. The developed methodology can be applied in small and medium-sized enterprises to enhance cybersecurity resilience in hybrid work environments.

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DEVELOPMENT OF A COMPUTER PROGRAM FOR MODELING THE ELECTRICAL IMPEDANCE OF A PIEZOELECTRIC CERAMIC TRANSFORMER

Abstract. *Nowadays, piezoelectric ceramic transformers are widely used in electronic devices due to their simplicity of manufacture, availability, low cost, and high throughput. To create them, complex mathematical models are developed to help reduce the time needed to determine parameters, materials, and costs during production. One of the main areas of focus in the creation and solution of modeling models is the use of software. The paper describes the features of a piezoceramic transformer and considers the main functions and an example of the software for calculating the electrical impedance of a piezoelectric ceramic transformer.*

Key words: *piezoelectric impedance, computer program, piezoelectric ceramic transformer.*

Introduction. More and more portable electronic devices are becoming miniature and lightweight, leading to the widespread use of piezoelectric elements. One of these many elements is the piezoelectric ceramic transformer, a device for transmitting electrical energy that was created in the 1950s [1].

The main purpose of a piezoelectric transformer is to convert energy using electromechanical coupling between adjacent piezoelectric actuators, sensors, and transducers. Piezoelectric transformers have such useful properties as compactness, absence of electromagnetic fields, and controllable voltage relative to frequency and resistance.

Due to their exceptional characteristics, piezoelectric transformers have been actively developed and used in many industries over the past decades, such as electronic ballasts for fluorescent light sources and DC converters.

Limited technical capabilities, such as production, research, and development of piezoceramic transformers, are at a low level of research and development. Most scientists are engaged in the development and research of new piezoelectric materials, gain coefficient, output power, efficiency under temperature load, and dimensions of PZT-type piezoceramic elements. Therefore, PZT is the main material used to manufacture piezoelectric transformers [2, 3].

Piezoelectric transformers are increasingly replacing magnetic transformers because they have certain advantages over their magnetic counterparts. One of the advantages is the absence of electromagnetic interference, since piezoelectric elements do not have the properties of magnetic energy transfer. They can also provide a high voltage gain. In addition, they do not require copper windings, which saves on design and size, especially when there is a significant voltage difference.

Modeling is the analysis of the capabilities and characteristics of research objects. An accurate model of a piezoelectric transformer is the basis for controlling and optimizing electromechanical processes. Nowadays, software is the basis for modeling research objects.

Modern programs cover various areas, helping to create new approaches to solving problems in modeling. Each computer program consists of complex software components, databases, and functions that are interconnected.

Creating such programs requires the use of complex programming languages and precise algorithms that are interconnected.

The **goal** of this work is to develop software for calculating the electrical impedance of a piezoceramic transformer that will meet user needs and business objectives as an effective, reproducible, and safe solution.

This software is developed using the Python programming language. This choice of programming language is due to its ease of learning, flexibility of settings, support for code

integration from different languages, and a large number of different library ecosystems, which simplifies the development of complex programs.

Currently, the program implements the ability to calculate electrical impedance for various shapes of PZT-type piezoceramic elements (Fig. 1).

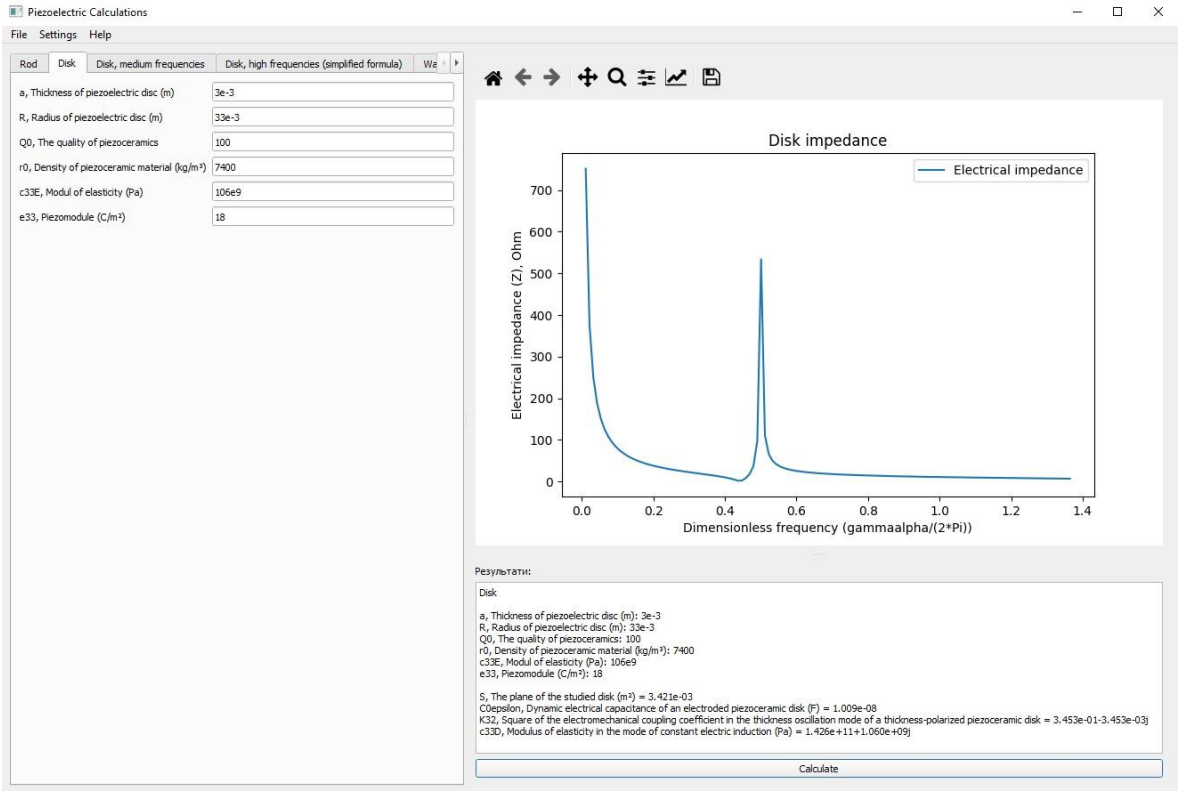

Fig. 1. Program for calculating the electrical impedance of a piezoelectric ceramic transformer

In the upper left working area, select the desired shape of the piezoceramic element (rod, disc, cylinder, washer, sphere, cylindrical shell). After selecting the shape of the test object, you will be prompted to enter the input data for calculation. The results are obtained using the “Result” command button in the lower right working area. The graph is displayed in the upper right part, where you can use the command buttons to customize the graph (axis step, graph scale, style and color of graph lines, marking points on the graph, saving the graph). The results of the selected piezoceramic element shape, the entered data, and the calculation results are displayed below the graph.

The program supports multiple languages (English, Ukrainian), theme selection (light, dark), as well as the ability to save the graph using the “Save graph” command button in ‘Png’ format and save the results and graph using the “Save to PDF” command button in “Pdf” format.

Conclusions. Thus, the paper analyzes, studies, and proves the importance of using piezoelectric ceramic transformers. The main aspects of software development are considered. For example, the calculation of the electrical impedance of a PZT-type disc-shaped piezoceramic transformer using a calculation program for piezoceramic elements is demonstrated, and the main features of this program are described, such as the selection of the shape of the object under study, changing the language and theme, and graph settings.

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DEVELOPMENT AND RESEARCH OF ENERGY INSTALLATIONS FOR SENSOR NETWORKS

Abstract. *The purpose of this work is to develop the technological principles for creating an energy harvesting unit based on renewable energy sources (solar and wind) to power low-power wireless sensors for explosive and toxic gases operating within wireless sensor networks (WSNs). The relevance of the task is driven by the limited battery life in wireless sensors, especially when monitoring flammable gases which consume significant energy, and the difficulty of replacing power elements in large networks or hard-to-reach locations. The research focuses on analyzing the energy consumption of wireless sensor components, studying the potential of various renewable energy sources, developing a hybrid energy harvesting and storage system (wind + solar) using supercapacitors and a backup lithium element. Efficiency is enhanced by developing power management algorithms, including a Maximum Power Point Tracking (MPPT) algorithm for the solar panel.*

Key words: *wireless sensor network (WSN), gas sensor, renewable energy sources, energy harvesting, solar energy, wind energy, supercapacitor, lithium element, DC/DC converter, MPPT.*

Introduction. Air quality control, particularly the concentration of flammable, toxic, and explosive gases, is an important task. Wireless sensor networks (WSNs) offer an effective solution for monitoring large areas. However, unlike wired systems, the operating time of wireless sensors is limited by battery capacity, which is especially critical for energy-intensive flammable gas sensors. Replacing batteries in large WSNs, especially in adverse conditions (e.g., oil and gas complexes), is labor-intensive. Therefore, ensuring stable autonomous power supply is a relevant task. One promising solution is powering sensors from renewable energy sources, such as sunlight and wind. The goal of this work is to develop the principles for creating an energy harvesting unit based on renewable energy sources to power wireless gas sensors.

Methods and Materials. An analysis of the energy consumption of the main components of a wireless gas sensor was conducted: the sensor, microcontroller (MCU), and transceiver. It was established that catalytic, semiconductor, and infrared gas sensors consume the most energy, while electrochemical sensors are the most energy-efficient. The autonomous operating time of typical CO and CH4 sensors powered by batteries of various capacities was calculated.

Various types of renewable energy sources (solar, wind, vibration, thermoelectric, etc.) and their power densities were analyzed. Solar and wind energy were identified as the most powerful and suitable for powering gas sensors.

A concept for a hybrid energy harvesting unit was developed, accumulating energy from a solar panel and a wind generator (Fig. 1). The system includes two independent energy harvesting channels, each charging its own supercapacitor (400 F, 2.7 V). Supercapacitors were chosen due to their ability to withstand a large number of charge-discharge cycles (over 5 10^4). A primary lithium element (3.6-3.7 V) is used as a backup power source, offering long service life and low self-discharge.

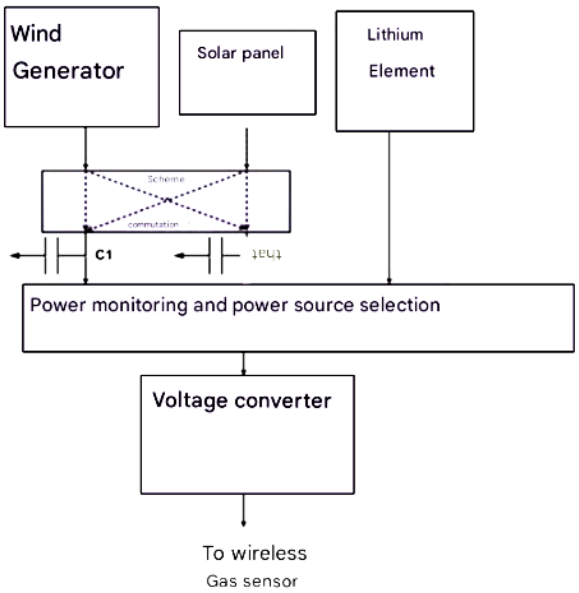

Fig. 1. Block diagram of the energy harvesting unit

A microcontroller is used to manage the charging processes and power source selection. Algorithms have been developed that monitor the voltage on the supercapacitors and the lithium element and switch the sensor's power source. Priority is given to the supercapacitor with the higher voltage (if it exceeds the minimum permissible level, experimentally determined as 0.9 V), and the lithium element is used only when the energy in the supercapacitors is insufficient. Cross-charging capability is implemented: if one supercapacitor is fully charged and the other is not, the source with higher power can charge both capacitors.

To optimize solar energy harvesting, a Maximum Power Point Tracking (MPPT) algorithm was developed, which adjusts the discharge time of the DC/DC converter's inductor to maximize the solar panel's output power. To convert the voltage from sources and storage elements to the level required by the sensor (1.8-5.5 V), various types of DC/DC converters were analyzed, and the TPS61200 boost converter was selected due to its ability to operate with low input voltages (from 0.3 V) and high efficiency. A prototype energy harvesting unit was developed as a printed circuit board. Experimental studies were conducted with a wind generator using different blade configurations and a solar panel to determine the charging time of the supercapacitors. The autonomous operation of carbon monoxide (electrochemical NAP-505) and methane (catalytic DTK-2) sensors powered by the developed energy harvesting unit was also investigated, using power-saving algorithms (periodic measurement mode).

Conclusions. A highly efficient energy harvesting unit for powering wireless gas sensors has been developed, utilizing hybrid energy storage from sun and wind in supercapacitors with backup from a lithium element. The proposed power management and solar energy harvesting optimization (MPPT) algorithms enhance the system's efficiency and reliability. The charging characteristics of supercapacitors from wind and sun were experimentally determined. The autonomous operation of CO and CH4 sensors was investigated: the operating time from a fully charged supercapacitor (400 F) is approximately 240 hours for the CO sensor and 28 hours for the CH4 sensor. The difference from theoretical calculations is explained by the self-discharge of supercapacitors and losses in the DC/DC converter, especially at low input voltages. The developed energy harvesting unit demonstrates potential for significantly extending the autonomous operation time of WSNs, particularly in the oil and gas industry.

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RESEARCH ON FLIGHT ROUTING DEVICES FOR UNMANNED AERIAL VEHICLES

Abstract. *The aim of the work is the development and research of methods for pre-flight optimal planning of flight routes for light unmanned aerial vehicles (UAVs) considering the influence of constant wind and limitations on flight duration. The relevance is driven by the fact that for light UAVs, the airspeed is comparable to the wind speed, which makes accounting for wind a critical factor for efficiency. Traditional routing approaches that ignore wind lead to suboptimal solutions and excessive energy consumption. In this work, routing problems (for closed-loop and open-loop routes, equivalent and weighted points, fixed or selectable start/finish points) are formalized as Boolean linear programming problems. To solve them, a computationally efficient procedure of iterative exclusion of "subtours" is applied. A parametric analysis was conducted, which shows that open-loop routes, unlike closed-loop ones, can demonstrate a time gain due to a "tailwind".*

Key words: *AV, light UAVs, flight routing, route optimization, wind influence, Traveling Salesperson Problem, Boolean linear programming, CPLEX, open-loop route.*

Introduction. Unmanned aerial vehicles (UAVs) are actively used to solve a wide range of civilian tasks: monitoring, aerial photography, pipeline control, in agriculture, and for cargo delivery. Effective execution of these missions requires solving the flight routing problem at the pre-flight preparation stage. For light UAVs (including micro- and mini-classes, such as multicopters), this task is complicated by the fact that their airspeed (50-150 km/h) is comparable to the wind speeds at which operation is permitted (up to 65 km/h). Ignoring wind, as is done in classic formulations of the Traveling Salesperson Problem (TSP), leads to significant errors in flight time estimation (up to 30-40%) and suboptimal energy consumption. Taking wind into account makes the problem asymmetric. More complex scenarios, such as limits on total flight duration or visiting weighted (prioritized) points, require powerful formalization methods, such as Boolean linear programming.

Methods and Materials. In this work, a systematization of routing tasks for light UAVs, considering wind, was conducted, classifying them by route type (closed-loop/open-loop), presence of constraints (in particular, on time), and point type (equivalent/weighted).

To solve these tasks, a unified approach based on formalization as a Boolean linear programming problem is applied. To avoid the computational complexity associated with the exponential growth in the number of constraints (which exclude subtours in the TSP), a procedure of iterative exclusion of "subtours" is applied.

Open-loop routes in a constant wind field were studied. Unlike closed-loop routes, for open-loop routes, the start (s) and finish (f) points are significant. Four options were considered: s/f are fixed; s is fixed, f is selectable; s is selectable, f is fixed; s and f are selectable. A parametric analysis of the influence of wind speed and direction was conducted. It was established that open-loop routes (unlike closed-loop ones) can demonstrate a time gain with a "tailwind" (Fig. 1).

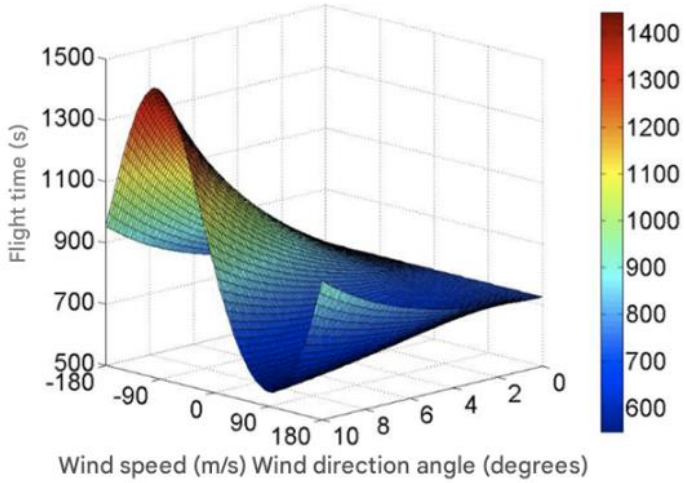

Fig. 1. The time of the fastest route traversal (n=10) on an open-loop route depending on wind parameters, demonstrating the "tailwind" effect

Routes with a limitation on flight duration ($T_{allowed}$) were studied.

For equivalent points, the problem is solved in two stages:

1. Maximization of the number of points (n^*) that can be visited within time $T_{allowed}$;
2. Minimization of the flight time (T_{actual}) among all routes that include м points.

For weighted points (with weight coefficients p_j), the criterion is the maximization of the total value $\sum p_j \cdot x_{ij}$ while adhering to the $T_{allowed}$ constraint.

It is shown that problems with time constraints often have multiple optimal solutions (a Pareto set), which allows for further optimization based on additional criteria.

A software package "UAVRouting" is described, implemented in MATLAB with a core based on CPLEX. Comparative testing of three software and algorithm variants was conducted (Fig. 2). It was established that variant 3 (CPLEX + iterative subtour exclusion) is the most effective, allowing for the stable solution of problems with dimensions up to 165 points.

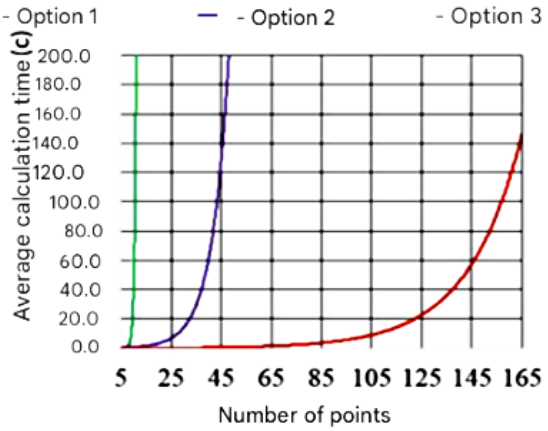

Fig. 2. Dependence of the average computation time on the number of points for three software variants

Conclusions. A series of new problems for optimal flight routing of light UAVs in a constant wind field were formulated and solved, including open-loop routes with the possibility of selecting start/finish points. It was proven that for open-loop routes, unlike closed-loop ones, a "tailwind" effect exists. A methodology for planning routes considering flight duration constraints was developed, which allows for maximizing either the number of equivalent points or the total value of weighted points. A procedure for finding the Pareto-optimal set of solutions for such problems was proposed. The "UAVRouting" software package was developed and implemented, which uses an effective computational approach (Boolean linear programming with iterative subtour exclusion based on CPLEX), allowing for the stable solution of large-scale problems (up to 165 points).

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STUDY OF THE AUTONOMOUS MECHATRONIC MODULE OF THE CAR CONTROL SYSTEM

Abstract. *The aim of this work is to develop a design methodology for an autonomous electro-hydraulic mechatronic module (AMM) for the steering system of multi-axle heavy-duty vehicles (MTS OBG). This is driven by the limitations of traditional systems (mechanical and electro-hydraulic with centralized power), including low efficiency, complexity, weight, and reliability, especially in military applications. The research focuses on a hydrostatic AMM with volumetric speed control (variable-speed electric drive + fixed displacement pump) and an involute actuator mechanism for a constant transmission ratio. Efficiency and reliability are enhanced through modular design and volumetric control. The work includes a functional diagram, mathematical model, design methodology, and experimental verification on a test bench.*

Key words: *autonomous mechatronic module (AMM), electro-hydraulic steering drive (EHSP), multi-axle heavy-duty transport vehicle (MTS OBG), steering system, hydrostatic drive, volumetric control, involute actuator mechanism, mathematical modeling, design methodology***.**

Introduction. Multi-axle heavy-duty transport vehicles (MTS OBG) play a key role in transporting large indivisible loads for industry and military needs. Due to large loads and dimensions, the steering system of such machines must provide high maneuverability and precision. Traditional mechanical and electro-hydraulic drives with centralized power supply have significant drawbacks: low efficiency due to throttle control, heavy weight, complex kinematics, and long hydraulic lines, which reduce reliability, especially in military applications. A promising direction is the creation of autonomous electro-hydraulic mechatronic modules (AMM) for each steered wheel. AMMs offer higher efficiency (up to 70%) due to volumetric control, increased reliability through module independence, and ease of installation and maintenance. However, scientifically substantiated principles for constructing and designing such AMMs for MTS OBG are lacking. The aim of this work is to develop a design methodology for AMM based on studying the patterns of its functioning.

Methods and Materials. Based on the analysis of existing types of autonomous electro-hydraulic drives (with reversible pump, with reversing valve, hydrostatic type, volumetric-throttle), a functional diagram of a hydrostatic-type AMM was developed featuring a non-reversible fixed displacement pump, whose rotational speed is controlled by an electric motor, and a four-way, three-position electro-hydraulic directional control valve (EHDV) for flow reversal (Fig. 1).

A key feature is the use of an involute actuator mechanism instead of the traditional hydraulic cylinder with lever transmission. The involute mechanism provides a constant transmission ratio (radius R_{HO}) between the linear displacement of the pistons and the angular rotation of the wheel, reducing the required piston stroke and maximum fluid flow rate. Control algorithms were developed that ensure volumetric control of the wheel turning speed proportional to the error signal, maintaining minimum motor speed in the neutral position to reduce energy consumption and ensure reliability.

A detailed mathematical model of the AMM was created as a block structure (Fig. 2), considering the dynamics of the electric motor, pump characteristics (including leakage), fluid compressibility (considering undissolved air), hydraulic resistance of pipelines and the directional valve, actuator dynamics, and the elastic-damping properties of the tire.

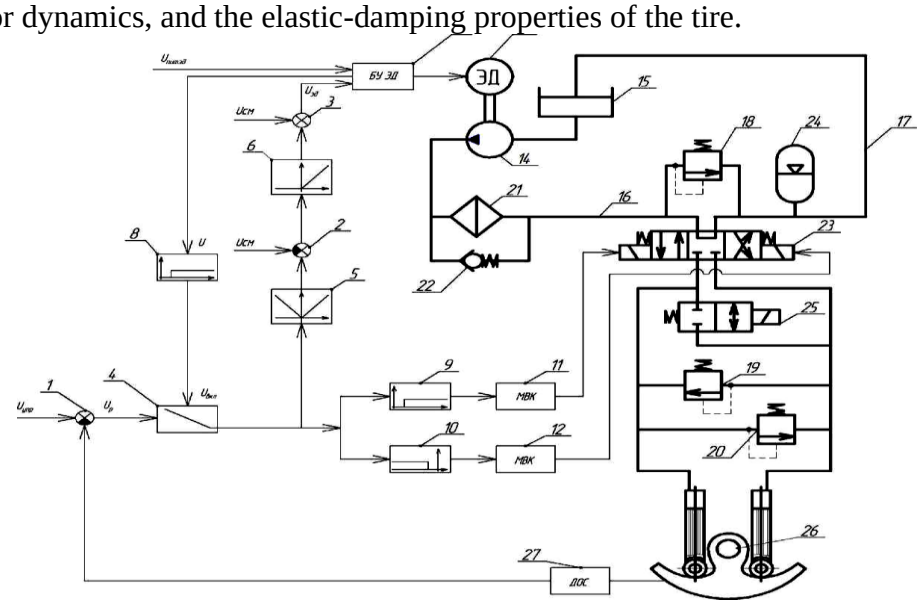

Fig. 1. Functional diagram of AMM

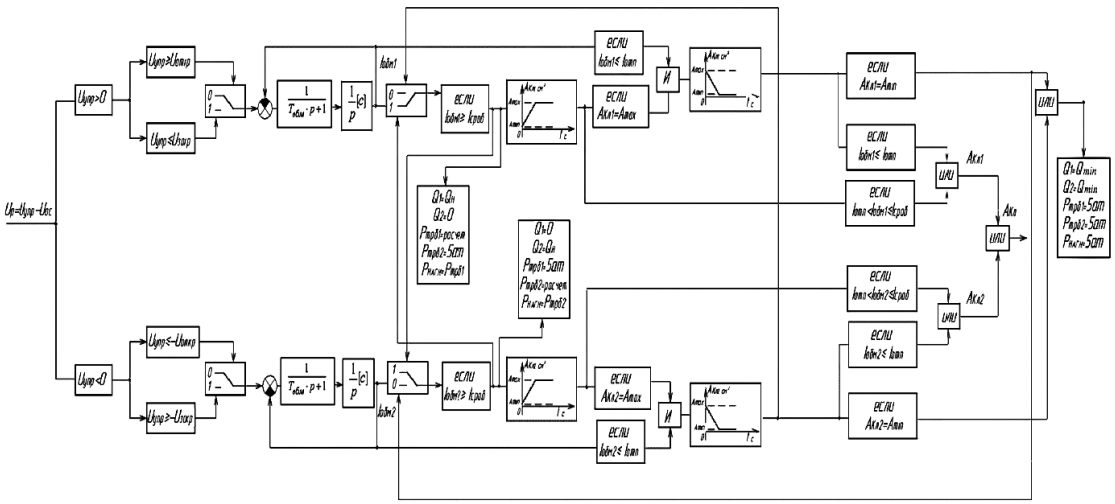

Fig. 2. Diagram of the generalized mathematical model of AMM

Modeling was performed in the Lazarus environment to analyze the dynamic characteristics of the system ("steering impulse", "steering reversal") under various loads and tire parameters, as well as to determine the optimal forward path gain (K_y) using Logarithmic Amplitude-Frequency Characteristic (LAFC) analysis. Based on the model, a design methodology for the AMM was developed, including the sequential calculation and selection of the pump, electric motor, directional valve, and determination of the control system gains. To verify the model and methodology, a test bench was created, and experimental studies of a prototype AMM were conducted.

Conclusions. The functional patterns and basic construction principles of the AMM for MTS OBG steering systems were established. A functional diagram of a hydrostatic-type AMM with an involute actuator mechanism was developed, and its advantages were substantiated. A mathematical model that adequately describes the dynamic processes in the AMM was created. Modeling confirmed the compliance of the AMM characteristics with the technical requirements (transient process time ~0.9 s, error < 2 deg, overshoot < 0.3 deg) and demonstrated the advantages of volumetric control – a direct relationship between power consumption and load. A universal design methodology for AMM was developed. Test bench experiments confirmed the adequacy of the mathematical model (convergence of results 12-15%) and the viability of the proposed technical solutions.

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IMPROVING THE QUALITY OF X-RAY DIAGNOSTIC IMAGES IN MATLAB ENVIRONMENT IN AUTOMATIC MODE

Abstract. *The aim of the work is to improve the quality of X-ray diagnostic images in the MATLAB environment in automatic mode. The potential of projection diagnostics methods is enhanced by the introduction of computerized technologies and digital image processing techniques. This research focuses on the methods for processing X-ray diagnostic images, emphasizing spatial filtering, frequency filtering, and image restoration in MATLAB. The quality improvement is achieved using combined methods of spatial image enhancement.*

Key words: *digital processing, medical images, MATLAB, X-ray images, spatial filtering, frequency filtering, image restoration.*

Introduction. Projection diagnostics, including radiography, plays a leading role in clinical research, helping to establish up to 60–80% of all primary diagnoses. X-ray images often look blurry, partly because X-rays cannot be focused using lenses, and their brightness might be shifted toward the dark area. To counter this, advanced digital image processing is used. The goal of the work is to improve the quality of X-ray diagnostic images in MATLAB in automatic mode [1].

Methods and Materials. The study focuses on digital processing of medical images in the MATLAB environment. A digital image $f(x,y)$is represented as an $M \times N$ matrix of pixels, where the origin (0, 0) is typically the upper left corner.

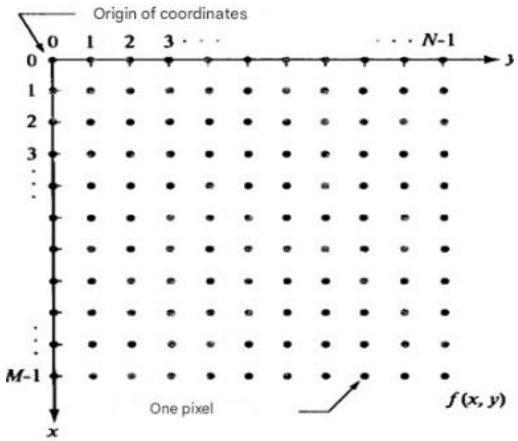

Fig. 1. System of digital image representation

Image processing is categorized into spatial domain methods (direct pixel manipulation) and frequency domain methods (via Fourier transformation).

Spatial filtering involves applying a filter mask (w) to the neighborhood of a pixel, moving the mask across the image. Spatial filters are used for smoothing (noise suppression) and sharpening (emphasizing fine details). Linear spatial filtering in MATLAB is implemented using the imfilter function, often with filter masks generated by fspecial (e.g., Laplacian, average).

Image restoration aims to reconstruct a distorted image objectively, utilizing a priori information about the distortion. The distortion model, shown in Fig. 2, involves a distorting operator H and additive noise $\eta(x,y)$.

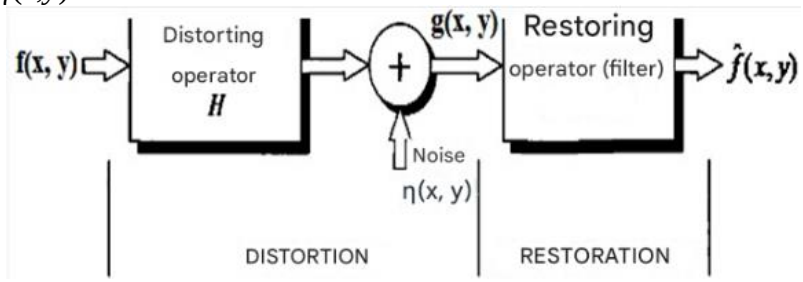

Fig. 2. Model of the image distortion / restoration process

Key restoration techniques include filters based on sequential statistics, such as the median filter, which is highly effective against impulsive noise (salt and pepper). The Wiener filter (or minimum mean square error filtering) is crucial as it accounts for both the properties of the distorting function $H(u,v)$ and the statistical properties of the noise $S\eta(u,v)$ [2].

Methods for image enhancement, such as modifying the intensity transfer function or using histogram processing, are employed to improve visual quality.

The technique of histogram equalization (histeq) improves image contrast by mapping the pixel values so that the resulting histogram of brightness levels is approximately uniform. This process converts the X-ray brightness to mid-tones, eliminating absolute black areas. The effect of histogram equalization is illustrated in Fig. 3 [3].

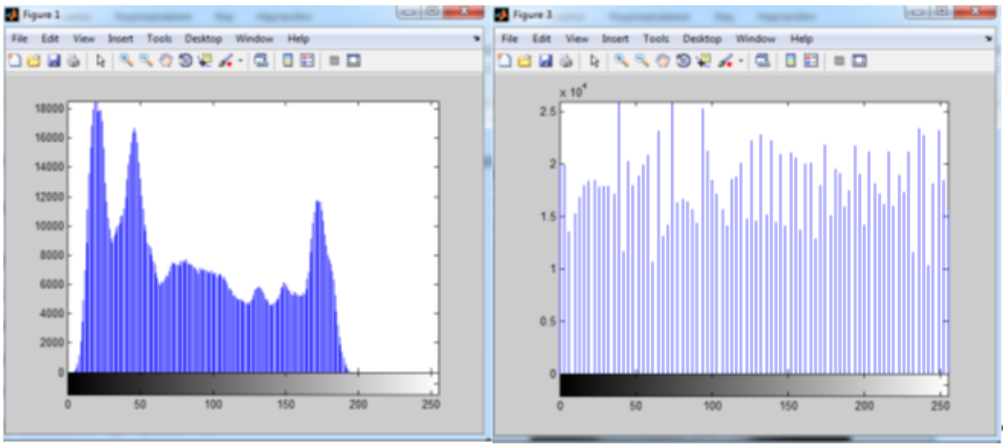

Fig. 3. Histogram equalization: a) histogram of the original X-ray image, c) equalized histogram of the transformed image

Conclusions. Analysis, segmentation, filtering, and enhancement of the X-ray image were performed in the MATLAB environment. The quality of image processing depends heavily on the specific research goals. It was concluded that a complex approach to processing, utilizing different methods sequentially, is necessary to extract high-quality information from the image. The implementation of spatial filtering, frequency filtering, and restoration methods successfully achieved the goal of improving the quality of X-ray diagnostic images in MATLAB.

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RESEARCH OF A HYBRID WIND-SOLAR-DIESEL SYSTEM FOR AUTONOMOUS ENERGY SUPPLY

Abstract. *The aim of this work is to analyze the potential for using solar and wind energy under the conditions of Central Ukraine (based on the example of Kirovohrad and Cherkasy regions), to examine the principles of constructing hybrid power supply systems based on these renewable energy sources (RES), and to develop and verify mathematical and simulation models of a photovoltaic (PV) solar power installation. The relevance of the topic is determined by the rising tariffs for conventional energy carriers, the need to ensure energy supply for decentralized areas, and the potential of renewable energy. The study includes an analysis of existing autonomous, grid-connected, and hybrid (wind-solar, diesel-backed) systems, an assessment of solar insolation and wind potential of the region based on meteorological data, and the development of a mathematical model of a photovoltaic converter that accounts for external factors, implemented in the MATLAB/Simulink environment. Experimental research was conducted on a custom-built solar installation equipped with a tracking system to validate the model.*

Key words: *hybrid power supply system, renewable energy sources (RES), solar energy, wind energy, photovoltaic installation, wind turbine, RES potential, modeling, MATLAB/Simulink.*

Introduction. The increase in gas and electricity prices makes traditional heating and energy supply systems economically inefficient, especially for large areas and remote facilities. Renewable energy sources (RES), primarily solar and wind energy, have significant technical potential and can contribute to the energy independence of decentralized regions [2]. Hybrid systems combining RES (wind, solar) with conventional energy sources (e.g., diesel generators) are considered a promising option [1, 3]. However, the renewable energy market often contains inaccurate information about the actual capacity and efficiency of installations, complicating consumer choice. In the context of Central Ukraine, where both solar and wind potentials are relatively moderate, the development of efficient and economically viable hybrid systems is particularly relevant. The objective of this work is to assess the renewable energy potential for this region and to develop analytical and simulation tools (models) for the analysis and design of such systems.

Methods and Materials. The study analyzed various types of power supply systems based on RES: autonomous, grid-connected, and hybrid (wind-solar, wind-diesel, solar-diesel, and wind-solar-diesel) [1, 3]. Their structural schemes, operating principles (including the use of batteries, inverters, charge controllers, and ballast loads), and specific operational modes (sequential battery usage, AC/DC bus coupling, parallel operation with diesel generators) were examined. The solar energy potential for Kirovohrad and Cherkasy regions was evaluated. Factors affecting solar radiation—direct and diffuse radiation, cloudiness, incidence angle, and Air Mass – were analyzed [2]. NASA and JRC datasets were used to determine annual and monthly total solar radiation incident on horizontal and inclined surfaces. The distribution of sunny days throughout the year was analyzed (Fig. 1).

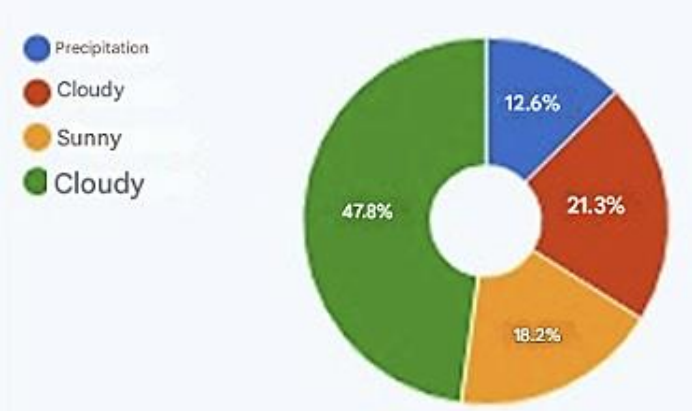

Fig. 1. Ratio of clear and cloudy days (example for Cherkasy city)

The wind energy potential for the mentioned regions was evaluated based on meteorological station data (rp5.ua) for the period 2012–2017. Statistical distributions of wind speeds at anemometer height (10 m) and at 30 m were calculated (Fig. 2). Wind roses for the main cities of the region were analyzed [3].

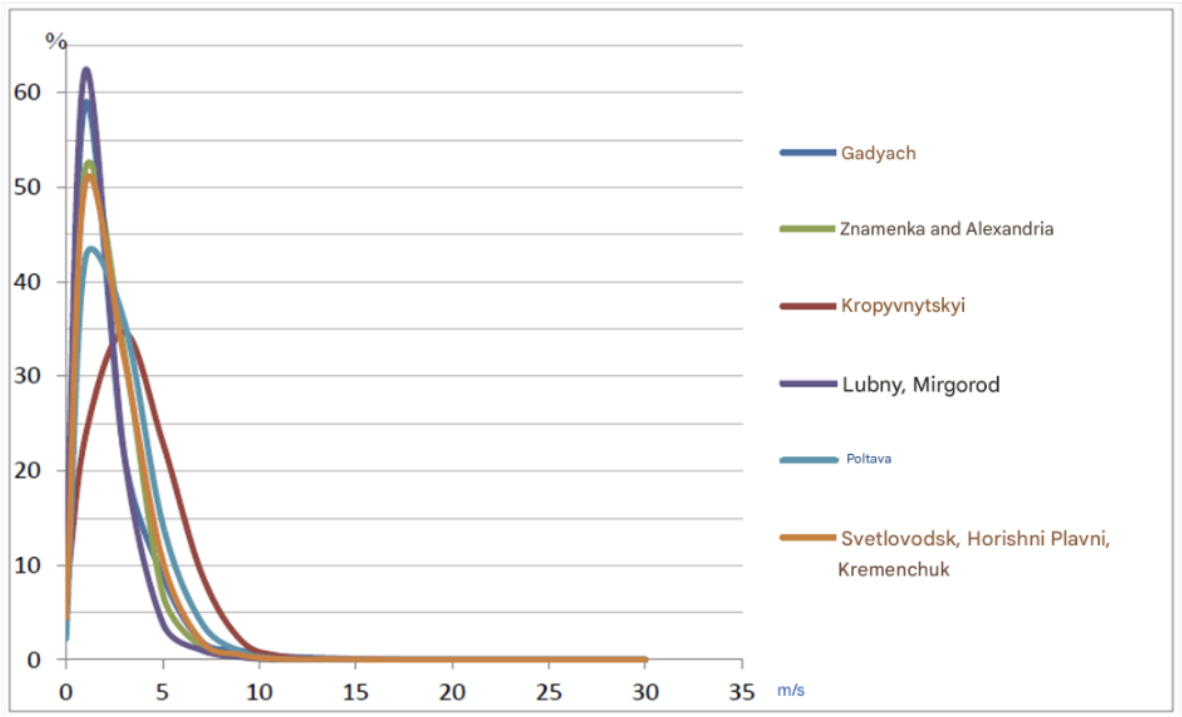

Fig. 2. Wind speed distribution (example at 10 m height)

A mathematical model of a photovoltaic installation was developed. It is based on the equivalent circuit of a real photovoltaic cell with a p–n junction, accounting for series resistance [3]. Analytical expressions for the current-voltage characteristic (I–V curve) were derived considering the influence of solar irradiance and cell temperature. Energy losses in protective glass depending on the angle of incidence (reflection, absorption, and transmission coefficients) were taken into account. Based on this mathematical model, a simulation model was created in MATLAB/Simulink consisting of three subsystems: modeling environmental conditions (calculating insolation and air temperature depending on geographic coordinates, day of the year, time of day, and surface orientation), calculating external factors (PV temperature, glass losses), and computing the output energy characteristics (I–V and P–V curves, power).

For model verification, an experimental photovoltaic installation was designed and assembled, including two solar panels, an azimuth and zenith solar tracking system, a charge controller, battery bank, and inverter. A data acquisition system based on a ZET 210 ADC and PC was created for parameter recording (voltage, current, PV temperature, air temperature, and illuminance). A methodology for experimental studies was developed.

Conclusions. Analysis of meteorological data showed that Central Ukraine (Kirovohrad and Cherkasy regions) has a moderate but sufficient potential for practical use of solar and wind energy. Solar insolation is relatively uniform across the region, while wind potential demonstrates higher local variability. For regions with high cloudiness (>50% of days), panels based on amorphous silicon are recommended, while for wind turbines – units with low cut-in wind speeds. A mathematical and simulation model of a photovoltaic installation in MATLAB/Simulink was developed, taking into account key external factors (insolation, temperature, wind speed, angles of incidence) and system parameters (type of PV module, orientation, and energy losses). An experimental installation and methodology were created for field testing and validation of the developed models. The results can be used for the design and optimization of hybrid wind-solar power supply systems in the conditions of Central Ukraine.

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AUTOMATED SYSTEM FOR CORRECTING MEASUREMENT ERRORS IN LIQUID FLOW METERS

Abstract. *The aim of this work is to develop an automated system for correcting measurement errors of liquid flow meters, particularly those using orifice plate type restriction devices. The relevance of the work stems from the need to improve the accuracy of commercial and technological accounting of liquid flow, especially in the context of energy saving, and to account for operational factors affecting the metrological characteristics of flow meters. The research focuses on analyzing the impact of inlet edge dulling of the orifice plate on flow measurement results. Using hydrodynamic modeling in the SolidWorks Flow Simulation environment, a quantitative relationship between the edge rounding radius and the measurement error was established. Based on these studies, the structure of an information-measuring system (IMS) is proposed, capable of automatically correcting the flow meter readings considering the identified dependency and measured flow parameters (temperature, pressure).*

Key words: *automated system, error correction, liquid flow meter, orifice plate, restriction device, edge dulling, measurement error, SolidWorks Flow Simulation, information-measuring system (IMS).*

Introduction. Accurate measurement of liquid flow is a critical task for effective process control and rational use of energy resources. Variable pressure drop flow meters with standard orifice plates are widely used due to their simplicity and reliability. However, their accuracy depends on the stability of geometric parameters, particularly the sharpness of the orifice plate's inlet edge. During operation, this edge inevitably dulls due to fluid friction, leading to a change in the discharge coefficient and, consequently, an additional systematic measurement error. Existing calibration methods and standards do not always fully account for this dynamic wear process. Therefore, the development of automated systems capable of correcting measurement errors caused by operational changes in flow meter parameters is a relevant task. The aim of this work is to develop such a system based on investigating the impact of orifice plate edge dulling.

Methods and Materials. An analysis of existing methods for measuring and calibrating liquid flow meters, as well as methods for improving measurement accuracy, including automatic error correction techniques, was conducted. The design parameters of standard orifice plates according to DSTU standards were examined in detail, and the influence of inlet edge dulling on flow hydrodynamics and the discharge coefficient was investigated.

To quantitatively assess the impact of edge dulling on flow measurement, computer modeling was used. A 3D model of the flow meter's flow path with an orifice plate was created in the SolidWorks environment. Using the Flow Simulation module, a series of hydrodynamic calculations of water flow were performed at a fixed pressure drop for various values of the inlet edge rounding radius (r_k). A computational mesh was generated using the finite volume method with refinement near the orifice plate (Fig. 1).

The dependence of the volumetric flow rate on the radius r_k and the corresponding relative measurement error were calculated. It was found that the error significantly increases with an increasing rounding radius.

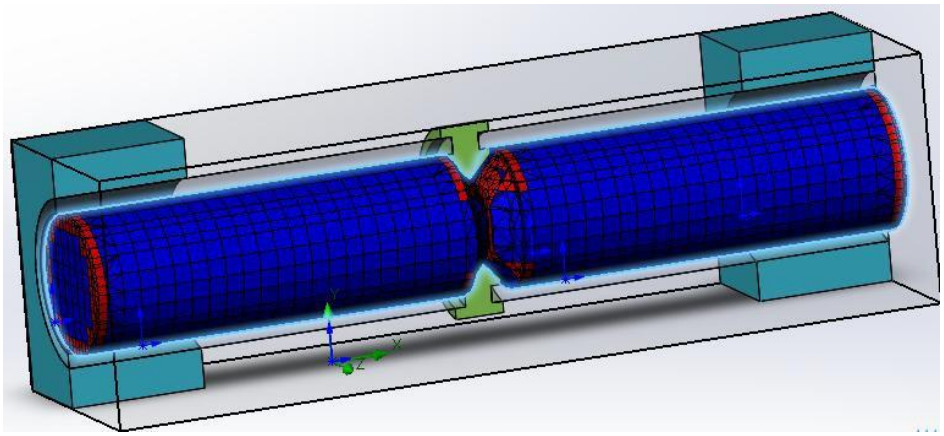

Fig. 1. Adaptive mesh of the model under study

Based on the analysis and modeling results, the structure of an automated error correction system integrated into an information-measuring system (IMS) for flow was proposed (Fig. 2).

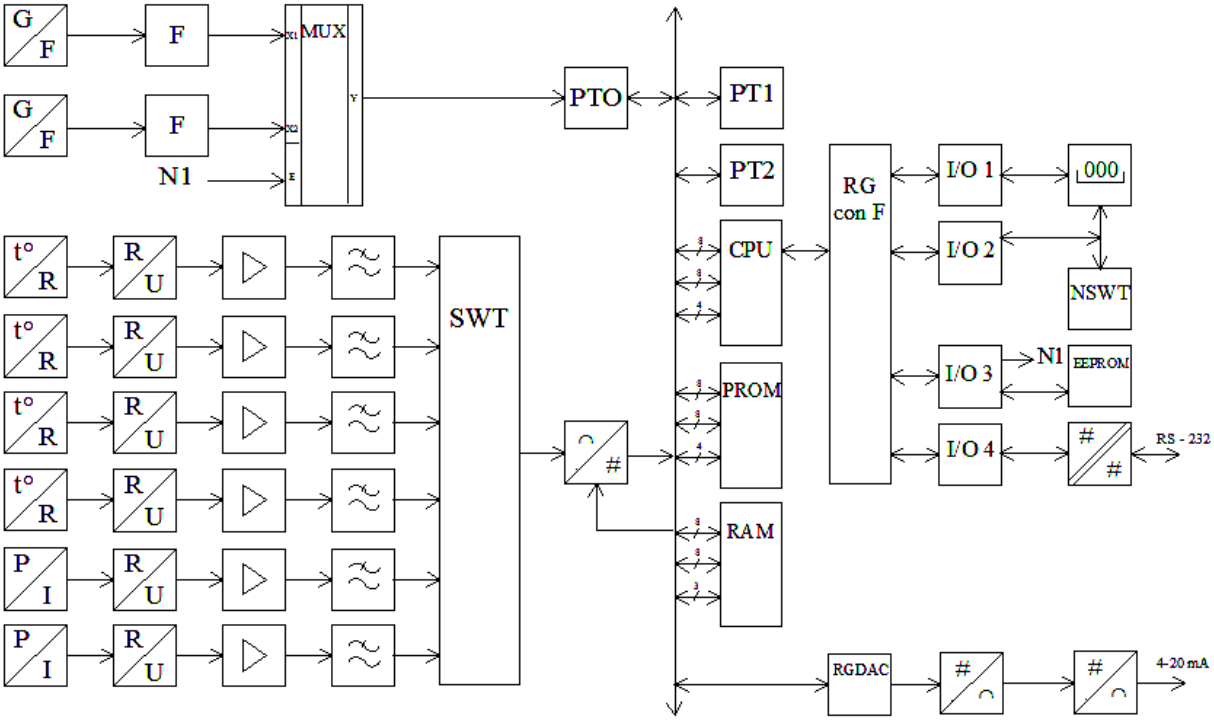

Fig. 2. Functional diagram of the IMS with correction capability

The IMS includes primary transducers for flow (e.g., electromagnetic), temperature (resistance thermometer), and pressure (pressure sensor). The system's microprocessor unit collects data from the sensors, performs ADC conversion, and calculates the flow rate, taking into account the temperature dependence of the fluid density. To correct the error associated with edge dulling (in the case of using an orifice plate flow meter), the introduction of a correction factor into the calculation algorithm is envisaged. This factor can be determined based on the error-r_k relationship obtained from modeling and data on the orifice plate's operating time (using empirical wear models) or from periodic measurements of the actual rounding radius.

Conclusions. The problem of the influence of operational wear (inlet edge dulling) of standard orifice plates on the accuracy of liquid flow measurement was investigated. Using hydrodynamic modeling in SolidWorks Flow Simulation, a quantitative relationship between the edge rounding

radius and measurement error was obtained, confirming the significance of this factor. The structure of an information-measuring system was developed, which measures the main flow parameters (flow rate, temperature, pressure) and allows for automatic correction of errors in variable pressure drop flow meters based on a model of the edge dulling effect. The proposed approach allows for increased accuracy in accounting for liquid flow over the long-term operation of flow meters.

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AUTOMATION OF ELECTRIC SPARK TESTING OF CABLE PRODUCTS

Abstract. *The aim of the work is a comprehensive solution to the scientific and technical problems of the effective use of the spark testing method in the production of cable products. This work investigates models of defective and non-defective insulation as a non-linear electrical load. A detailed analysis of the possibility of detecting defects using voltage of various forms and frequencies (AC HF, 50 Hz, DC, and pulse) was conducted. It is proven that it is impossible to apply control based on the partial discharge level on a production line due to the high level of background surface discharges. A block diagram of a test bench for the certification of spark testers has been developed.*

Key words: *spark testing, spark tester, cable insulation, partial discharges, dielectric strength, equivalent circuit, test voltage.*

Introduction. The spark testing method is the primary and mandatory method in the production of cable products (CP) with polymer insulation. Its essence lies in applying a high voltage to the surface of the insulation of a moving cable; when a defective section passes, a spark discharge occurs, which is registered by a flaw detector.

Despite the long experience with the method's application, a number of unresolved issues remain. There is no qualitative and quantitative description of the types and geometry of defects that are reliably detected by this test. Models of defective and non-defective insulation as an electrical load during testing have not been described. The differences in the effectiveness of testing with voltage of different forms and frequencies have not been sufficiently studied. The aim of the work is a comprehensive solution to the scientific and technical problems of the effective use of the spark testing method in the production of cable products.

Methods and Materials. In this work, the cable product was considered as an electrical load, the simplified equivalent circuit of which consists of the insulation resistance (R_{ins}) and insulation capacitance (C_{ins}) connected in parallel. Studies have shown that insulation is a non-linear load: its equivalent capacitance and resistance significantly depend on the applied electric field strength and frequency. A critical factor affecting the parameters is the temperature of the polymer. Heating of the insulation at the exit from the cooling bath (up to 80°C) can lead to an increase in dielectric losses by 2-5 times (depending on the material grade).

An analysis of different defect detection mechanisms was carried out:

1. Detection by electrical breakdown (primary method). Calculations showed that this method reliably detects through-hole defects (minimum calculated diameter – 30 μm) and significant local thinning of the insulation. Electrothermal breakdown consistently occurs when the insulation thickness at the defect site is 13-28% of the nominal (depending on the material – PVC, polyethylene, rubber).
2. Detection by partial discharge (PD) level. Studies have proven the impossibility of using this method on a production line. The reason is the high level of background surface discharges (corona) on the spark tester electrode. As seen in (Fig. 1), these discharges have a high amplitude. The background noise level exceeds the useful signal level from PD in a conditional defect (100 μm) by more than 1000 times.

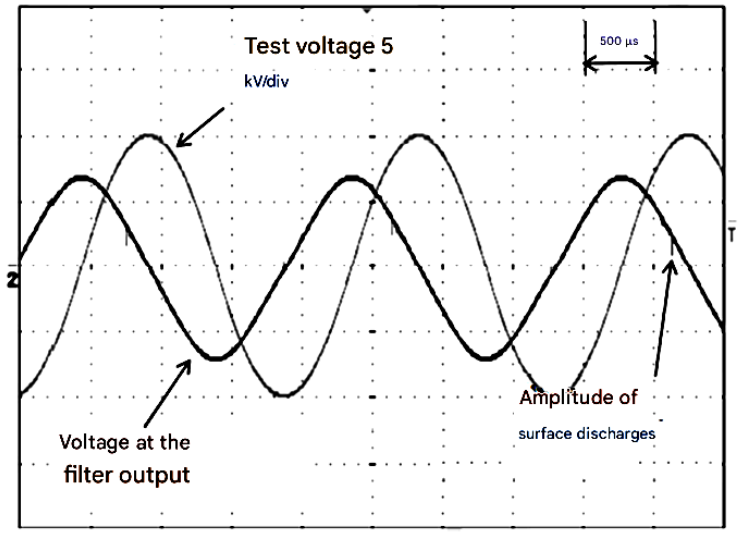

Fig. 1. Oscillogram of voltages during the test of mounting wire NV-1

3. Detection by change in specific capacitance. This method was found to be insensitive for detecting small defects. Due to the product's vibration in the electrode, the presence of moisture, and other technological factors, the spread of capacitance values for non-defective sections reaches ±20-23%. This only allows for the registration of significant and extensive geometric changes (thinning or thickening).

A key area of the research was comparing the effectiveness of testing with voltage of different forms and frequencies. It was established that the dielectric strength of the insulation (breakdown voltage U_{br} significantly depends on the frequency. As the frequency increases, the breakdown voltage decreases (Fig. 2).

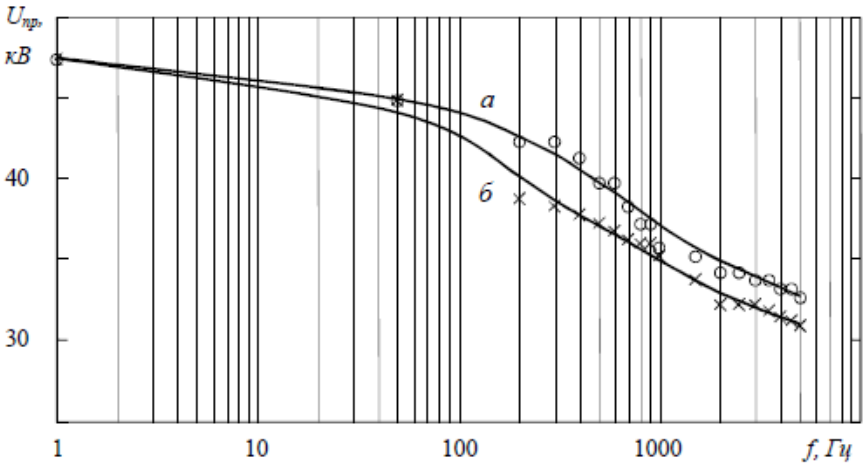

Fig. 2. Dependence of breakdown voltage on high voltage frequency for telephone wire KSPV 4 0.12 (a) and LAN cable KSSPV UTP 4 Cat. 5e (b) wires

This proves that high-frequency (HF) AC voltage (e.g., 1-3 kHz) is more effective (detects defects at a lower voltage) than 50 Hz voltage or direct (DC) voltage.

To solve the problem of test reliability and ensure measurement uniformity, a test bench for the certification of spark testers was developed (Fig. 3). The bench allows for certification directly at the equipment's operation site and can simulate various types of loads and defects.

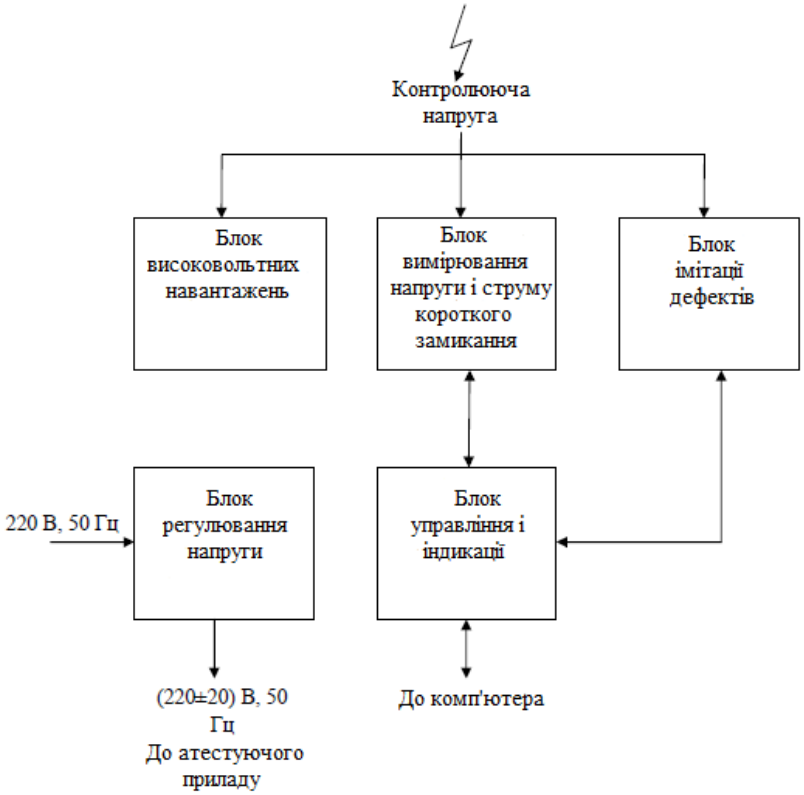

Fig. 3. Block diagram of the installation for certification of spark testers

Conclusions. The studies have proven that the spark testing method reliably detects through-hole defects larger than 28 μm and critical insulation thinning (down to 13-28% of the nominal). However, control by partial discharge level was found to be impossible on the production line due to the extremely high level of background surface discharges (exceeding >100 times). Similarly, control by capacitance change is limited by high levels of technological noise (up to ±23.5%). An analysis of the influence of voltage form and frequency was conducted, which proved that testing with high-frequency AC voltage (> 500 Hz) is more effective than testing with 50 Hz voltage. To address reliability issues, a block diagram of a mobile test bench for certifying spark testers is proposed.

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RESEARCH ON AN AUTOMATED ACCESS CONTROL SYSTEM BASED ON FINGERPRINT BIOMETRICS

Abstract. *The aim of the work is to investigate existing biometric access control systems and analyze the impact of biometric data comparison algorithms on the system's accuracy, specifically fingerprint identification. The relevance of the topic is determined by the widespread implementation of biometric technologies in security systems (ACS), time tracking systems, as well as in government and financial sectors. The research focuses on the analysis of methods for scanning papillary lines (optical, semiconductor) and comparison algorithms (correlation-based, minutiae-based, pattern-based). The method of Hierarchical Analysis (AHP) was used to choose the optimal component base of the system. Based on the analysis, a mathematical model for fast fingerprint image processing was developed, including the construction of flow and line period matrices, segmentation, filtering using Gabor filters, and skeletonization for minutiae extraction.*

Key words: *biometrics, access control system (ACS), fingerprint, papillary lines, comparison algorithm, minutiae, Analytic Hierarchy Process (AHP), FAR, FRR.*

Introduction. Identity identification is a fundamental task in many areas. Historical methods, such as Bertillonage, proved to be insufficiently reliable. The introduction of fingerprinting (Henry Classification System, 1897) and its subsequent scientific development by Karl Pearson laid the foundation for modern biometrics. Today, biometric systems are used in forensics, security systems, time tracking, as well as in financial and governmental services (ICAO passports, visas). Despite high accuracy, biometric systems face Type 1 errors (FRR - false rejection of a registered user) and Type 2 errors (FAR - false acceptance of an unauthorized user). This is due to the fact that biometric samples are never identical due to varying reading conditions (position, pressure, skin condition). The purpose of this work is to investigate existing biometric systems and fingerprint comparison algorithms to develop a combined algorithm that will increase the accuracy of access control systems.

Methods and Materials. An analysis was conducted on static (fingerprints, iris, hand geometry) and dynamic (voice, handwriting) biometric identification methods. Fingerprint scanning technologies were examined in detail: optical (based on total internal reflection), semiconductor (capacitive, thermal scanners), and ultrasound. Three main types of fingerprint comparison algorithms were analyzed:

- Correlation Comparison: Direct overlay of pixel images. This method is computationally demanding but less sensitive to image quality.
- Minutiae-based Comparison: A template is formed based on the coordinates and orientation of ridge endings and bifurcation points (Fig. 1). This is the most common and fastest method but requires high-quality images.
- Pattern-based Comparison (Texture-based): The image is divided into cells, and the line structure in each is described by sinusoidal wave parameters. This method is complex to implement but fast and less demanding on image quality.

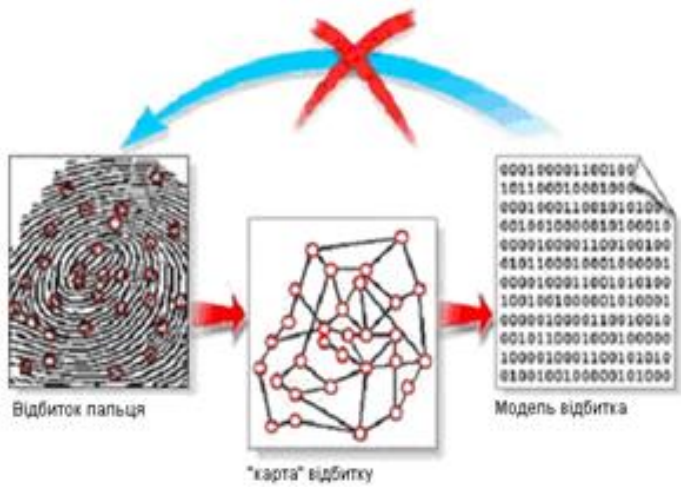

Fig. 1. Formation of a digital template (fingerprint model)

To select the optimal scanner for the developed system, the Analytic Hierarchy Process (AHP) by Thomas Saaty was used. A hierarchical model (Fig. 2) was constructed with the goal of "Selecting the Sensor" and five criteria: FRR, FAR, registration time, identification time, and price. A pairwise comparison of the criteria was conducted, with FAR (0.41) and Price (0.39) being prioritized. Pairwise comparisons of four alternative sensors (S400, 100MA, SR100, U.are.U) were conducted, resulting in the selection of the Sagem 100MA sensor.

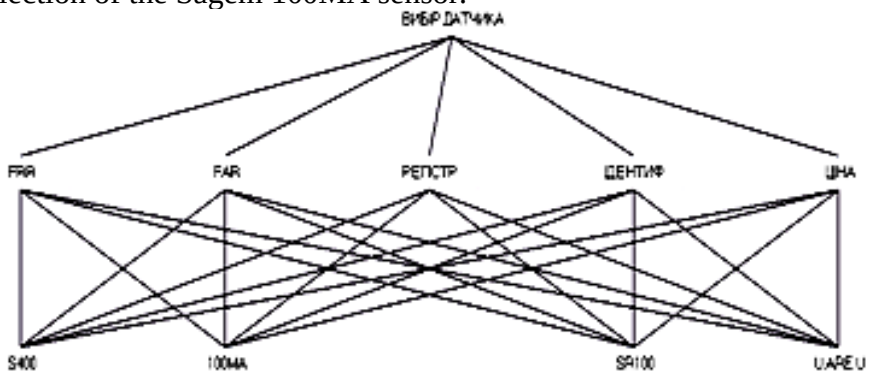

Fig. 2. Hierarchical model for selecting a biometric sensor

A mathematical model for fast image processing was developed for feature extraction. The model includes five stages:

1. Flow Matrix Construction (calculating line orientation using Sobel operators);
2. Line Period Matrix Construction (based on autocorrelation function);
3. Segmentation (to separate informative areas);
4. Filtering (using Gabor filters to remove noise) ;
5. Skeletonization and Minutiae Recognition (endpoints and bifurcations) .

Conclusions. In the course of the work, modern biometric systems were analyzed, along with their advantages and drawbacks. It was determined that fingerprint identification is one of the most widely used, reliable, and accessible technologies. Comparison algorithms (correlation, minutiae-based, pattern-based) were analyzed, forming the basis for the proposal to develop a combined algorithm. Using the Analytic Hierarchy Process, a reasoned selection of equipment for the designed system (Sagem 100MA) was made based on priority criteria (minimal FAR and price). A mathematical model for fast image processing and minutiae extraction was developed, which forms the basis for the software implementation of the biometric access control system.

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RESEARCH ON AN AUTOMATIC CONTROL SYSTEM FOR A MANIPULATOR FOR MOVING OBJECTS

Abstract. *The aim of this work is the development and research of methods for automatic planning and motion control of a robotic system consisting of a manipulator ("hand") and a multi-fingered grasping device ("wrist") during object grasping and manipulation operations. The relevance is driven by the limitations of remote control in hazardous environments and the need to increase the reliability and versatility of automatic manipulations, especially when performing power (enveloping) grasps using not only the wrist's fingers but also the links of the hand itself. The research focuses on developing a unified approach to controlling the "hand + wrist" system, analyzing the grasp properties for such a combined system, developing methods for planning the coordinated motion of all links, and creating a control system that ensures trajectory tracking.*

Key words: *robotic system, manipulator, grasping device, object grasping, power grasp, motion planning, motion control, grasp theory, Jacobian matrix, grasp quality criteria.*

Introduction. The use of robots for manipulation in hazardous or inaccessible environments is often limited by the shortcomings of remote control. Automatic control systems are an alternative but require effective methods for planning and executing operations, particularly object grasping. Traditional approaches often treat grasp planning (selecting contact points on the wrist) and manipulator (hand) motion planning as separate tasks. This limits the system's capabilities, especially when performing power grasps where the object contacts not only the fingers but also other links of the wrist or even the hand. Using the hand's links for grasping allows manipulating larger objects and increases holding reliability at low friction coefficients. However, methods for planning and controlling the coordinated motion of the entire "hand + wrist" system as a single entity have not been sufficiently studied. The aim of this work is to develop such methods for the automatic execution of grasping and transportation operations

Methods and Materials. The work is based on the analysis of existing "hand + wrist" type robotic systems and their control methods. The fundamental principles of grasp theory are applied, particularly the concepts of the grasp matrix (G) and the Jacobian matrix (J). Unlike classical approaches that consider the "wrist + object" system, matrices for the complete "hand + wrist + object" system (J_{PKO}) are analyzed here. It is shown that the Jacobian matrix of such a system differs from the wrist's Jacobian matrix by the presence of additional columns corresponding to the hand's degrees of freedom.

Based on the analysis of the null spaces and ranges of the matrices G and J_{PKO}, conditions for ensuring desired grasp properties (feasibility, determinacy, non-defectiveness, controllability, non-hyperstaticity) are formulated specifically for the combined system. It is proven that using the hand's degrees of freedom allows achieving desired properties (e.g., controllability or non-defectiveness) even when a grasp performed solely by the wrist does not possess them.

An approach for planning the coordinated motion of all system links has been developed. It includes:

1. Grasp Planning: Determining the hand and wrist configuration that ensures the desired grasp properties for the "hand + wrist + object" system. A modified approach based on a discretized reachability space is used.

2. Trajectory Planning: Calculating the system's motion trajectory from the initial position to the grasping configuration and further to the target position with the object. A modification of the RRT (Rapidly-exploring Random Trees) method, adapted for the "hand + wrist" system, is used, considering the need to change configuration for power grasping and collision avoidance. The Velocity Field Control (VFC) method is applied to generate local wrist trajectories when enveloping the object.

To control the system's motion along the calculated trajectory, a controller is used that ensures asymptotic tracking in the joint space despite uncertainties in the system dynamics.

Modeling of the developed methods was performed in the ROS software environment for a model of the Kawasaki FS020N manipulator with a Schunk WSG-50 two-finger gripper (Fig. 1).

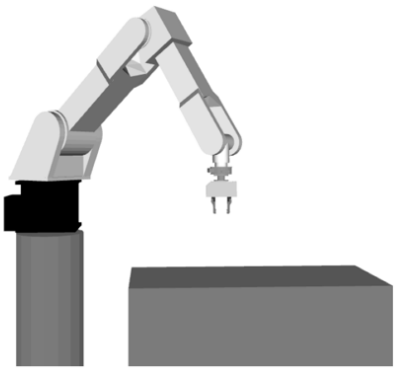

Fig. 1. Software model of the experimental setup

A comparative analysis of grasp quality (using various criteria) was performed for cases of grasping only with the wrist and with the "hand + wrist" system. Physical experiments were conducted on real equipment to verify the modeling results and the performance of the control system (Fig. 2).

Fig. 2. Process of grasping a bulky object

Conclusions. Methods for planning and control for automatic grasping and manipulation of objects by a "hand + wrist" type robotic system have been developed and investigated. The proposed approach, unlike existing ones, considers the hand and wrist as a single system, allowing the use of the hand's degrees of freedom to ensure reliable power grasps, manipulation of larger objects, and increased overall payload capacity. Mathematical conditions for ensuring desired grasp properties for the "hand + wrist + object" system have been formulated, and criteria for the quality of such grasps have been analyzed. Algorithms for planning the coordinated trajectory of the hand and wrist links have been developed. Results from computer modeling and physical experiments confirmed the effectiveness of the proposed methods and the advantages of using the entire "hand + wrist" system for performing power grasps. It was shown that grasps utilizing the hand links exhibit better quality metrics.

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AUTOMATED CONTROL SYSTEM FOR VALVE-INDUCTOR DRIVES

Abstract. *The purpose of the work is to create a unified control system for a series of five- and six-phase Switched Reluctance Drives (SRDs) with a regulated DC link, with a power range from 1.1 to 32.5 kW. The relevance of the work is determined by the need to create a domestic competitive electric drive for mobile objects (transport, fleet) powered by an unstable DC on-board network. The research focuses on developing a control system structure that ensures the minimization of torque ripple and noise due to multi-phase design and the absence of current limiting. An adaptive speed controller with torque limiting is proposed to enhance the smoothness of start-up and protect the drive.*

Key words: *Switched Reluctance Drive (SRD), multi-phase motor, control system, DC/DC converter, speed controller, adaptive control, torque ripple, overload protection.*

Introduction. Switched Reluctance Drives (SRDs) are gaining popularity due to the high reliability of the motor (absence of windings on the rotor) and potentially high energy performance. However, SRDs have inherent drawbacks, such as high noise due to torque ripple and a decrease in efficiency when operating with current limiting at low speeds. This work examines the implementation of SRDs with a large number of phases (five and six), which helps reduce torque ripple. Power is supplied from an unstable DC on-board network, whose voltage can vary significantly. The relevance of the work lies in creating a domestic drive capable of operating with high efficiency and low noise/vibration in such conditions. The goal is to create a unified control system for a series of multi-phase SRDs with a regulated DC link.

Methods and Materials. A mixed commutation law is used to control the motor, which allows operation without current limiting in the phases. Control is achieved by adjusting the voltage applied to the inverter using a DC/DC converter at the input. The DC/DC converter is capable of operating in buck and boost modes, which is necessary to maintain the nominal speed and shape the phase currents, avoiding the current limiting mode. The power converter is implemented using intelligent IGBT modules.

- Control Structure: A control structure featuring a PI speed controller and a Relay Integrator of Speed Controller Output (RISCO) (Fig. 1) is proposed as an adaptive solution.
- Adaptive Controller: The combination of the PI controller and RISCO ensures smooth transients and allows the system to operate under load and at no-load without reconfiguring the voltage curve.
- Protection and Diagnostics: To protect against overload (a critical issue for the series-excited characteristics of SRDs), a regulator with a switchable structure and torque cut-off has been developed (Fig. 2). This regulator provides protection against shaft overloads and the smoothest start-up.
- Measurement: A Rotor Position Sensor (RPS) is used to determine the rotor position, which is reliable and suitable for harsh environments, unlike quadrature encoders.

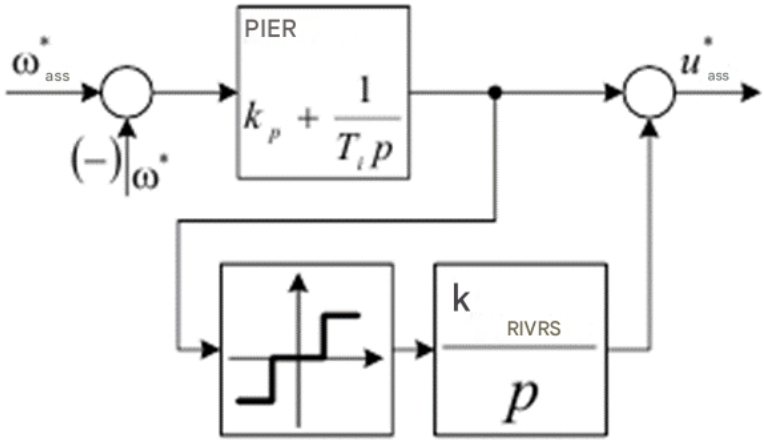

Fig. 1. Block diagram of the Relay Integrator of Speed Controller Output (RISCO)

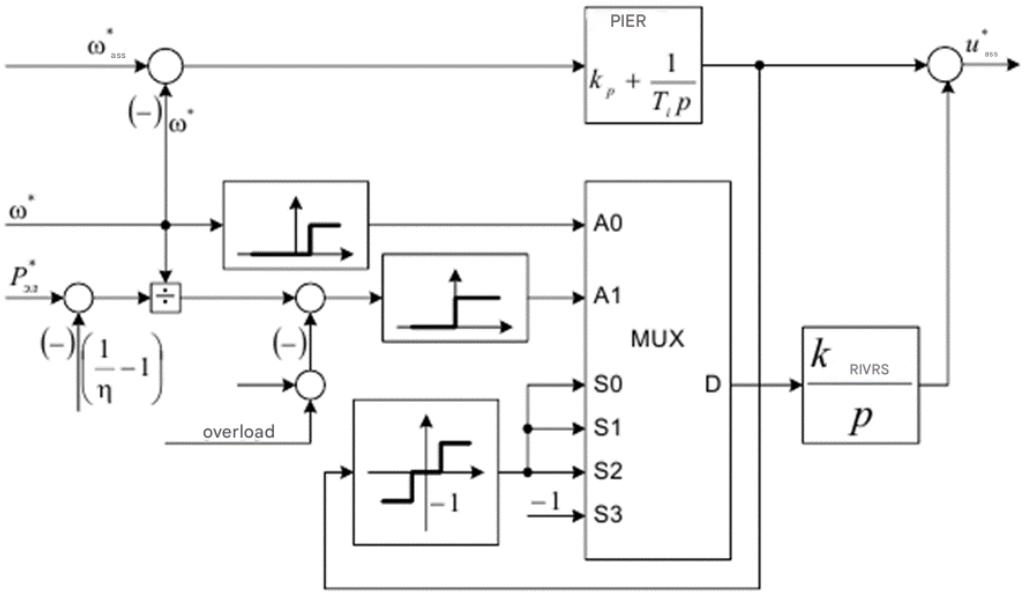

Fig. 2. Complete scheme of the adaptive regulator with switchable structure for torque overload protection

Conclusions. The advantages and disadvantages of SRDs have been analyzed, and an original control system structure with an adaptive speed controller and torque cut-off has been proposed. The system is adapted for multi-phase motors (5-6 phases) and controlled via a DC/DC converter with current control, which allows operation without current limiting (maximum efficiency mode). Simulation confirmed that the adaptive regulator ensures the smoothest start-up, which solves the problem of RPS operation at low speeds. The results can be extended to drives powered by an on-board unstable DC network.

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AUTOMATION OF NON-INVASIVE HEALTH MONITORING

Abstract. *The aim of the work is the development and research of the principles for creating a non-contact blood glucose meter and a glycemia prediction algorithm based on machine learning methods. The relevance of the topic is due to the need for non-invasive, continuous, and accurate glucose monitoring for effective management of diabetes mellitus. The research includes the analysis of the structural and optical properties of biological tissues and cells, the selection of the optimal radiation source and photoreceptor, the development of the structural diagram of the meter, and the creation of a signal processing algorithm. The central part of the work is the development and experimental study of the glycemia prediction algorithm using machine learning (ML) methods, which allows for the timely anticipation of changes in blood sugar levels.*

Key words: *blood glucose, non-contact measurement, optical properties of tissues, prediction algorithm, glycemia, machine learning, non-invasive monitoring.*

Introduction. Diabetes mellitus is one of the most common diseases worldwide. Its effective treatment requires constant monitoring of blood glucose levels, which is traditionally done using invasive methods (glucometers) that are painful and cannot ensure continuous monitoring. The development of non-invasive measurement methods is a priority task in medical engineering. A promising direction is the use of optical methods, which, based on the analysis of light absorption or scattering by biological tissues, can provide non-contact and continuous glucose determination. Equally important is the task of glycemia prediction, which allows patients and "artificial pancreas" systems to prevent hypo- and hyperglycemic states. The goal of this work is the development and experimental verification of a hardware-software complex for non-contact measurement and prediction of glucose levels.

Methods and Materials. The work includes an analysis of the structural features of biological tissues and their optical properties, which form the basis for non-contact measurement (Fig. 1). It is established that the key factors are the absorption and scattering of light by the main components of blood and tissues. The selection of the radiation source (LTE-209 LED) and photoresistor (VT935G) is substantiated based on their spectral characteristics and correspondence to the optical transparency window of biotissues.

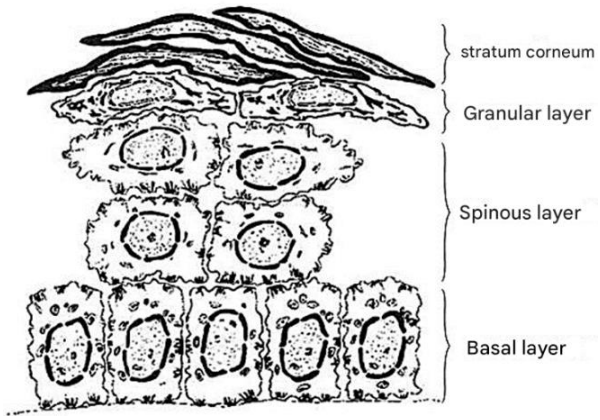

Fig. 1. Scheme of light propagation in biological tissues

A structural diagram of the non-contact meter was developed, which includes a light source, a receiving element, a signal processing unit, and a microcontroller for control and display. A theoretical calculation was performed, and a stand was built for conducting experiments. The classification of mathematical models for glycemia prediction (physiological, empirical, based on machine learning) was analyzed in detail. Machine learning (ML) methods are applied for the development of the glucose prediction algorithm, as they are the most flexible and adaptive. An algorithm for glucose prediction was developed using experimental data collected on the created stand. An experimental study of the prediction algorithm with an assessment of its accuracy was conducted (Fig. 2).

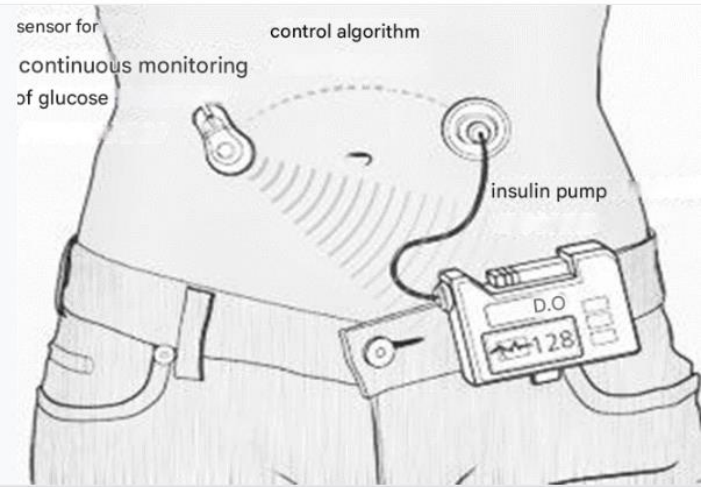

Fig. 2. Results of blood glucose level prediction using the machine learning method

The prediction results were analyzed using clinical assessment based on Clarke Error Grid Analysis criteria, which is the standard for evaluating glucometer accuracy.

Conclusions. A structural diagram of a non-contact blood glucose meter and a signal processing algorithm that considers the optical properties of biological tissues were developed. Theoretical calculations were performed, and a physical stand for data collection was created. An algorithm for glycemia prediction based on machine learning methods, which uses experimental data collected on the developed stand, was researched and developed. The analysis of the prediction results confirmed the high accuracy of the developed algorithm, indicating its potential for use in "artificial pancreas" systems and the improvement of diabetes monitoring.

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RESEARCH ON A WIRELESS MONITORING SYSTEM FOR SERVO DRIVE PARAMETERS

Abstract. *The purpose of the work is to develop an optimal Electric Drive Control System (EDCS) for direct-drive servos aimed at increasing the productivity and accuracy of machine-building equipment while minimizing the total product cost. The relevance is due to the need for domestic developments to compete with leading global manufacturers (Siemens, Yaskawa, Hitachi) and the inefficiency of achieving high performance solely by increasing power or complicating measuring systems. The research focuses on utilizing the potential of digital technology to implement complex, effective control algorithms. The work includes a review and analysis of electric drive parameter identification methods, compiling a detailed mathematical description of the servo drive, as well as designing and assembling an experimental setup to verify the developed EDCS.*

Key words: *servo drive, direct drive, control system, optimization, accuracy, productivity, parameter identification, digital control, metalworking equipment.*

Introduction. In precision machine building, direct (gearless) drives have found widespread application for fast and high-precision movements. Achieving high operational performance of domestic servo drives is realized not only by improving the design of the machine tool and the electromechanical converter, but also, to a large extent, by the optimal design of the Electric Drive Control System (EDCS). The continuous improvement of operational characteristics is made possible by the development of digital technology, which allows for the implementation of more complex and effective control algorithms. Thus, the current task of meeting the growing demands for equipment productivity and accuracy is solved by building a more efficient Control System (CS).

Methods and Materials. To achieve the goal, the following tasks were consistently addressed: a review of parameter identification methods was conducted (active/passive, deterministic/statistical), and the frequency identification method was chosen as the most appropriate for this structure. A mathematical description of the servo drive with a DC motor and a gearbox was compiled, presented as a system of differential equations, and in operator form — as a transfer function. The model accounts for electromagnetic torque, EMF, and moment of inertia.

Based on the mathematical description, a Simulink model of the servo drive was created (Fig. 1), which includes a PID controller as a control system.

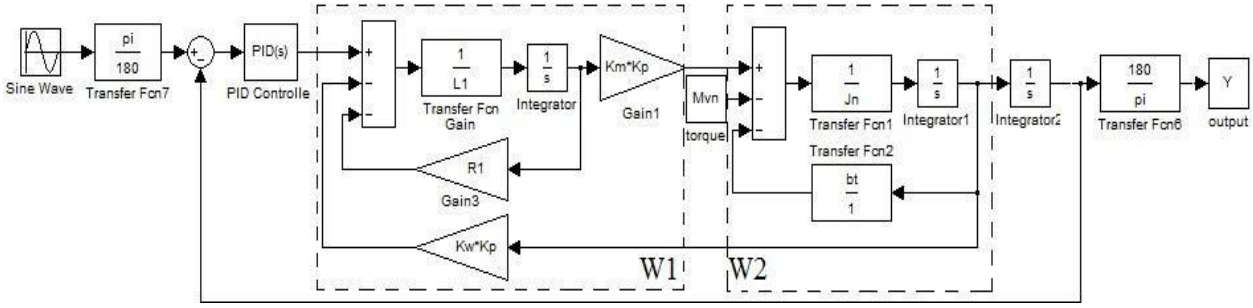

Fig. 1. Simulink model of the Dynamixel rx24-f servo drive

To identify unknown parameters (armature resistance, gearbox viscous friction coefficient, moment of inertia, PID controller parameters) and verify the model, an experimental test bench was designed and assembled (Fig. 2). Measurements on the bench were performed using an encoder and a current sensor (based on a shunt and an INA337 measuring amplifier).

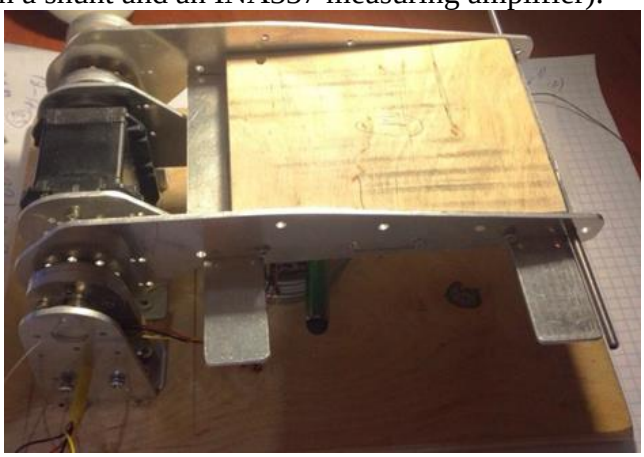

Fig. 2. Test bench for servo drive parameter identification

A separate stage is the development of a wireless control device (Fig. 3), which allows for the automation and flexibility of the system. The control block diagram involves the use of a tone encoder/decoder and radio modules, which provide switching of executive relays.

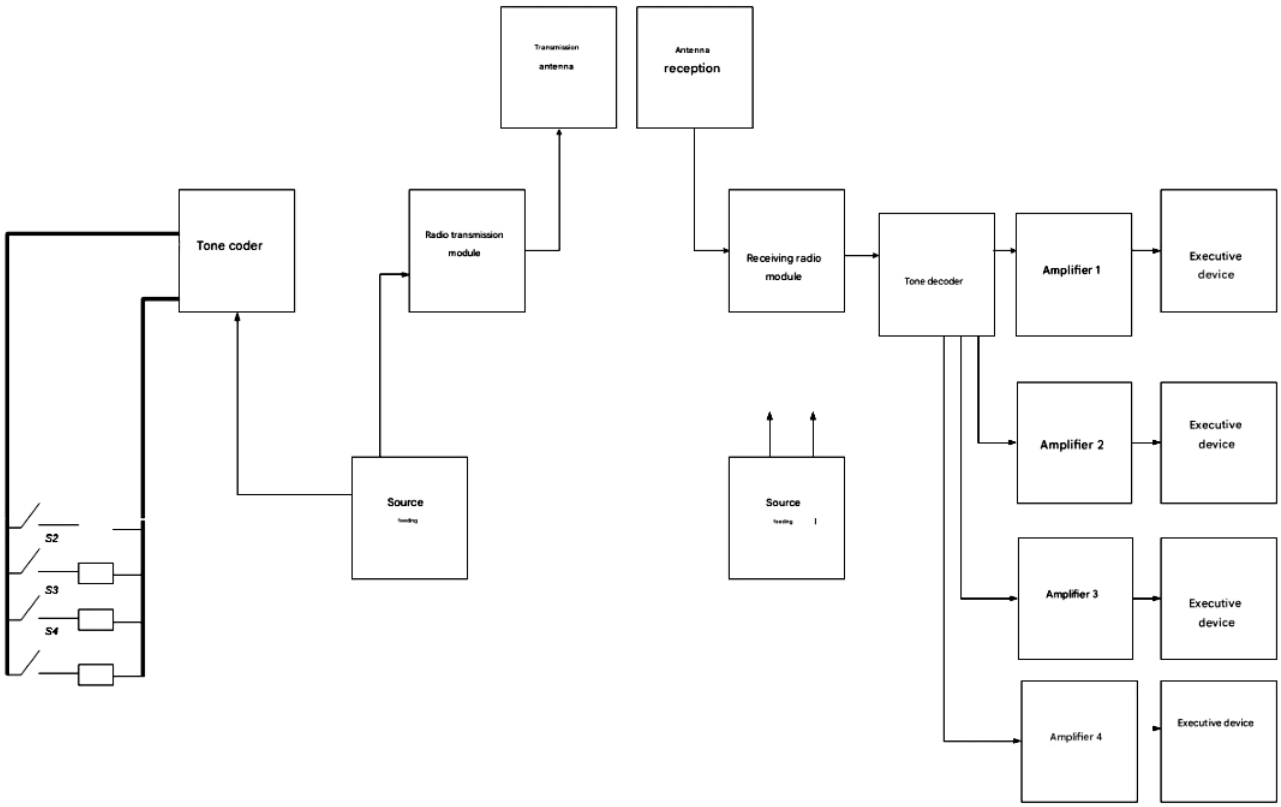

Fig. 3. Block diagram of the servo drive control unit (wireless device)

Conclusions. During the course of this work, the relevant task of developing an optimal control system for a servo drive was addressed. To achieve this, existing identification methods were analyzed, and the frequency method was selected. Based on this, a detailed mathematical description and a digital model of the system in Simulink were created. An experimental test bench was designed and assembled to verify the model and identify unknown parameters. Furthermore, a concept for a wireless control device was developed. This work, combining modeling and experimentation, lays the foundation for further algorithm optimization and the creation of competitive domestic electric drive control systems capable of increasing equipment accuracy and productivity.

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DEVELOPMENT AND RESEARCH OF AN AUTOMATED GAS CONSUMPTION CONTROL SYSTEM

Abstract. *The purpose of this work is to develop a gas flow regulator (GFR) based on standard components from SMC. The problem is that existing integrated GFRs on the market are expensive, whereas the components for assembling them (flow meters and proportional valves) are available, but SMC does not offer a ready-made controller. This work proposes the creation of a modular control system with feedback, consisting of a flow meter (PF2A/PFM), a proportional valve (VEF), and a programmable logic controller (PLC). A mathematical model of the system was developed in Simulink, and a physical prototype was built based on a Mitsubishi PLC. A control algorithm was developed and implemented in Ladder Diagram language, ensuring precise maintenance of the set gas flow by compensating for changes in inlet pressure. Experimental studies confirmed the system's functionality and accuracy.*

Key words: *gas flow regulator (GFR), SMC, PLC, feedback, proportional valve, flow meter, Ladder Diagram, PI-controller.*

Introduction. A gas flow regulator is a device that allows for the precise control of the gas flow rate. Accurate regulation is necessary because flow depends on multiple parameters: channel cross-section, pressure, and temperature. Simple throttling does not guarantee a precise flow rate without accounting for these factors. For precise regulation, a closed-loop control system is required, which includes an actuator (valve), a sensor (flow meter), and a controller.

Existing integrated GFRs on the market are expensive devices. SMC, a leader in the pneumatics market, produces individual components (proportional valves of the PVQ/VEF series and flow meters PF2A/PFM) but does not offer a ready-made integrated regulator. Therefore, creating a flexible, modular, and cost-effective regulator based on these components is a relevant task. The purpose of this work is to develop a gas flow regulator based on SMC components.

Methods and Materials. To achieve this goal, an automatic control system was developed based on the principle of a tracking system with negative feedback.

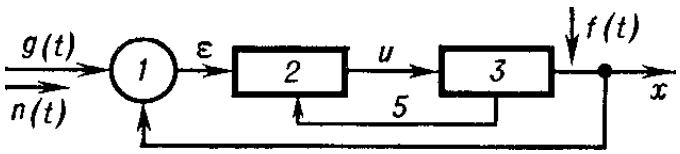

Fig. 1. Block diagram of a tracking system (1 - comparator, 2 - amplifier-converter, 3 - actuator, g(t) - setpoint, x - output value)

In the developed system (Fig. 1), the setpoint $g(t)$ (required flow rate) is compared with the actual output value x (signal from the flow meter). The error signal ε is sent to the controller (2), which commands the actuator (3) – the proportional valve.

The system was physically implemented using the following components:

- Flow Meter: SMC PF2A511 (with 1-5 V analog output).
- Valve: SMC VEF 3121 electropneumatic proportional valve.

- Amplifier: SMC VEA250 (to convert the control signal to a 0-1 A current and modulate it to overcome spool friction).
- Controller: Mitsubishi Electric FX1N PLC with an FXon-3A analog module.

The control algorithm (a software PI controller) was implemented in the relay-contact logic language (Ladder Diagram) (Fig. 2).

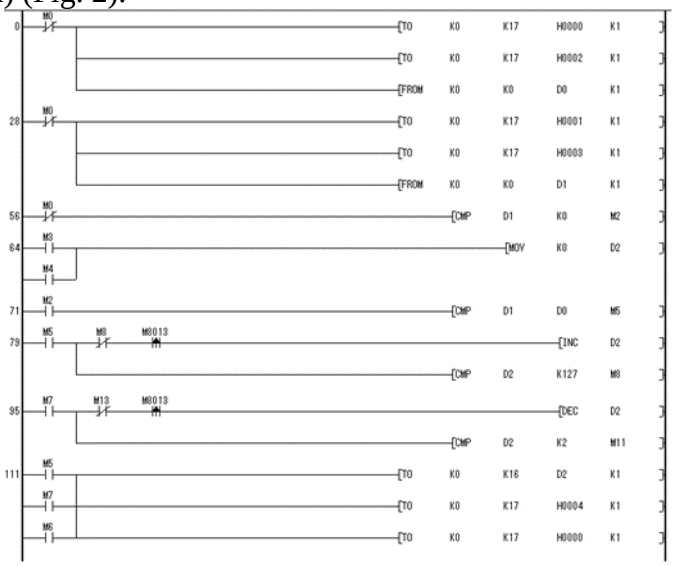

Fig. 2. GFR operation program in Ladder Diagram language

The algorithm (Fig. 2) constantly compares the setpoint (from register D1) with the actual value (from register D0). If the actual flow is less than the setpoint (D1 > D0), the program increments (INC) the output register D2, slowly opening the valve. If the flow is greater (D1 < D0), the register D2 is decremented (DEC). To avoid rapid oscillations (hunting) of the valve, the increment/decrement is performed smoothly, with a clock pulse of once per second (marker M8013), which ensures high regulation accuracy.

The results of experimental studies (Fig. 3) showed the system's response to a change in the setpoint signal ($U_З$) and the system's ability ($U_{ВХ}$) to accurately follow the stepped changes in the setpoint.

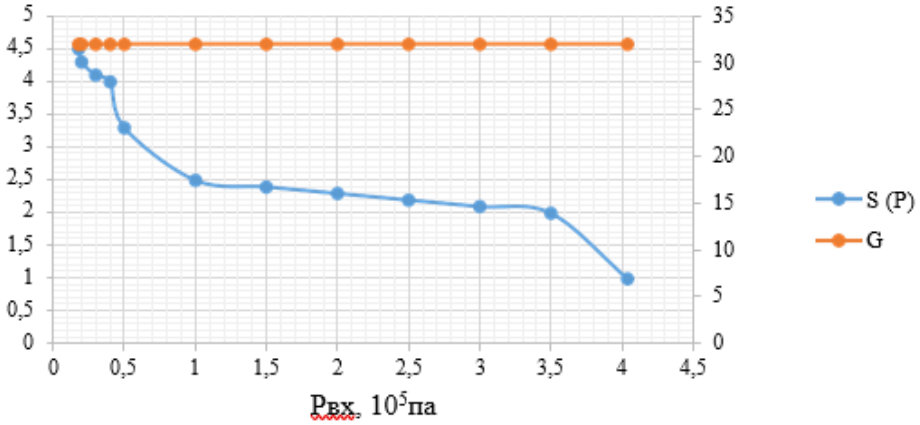

Fig. 3. Experimental transient response of the GFR to a setpoint change

Conclusions. During this work, a gas flow regulator was developed and physically implemented based on standard SMC components (PF2A flow meter, VEF valve) and a Mitsubishi PLC. A mathematical model was created, and a feedback control algorithm was developed and implemented using Ladder Diagram language. Experimental tests of the assembled bench proved its full functionality. The developed GFR successfully meets the objective: it automatically maintains the set gas flow rate by compensating for disturbances (a drop in inlet pressure) by changing the control voltage to the valve. The created device is not inferior to existing expensive analogs in terms of regulation accuracy, but it is significantly cheaper and more flexible for configuring for specific technical tasks.

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AUTOMATED MEASURING STAND FOR SPACECRAFT CONTROL

Abstract. *The aim of the work is to increase the level of metrological support for automated measurement and computation complexes for mass geometry parameters (MGP) of spacecraft (SC) by combining the measurements of mass, center of mass (CM) position, and components of the tensor of inertia (TI) on a single piece of equipment. The problem of high cost, low unification, and high operational expenses of traditional separate-base test benches is being solved. A combined scheme is proposed, which integrates the method of forced balancing in an unstable position for measuring static MGP and the physical pendulum method with an elastic coupling for dynamic MGP. The key innovation is the replacement of expensive aerostatic bearings with standard rolling bearings, incorporating a developed system for active compensation of dissipative forces (friction)]. An experimental prototype of the "AMIK" test bench confirmed the achievement of high accuracy indicators, equivalent to those of separate-base benches.*

Key words: *mass geometry parameters (MGP), spacecraft (SC), center of mass (CM), moment of inertia (MOI), tensor of inertia (TI), combined test bench, friction compensation.*

Introduction. The task of a spacecraft's (SC) control system is to ensure its stable movement along a given trajectory. The reliability of this system directly depends on the accuracy of the input mass geometry parameters (MGP): mass, center of mass (CM) position, and components of the tensor of inertia (TI) [4]. MGP control is a mandatory procedure during the final assembly stage of the SC. Modern MGP test benches are divided into traditional (measuring a single parameter) and combined [3]. Traditional benches have high accuracy but are characterized by high operational costs, a low level of unification, and require manual operation. Existing combined benches are either low-accuracy (domestic) or extremely expensive (foreign) due to the use of complex aerostatic bearings for friction compensation [1].Thus, the aim of the work is to increase the level of metrological support for automated MGP measurement and computation complexes by combining the measurements of mass, CM, and TI on a single piece of equipment, achieving a high level of accuracy (horizontal $CM \pm 0.1\%$, axial $MOI \pm 0.1\%$), and reducing operational and production costs.

Methods and Materials. As a result of analyzing existing methods, a combined test bench scheme was chosen. For measuring static MGP (mass and CM), the method of forced static balancing of the moving system in an unstable equilibrium position was selected. The scheme (Fig. 1) involves tilting the platform (1) with the object (9) relative to an axis (5) until the total CM is above the tilt axis. By measuring the tilt angles at four plan-table positions (0°, 90°, 180°, 270°), all three CM coordinates are calculated. Mass is determined by an additional measurement using a counterweight.

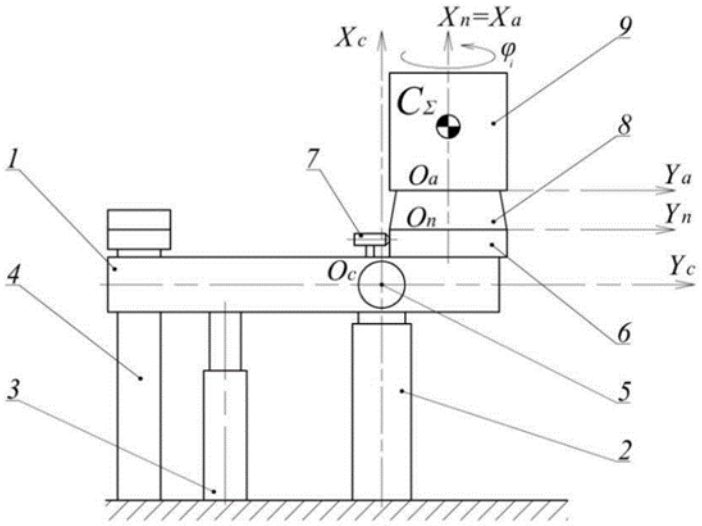

Fig. 1. Schematic diagram of center of mass coordinate measurement (1 - platform, 5 - tilt axis, 9 - test object)

For measuring dynamic MGP (moments of inertia), the pendulum method with an elastic coupling (inverted physical pendulum method) was chosen. The oscillation axis is aligned with the bench's tilt axis, and oscillations are generated by a spring unit.

The key problem for combined benches is friction in the supports, which introduces errors in both static measurements (stiction moment) and dynamic measurements (energy dissipation, oscillation damping, period change). Instead of expensive aerostatic bearings [1], it is proposed to use standard rolling bearings combined with an active friction compensation system [2].

The support design (Fig. 2) implements the principle of "decoupled bearings." An electric motor (6) forcibly rotates or oscillates an intermediate shaft (4), breaking the adhesive bond in the support bearings (3).

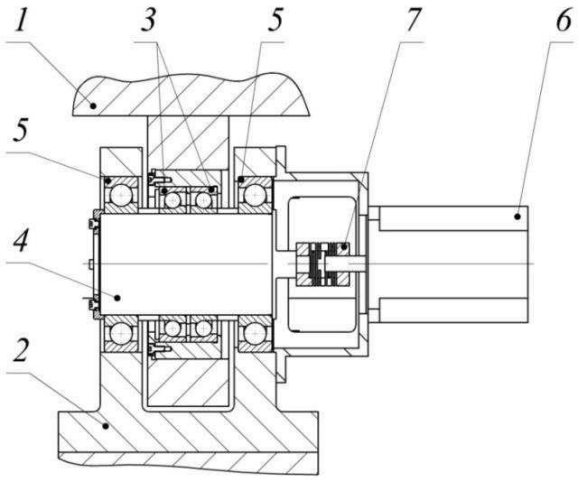

Fig. 2. Schematic design of the support with friction compensation (3 - support bearings, 4 - intermediate shaft, 6 - electric motor)

During static measurements (CM), a vibrational friction reduction mode is activated. During dynamic measurements (MOI), a tracking system with feedback on the tilt angle is engaged. A PID controller manages the motors, synchronizing their movement with the platform's oscillations. This fully compensates for energy dissipation and creates stable, undamped self-oscillations [2], allowing the period to be measured with high precision (Fig. 3).

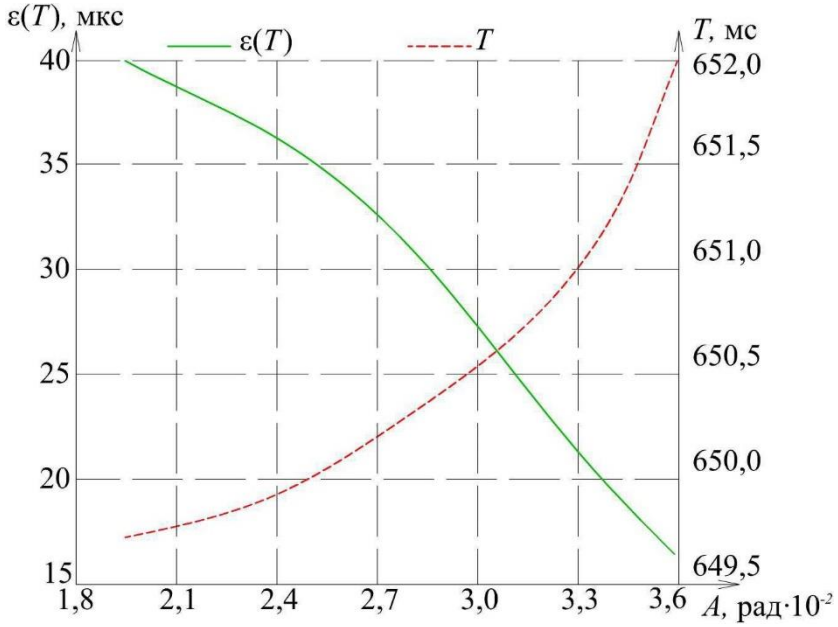

Fig. 3. Empirical dependencies of the period (T) and random error (epsilon(T)) on the amplitude (A) with active friction compensation

Conclusions. A combined complex for measuring MGP (mass geometry parameters) of spacecraft on a single piece of equipment has been developed, addressing the problems of high cost and low unification of traditional test benches.

The key innovation is the replacement of expensive aerostatic bearings with standard rolling bearings, combined with a system for active friction compensation.

This made it possible to achieve high metrological accuracy, equivalent to separate benches, which was confirmed by the "AMIK" experimental prototype. The work opens the way for creating cost-effective and automated MGP control complexes.

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RECONSTRUCTION OF SURFACES WITH SCALE-INVARIANT MORPHOLOGY USING ATOMIC FORCE MICROSCOPY

Abstract. *The article proposes a coherent method for reproducing the topography of surfaces with statistical scale invariance based on atomic force microscopy (AFM) data. It is shown how the combination of preliminary probe shape estimation, spectral relief analysis and probe-sample convolution correction makes it possible to obtain stable fractal parameters (fractal dimension or Hirst index, correlation length) and reduce the error of amplitude estimates. surfaces and real samples, and an example of a minimum set of control checks for the quality of reconstruction is given. The method is suitable for thin films, polymers and functional coatings, where surface roughness determines performance properties (adhesion, friction, wettability). The applicability of the approach for migration between different AFM modes and scan parameters without loss of reproducibility of results is demonstrated.*

Key words: *fractal dimension, spectral analysis, correlation length, probe artifacts, measurement validation.*

Introduction. Surface morphology with large-scale invariance occurs in thin films, coatings and composites and significantly affects adhesion, corrosion resistance, optical and tribological properties. To quantitatively describe it, fractal parameters and power spectrum analysis are increasingly used, which better preserves information at different spatial scales than single roughness parameters [1]. At the same time, the results critically depend on the quality of the initial AFM data and the correct correction of distortions due to the shape of the probe.

Methods for reconstructing the real profile of the probe and "blind" deconvolution, including differentiated approaches that increase the reliability of relief estimates, are actively developing in the world [2–3]. Applied AFM studies of thin films and nanostructures using fractal analysis have long been conducted in the world, but systematic procedures for probe-sample convolution correction are not always used. This necessitates a technique that combines probe evaluation, deconvolution, and spectral analysis with transparent quality checks [4–5].

The article is aimed at describing a practical method for reproducing scale-invariant surfaces according to AFM data with a minimum set of steps, namely: estimation of the probe shape; correction of artifacts; stable determination of fractal parameters; validation on test and real samples.

Let us consider in detail the sequence of implementation of the method of reproduction of scale-invariant surfaces according to AFM data. So, before processing this data, the scanning mode and parameters (field, step, speed, filters of the device) are recorded. It is recommended to provide at least two observation scales to verify the scale invariance and stability of spectral estimates [1, 4].

For high-quality deconvolution, the size and shape of the probe (vertex radius, taper, possible chipping) are required. This is achieved by measuring reference structures and subsequent image inversion, and modern approaches allow the wear of these probes to be taken into account [2].

After leveling the plane, deconvolution is performed. "Blind" methods and their differential modifications reduce the displacement of spectrum amplitudes and restore acute profile features, which is critical for correct estimates of fractal parameters [3].

Based on the cleaned relief, 1D/2D-PSD is calculated, and on the scale-invariant segment, the slope of the spectrum and related parameters (Hurst score or fractal dimension), as well as the correlation length, are determined. For nanofilms, this allows tracking the evolution of the terrain [1].

Next, simple tests are introduced: parameter stability when changing the window size and mesh pitch, anti-aliasing invariance, and sensitivity to probe model variations. We offer a minimum list of control metrics, Table. 1.

Table 1. Minimum set of renovation quality checks

Check	Measure/Criterion	Expected result
Resize a window	Deviation of parameters < 10%	Stability of fractal parameters
Effects of anti-aliasing	PSD Tilt Change < 0.05	Slight sensitivity in the operating range
Probe model variation	ΔH, Δξ within the margin of error	Robustness to probe error
Repeatability of measurements	rRMSE profile < 5%	Reproducibility between scans

Validation on standards and real samples occurs as follows. First, the method is tested on calibration gratings (standards with known parameters), then on real films (coatings). For surfaces after heat treatment, a change in the slope of the spectrum and correlation length in the predicted direction is expected [5].

As practical recommendations for laboratories, the following is proposed: the steps from data acquisition to reporting are systematized: a log of scanning parameters; a file with the geometry of the probe; version of the deconvolution algorithm; PSD graphics; a table of parameters with confidence limits. This dramatically increases reproducibility between installations.

Therefore, the method stated in the article is suitable for obtaining topographies of thin films without sharp overhangs and subject to the correct assessment of the probe. At the same time, for strongly anisotropic structures, 2D-PSD and angular analysis are recommended. Compressed scanning and integration with AFM electrical and mechanical channels are promising.

Conclusions. A practical sequence of steps for the reproduction of scale-invariant surfaces according to AFM data with probe-sample convolution correction and subsequent spectral analysis, which provides stable receipt of fractal parameters, is proposed.

The use of probe shape and deconvolution estimation procedures reduces the distortion of high-frequency relief components and increases the reliability of the interpretation of technological influences.

A minimum set of quality checks for reconstruction is given, sufficient for routine validation in laboratory practice.

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DEVELOPMENT AND RESEARCH OF AN OPTICAL TELEVISION SYSTEM FOR MONITORING AIRSPACE

Abstract. *The architecture of an optical television system for airspace monitoring is proposed, combining a high-quality optical path with translucent multilayer coatings, a controlled PTZ camera and intelligent video processing modules for detecting small air targets. The role of the selection of optical materials and anti-reflective coatings in increasing contrast, as well as the need to take into account atmospheric turbulence (stabilization, adaptive optics and digital compensation) is shown. For Object detection uses modern algorithms of small-object detection in aerial photographic images. Requirements for calibration, reliability and reproducibility of measurements based on approaches to the design of optoelectronic systems and thin coatings are given. The system is focused on critical infrastructure protection and border control and provides scalability for different surveillance scenarios.*

Key words: *adaptive optics, atmospheric turbulence, anti-reflective coatings, detection of small targets, PTZ guidance.*

Introduction. Airspace monitoring is complicated by the simultaneous action of two factors: optical distortion due to the atmosphere and small dimensionality or low contrast of targets against the sky. Therefore, optical television systems must combine a high-quality optical path (lens, coating, radiation receiver) with stabilized guidance mechanics and intelligent image processing. In the general structure of optoelectronic devices, the key is the "lens → radiation receiver" unit, which connects the optical and electronic parts and determines the metrological properties of measurements.

The world is creating EO systems for early detection of drones, combining multispectral sensors and AI video analysis. However, challenges remain: turbulence reduces detail, and typical detectors degrade accuracy on exemplary targets [1, 5]. Additionally, optical losses affect performance, which requires optimization of anti-reflective (AR) coatings and thin-film materials [3]. Therefore, the purpose of the article is to harmonize the requirements for optics, mechanics and algorithms and establish a holistic approach to the design of such a system.

Let's consider the system requirements and the general architecture of such a system. The latter includes: a lens with AR coatings; CCD/CMOS sensor; Managed PTZ platform for wide field of view and quick pointing; pre-stabilization module; module for detecting small objects; telemetry and archive channel. Modern PTZ cameras support auto-tracking and routing presets, which is critical for large viewing sectors [4].

The reproducibility of spectral characteristics and low reflection losses ensure the correct selection of multilayer coatings (SiO_2, MgF_2, TiO_2, etc.) and control of deposition modes. This directly increases the contrast of low-contrast targets against the background of the sky [3]. In the technological part, developments in the design and analysis of optical coatings and software optimization of their thicknesses are useful, which reduces the total reflection coefficient of the lens → receiver assembly.

For long distances, beam expansion, scintillations and phase disturbances must also be taken into account. Practical approaches for this are: hardware adaptive optics (deformable mirrors or wavefront sensors) and/or digital compensation (superresolution, registration, "lucky imaging") [2, 6, 7]. The dynamics of the control system (bandwidth, number of drives) are consistent with the assessment of turbulence on the track.

Detection of small targets against the background of the sky occurs in this way. Small UAVs have a few pixels on the long side, so specialized detection architectures with improved backbon, SE modules, advanced Mosaic, and super-resolution preprocessing are required [5, 8]. In sky-to-ground problems, the steps of pre-segmenting the sky, noise filtering, and post-track with sequence checking are useful to reduce false positives.

At the same time, calibration of internal and external parameters, assessment of MTF/PSF, verification of the stability of AR coatings and reproducibility of measurements should be part of the regulations. In design, the calculation of the accuracy of assembly work, manufacturability, reliability and error control, which is laid down at the stage of designing the surveillance system, are important.

Applied implementation and testing. Typical configuration: 25×-50× lens, 4-8 MP sensor, PTZ with auto-tracking, compute module (GPU/Jetson), weather sensors (wind speed, visibility). It is advisable to conduct pilot tests in two modes: static inspection (we look for the range of response on known targets) and the "target maneuver" scenario (we evaluate recall – precision with stabilization).

Conclusions. The effectiveness of airspace monitoring is determined by the balance of optics (AR coating), guidance mechanics (PTZ stabilization) and algorithms for detecting small objects.

Accounting for turbulence by hardware or software increases detection range and reduces false positives.

Consistent calibration and quality control procedures ensure the reproducibility and metrological reliability of the system in the field.

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DEVELOPMENT AND RESEARCH OF A COMBINED 3D SCANNER WITH PRECISE DETERMINATION OF THE GEOMETRY OF DARK AND TRANSPARENT OBJECTS

Abstract. *The architecture of a combined non-contact 3D scanner is proposed, which combines structured lighting, polarization imaging and an auxiliary depth channel (ToF/stereo) for reliable measurement of complex surfaces – superblack, shiny and transparent. A consistent sequence of calibrations, channel matching algorithms and glare screening, as well as rules for switching modes to the material and scene conditions are described. It is shown that the use of cross-polarization and multi-turn phase Depth safety coding increases the stability of phase deployment and reduces errors in high-contrast areas. An example of hardware configuration and a table of recommended modes for typical materials are given. The solution is focused on engineering metrology, restoration of cultural heritage and quality control of glass and polycarbonate products, where standard methods fail due to pixel saturation or refraction.*

Key words: *non-contact measurements, structured radiation, polarimetry, time-lapse depth, glare reduction, multimodal registration.*

Introduction. The task of accurate 3D reproduction of complex materials (with low reflection (super-black coatings), with a significant mirror component (polished metals) and with transmittance (glass, PMMA) remains open to most commercial scanners. double passages through the boundaries of the media [1–3]. More recent work also demonstrates the usefulness of merging depth sensors (ToF/stereo) with structured lighting to resolve ambiguities and phase deployment in problem areas [4].

In Ukraine and the world, polarization cameras and cross-polarization schemes that suppress mirror reflections and increase the contrast of bands are being actively studied; For transparent bodies, combinations of polarimetry with stereo vision or laser scanning are offered. However, such approaches often depend on harsh lighting conditions, have ambiguity at the zenith angle, or require complex calibrations of multi-channel sensors, which makes repeatability and portability between scenarios difficult [2, 5]. Therefore, a practice-oriented system is needed that coordinates channels, minimizes reflection and refraction artifacts, and automatically selects the shooting mode.

The article is aimed at describing the hardware and software architecture of the combined scanner and the methods of its operation with recommendations for modes for different materials, based on modern developments in polarized structured light, reconstruction of transparent bodies and fusion of deep sources [1–4].

Consider the architecture and measurement channels. The scanner consists of a structured light projector with controlled polarization, an RGB or monochrome camera with a rotary analyzer, an auxiliary depth channel (ToF or stereo pair), a synchronization unit and a rotating platform for multi-view shooting. Basic patterns (multi-frequency phase bands) for reflective surfaces are projections of polarized bands with four-channel polarization reading. This combination increases resistance to overexposure and "dips" in shadows [1, 2].

To coordinate the calibration procedure, the following sequence is proposed: internal calibration of the chambers or projector (through a chessboard and phase templates); polarization zero-setting (cross-polarization to estimate leakage); joint calibration of the depth channel with the visual channel (through rigidly fixed targets and multi-plane scenes) – for correct geometric registration and scaling [4, 6].

The algorithmic processing pipeline is as follows. After synchronous readout, the frames undergo HDR fusion of exposures, polarized band orientation estimation, phase demodulation, and spatial unfolding using a rough depth map from ToF or stereo as hints. Next, local point clouds are combined from different angles and their joint optimization is performed. For transparent objects, a "refractive mask" is added - cutting off rays with an inappropriate polarization vector [1, 3, 5].

Switching rules were also proposed: for super black - increased projector power, multiple exposures; for mirror – cross-polarization and reduction of the contrast of the stripes; for transparent ones – polarized structured light with safety depth and multi-species registration [1–3].

An example of the configuration of the hardware part **of the combined scanner is given in Table 1, and** the recommended modes for typical materials are given in Table 2.

Table 1. Example of Combined Scanner Node Configuration

Knot	Example of parameters or requirements	Reason for choosing
Structured Light Projector	LED/NIR, Controlled Polarization, Multi-Frequency Patterns	Overlight control, polarimetry compatibility
Camera	(mono) polarizing, global shutter, variable filter	Minimize blur, suppress glare
Deep Channel	ToF or stereo (60-120mm base)	Hint for phase deployment, recovery of dips
Sync	hardware triggers, TTL	Phase and exposure matching
Sample rotation	360°, deterministic pitch	Closing "dead zones"

Table 2. Selection of modes for the material and condition of the scene

Material or condition	Lighting	Polarization	Deep Channel	Comment
Super black, matte	High intensity, multi-frequency bands	Off	ToF and stereo enabled	Reducing Shadow Dips
Polished metals	moderate intensity	Cross	as needed	Glare suppression, stable phases
Transparent (glass, PMMA)	polarized stripes	crossover + channel analysis	Preferably	Cutting off rays with refraction
Variable lighting	NIR band	Behind the Scenes	Preferably	Desensitization to backlights

Consequently, polarized structured light confirms performance on mirror surfaces, and for transparent bodies, modern robots use a combination of polarization prompts and stereovision and machine learning; The 2022–2024 reviews capture these trends and note challenges – dependence on lighting geometry, ambiguity of angles, and demanding calibrations [2, 3, 5]. The addition of a depth channel removes some of the ambiguities and facilitates phase deployment in high-contrast areas [4].

Conclusions. The proposed combined architecture aligns the advantages of structured light, polarimetry, and ToF and stereo, making measurements resistant to glare and transparency.

The described sequence of calibrations and mode switching rules ensure repeatability and portability between scenes.

Recommendations for settings for different materials allow you to practically implement the system in metrology, restoration and quality control of glass or polycarbonate products.

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COMPARATIVE ANALYSIS OF SCANNING PROBE MICROSCOPY METHODS

Abstract. *The paper discusses the main methods of scanning probe microscopy (SPM), which are key tools of modern nanotechnological research. SPM covers a set of methods based on the analysis of the interaction between the physical probe and the surface of the sample, which makes it possible to obtain three-dimensional images with spatial resolution at the level of individual atoms.*

The paper provides a detailed description of the principles of operation, advantages and limitations of scanning tunneling (STM), atomic force (AFM), magnetic force (MSM), electrostatic force (ESM) and scanning near-field optical microscopy (SNOM).

The comparative analysis shows that each of the methods is characterized by its own sphere of effective use and has both advantages and disadvantages. STM provides the highest resolution, but is limited to the study of conductive materials, requires vacuum and cryogenic temperatures. AFM exhibits versatility by allowing the study of conductors, dielectrics, and fluids without special conditions. MFM and EFM are focused on analyzing the magnetic and electrical properties of materials, respectively, while SNOM makes it possible to overcome the diffraction limit in optical microscopy. According to the totality of parameters, the most universal and practical method is atomic force microscopy, which combines high accuracy, stability and the ability to study different types of samples in a wide range of media, while providing a sufficiently high accuracy of measurements.

Key words: *spatial resolution, topography and surface properties, experimental conditions, error estimation, reproducibility.*

Introduction. The modern development of nanotechnology is impossible without tools capable of visualizing structures with spatial resolution at the level of individual atoms [1]. One of the most powerful classes of microscopy techniques is scanning probe microscopy (SPM), which encompasses a range of techniques based on the interaction between the physical probe and the sample surface [1-6].

Unlike optical microscopes, in SPM, the image is formed by analyzing the interaction of the probe with the surface during its gradual movement.

The purpose of the article **is to** build a unified system for comparing key approaches of SPM according to agreed criteria (resolution, information content on properties, requirements for the environment, performance, reproducibility) and to formulate practical recommendations for the selection of tools for specific nanocharacterization tasks.

The main methods of scanning probe microscopy include [1-6]: scanning tunneling microscopy (STM), atomic force microscopy (AFM), magnetic force microscopy (MFM), electrostatic force microscopy (ESM), scanning near-field optical microscopy (SNOM).

Thus, for a comprehensive analysis of the properties of materials at the nanolevel, a number of methods of scanning probe microscopy (SPM) are used, each of which has its own technical features, operating conditions and scope of application. Table 1 shows the comparative characteristics of the main methods, namely: scanning tunneling (STM), atomic force (AFM), magnetic force (MFM) and electrostatic force (EFM) microscopy.

Table 1. Comparison of the characteristics of AFM methods

SPM method	Resolution		Environment		Samples	Special requirements for measurements
	Lateral, nm	Vertical, nm	Vacuum	Atmospheric pressure		
STM	>0,1	>0,01	+	-	Conductors	Ultra-high vacuum, too low temperature (0.3°K)
AFM	>1	>0,1	+	+	Conductors, semiconductors, dielectrics, Fluid	Stable environment (no temperature changes, humidity), minimal vibrations
MFM	>30	>10	+	+	Magnetic materials	Stable magnetic field
EFM	>10	>1	+	+	Conductors, semiconductors	Maintaining a stable electrical potential, shielding against electrical noise
SNOM	~30-50	~10	-	+	Conductors, semiconductors, dielectrics	Luminous flux stability, minimal vibrations, high cost and manufacturing technology

Scanning tunneling microscopy (STM) provides the highest both lateral (>0.1 nm) and vertical (>0.01 nm) resolutions. However, it is only suitable for conductive surfaces, requires ultra-high vacuum and ultra-low temperatures (up to 0.3 K).

Atomic force microscopy (AFM) is more versatile, as it can work with conductors, semiconductors, dielectrics and even liquids. Its operation is based on measuring the forces of interaction between the probe and the surface, so the method does not require electrical conductivity of the sample. Optimal results are achieved in a stable environment without sudden fluctuations in temperature, humidity or vibrations.

Magnetic force microscopy (MFM) is used to study magnetic materials and domain structure. It has a lower spatial resolution (>30 nm), but provides a detailed analysis of the magnetic properties of surfaces.

Electrostatic-force microscopy (EFM) is designed to study the electrical characteristics of surfaces - potential distribution, charge effects and capacitive properties. Its resolution is about 50 nm, and for correct results, it is necessary to maintain a stable electrical potential and a well-insulated environment.

In general, the applicability of these types of microscopies in world science and technology is shown in Fig. 1.

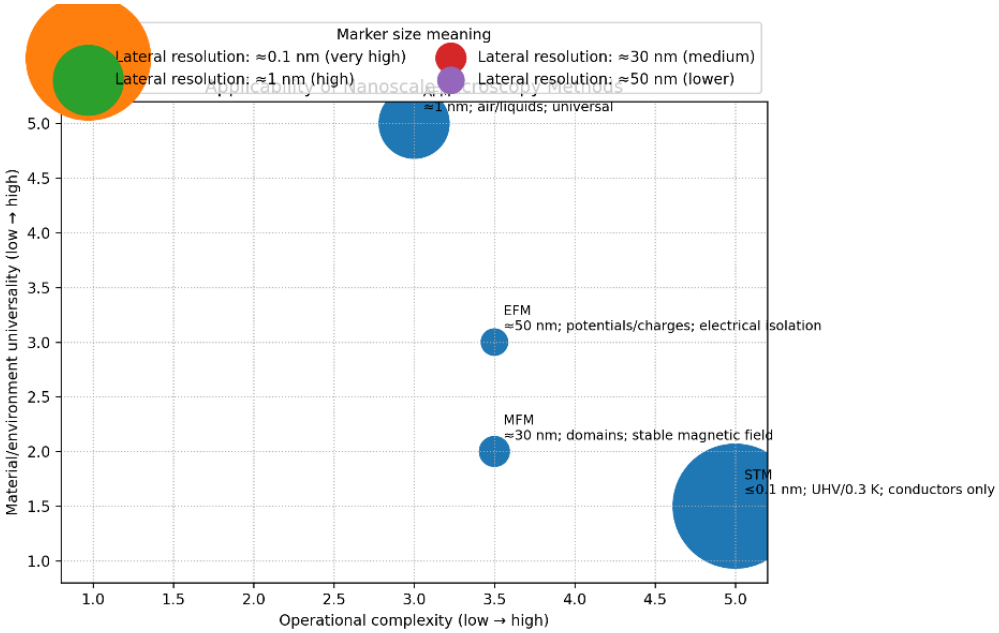

Fig. 1. Applicability of Types of Scanning Probe Microscopy in World Science and Technology

The diagram in Fig.1 shows the trade-off between the complexity of the operation of SPM methods (X-axis) and their versatility in terms of materials and media (Y-axis), and the size of the "bubble" shows the quality of lateral resolution. STM has the largest "bubble" (highest resolution), but is located in the zone of maximum complexity and minimum versatility. AFM occupies the opposite niche: high versatility (works with conductors, dielectrics, liquids) with moderate complexity and with a resolution sufficient for most application problems.

MFM and EFM lie in the middle in terms of complexity, but are inferior in versatility and resolution; instead, they add unique functionality: MFM – mapping of domain structure and magnetic properties, EFM – control of potentials, charges, and capacitive effects. Therefore, the choice of method is determined not only by the need for the "maximum" resolution, but also by what properties need to be measured and in what conditions the laboratory operates. Bottom Line: AFM is the best basic tool for a wide range of tasks and environments; STM is appropriate for atomic-detailed studies of conductors; MFM/EFM – specialized modules that complement morphology with functional maps.

Conclusions. Analysis of scanning probe microscopy methods shows that each of them has its own advantages related to the type of interaction between the probe and the surface, however, according to the totality of characteristics, the most versatile and practical method is atomic force microscopy (AFM). It provides high spatial resolution (up to 1 nanometer in the lateral and up to 0.1 nanometers in the vertical directions), at the same time: it does not require special conditions (ultra-high vacuum, cryogenic temperature, etc.), as opposed to scanning tunneling microscopy. AFM allows you to study both conductive materials, dielectrics, as well as liquids, which significantly expands the scope of its application.

Due to the ability to work in different modes (contact, semi-contact, non-contact), AFM combines measurement accuracy with minimal impact on the surface. It not only forms a topographic image at the nanolevel, but also allows you to study the mechanical, electrical and other properties of materials. Ease of implementation, lack of requirements for complex vacuum systems, high accuracy and reproducibility of results make atomic force microscopy the most promising direction in the development of modern probe methods of nanoresearch.

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IMPROVEMENT OF PIEZOELECTRIC DRIVE FOR MICRO-ROBOT CONTROL

Abstract. *The article is devoted to improving the accuracy, speed and reproducibility of the piezoelectric drive of the microrobot. A set of improvements is proposed: hybrid control "charge + voltage" with hysteresis compensation, automatic maintenance of the operating mode in the resonance region, rationalization of the topology of electrodes and elastic subsystem, as well as calibration and verification procedures. elements allows you to reduce nonlinearities, stabilize the inertial displacement step and reduce energy consumption. The proposed technique is focused on micropositioning, micromanipulation and movement of platforms on a ball support, is compatible with multichannel high-voltage excitation and can be reproduced in laboratory conditions.*

Key words: *inertial step motion, hysteresis compensation, resonance tuning, micro-positioning, repeatability, energy efficiency.*

Introduction. Piezoelectric actuators are the basis of microrobotics due to their nanometer resolution, high specific force and insensitivity to electromagnetic interference. Modern reviews record rapid progress in materials, excitation circuits and types of drives (stack, bimorphic, inertial, ultrasonic), but emphasize the problems of nonlinearity (hysteresis, creep), narrow frequency range and dependence on contact conditions in stepper mechanisms [1, 2, 4].

For ball-bearing microrobots and inertial microdrives, step stability, accurate retention of resonant modes and rational electrode topology of the element that determines force flows are decisive. Recent works demonstrate that changing the configuration of electrodes significantly affects radial forces and controllability, and hysteresis models require frequency-dependent correction [1, 2, 3].

The purpose of the article: to describe and practically substantiate a set of improvements for the piezoelectric drive of a microrobot, namely: conducting hybrid control with reducing hysteresis, developing an algorithm for automatic resonance, recommendations for electrode topology and elastic-friction subsystem, reproducing the calibration and verification procedure.

The paper discusses two common versions of actuators: a piezo tube with a set of sector electrodes and a disc bimorph. In the available laboratory layouts, excitation is carried out by a multi-channel generator up to 300 V and tens of kilohertz with phase shift control and auto-maintenance of resonance. This ensures the formation of a traveling wave of bending deformations and the processional movement of the ball joint with an accuracy of tenths of a micrometer.

For this purpose, a hybrid scheme is proposed: charge excitation to form a "linear" response and small voltage reverse correction by a displacement or velocity sensor (optical or strain gauge). Mathematical core: an inversion model of hysteresis with frequency-dependent parameters, consistent with experiments for bimorphs [3]. The expected effect is a reduction in the width of the loop and positioning errors at high frequencies.

For inertial and ultrasonic modes, the speed directly depends on the accuracy of hitting the natural frequencies. An algorithm for automatic "pick-up" of resonance is proposed: periodic micro-scanning of the frequency with a phase criterion for the maximum of mechanical energy; in case of deviation - phase auto-adjustment. The approach is consistent with practices in ultrasonic motors [2].

In this case, an increase in radial and tangential forces is achieved by changing the pattern of the electrodes. For tubular elements, multi-section or spiral electrodes with a uniform pitch are advisable – this reinforces the controlled radial component and improves grip and retention in microgrips [1, 2]. For disk bimorphs, sectorization with phase shifts for a quarter of the period to form a traveling bending wave.

As an elastic-friction subsystem, rigid parallelograms with low parasitic play and adjustable prepress at the "ball-table" contact are recommended. The higher the quality of ball processing and load stability, the better the repeatability of the step. Working at ultrasonic frequencies increases the resolution of the positioning.

To select modes, MSC modeling (ANSYS/COMSOL) is offered with the allocation of natural oscillation forms and forced response modes. This has already shown efficiency for tubes and disks (shape search at frequencies of 32–34 kHz; 10–12 kHz, respectively). The results of the direction simulation are used to configure the control.

The procedure for calibrating and validating the results was as follows:

– identification of static and dynamic transmission characteristics;
– construction of an inversion model of hysteresis;
– setting the frequency "pick-up";
– assessment of pitch and drift repeatability under different cycles under different loads;

Stability check when temperature or humidity changes.

Separately, it is necessary to record "electrical" limitations and mechanical strength – power supply, which are not covered by a simplified electrical substitution circuit.

In general, in t*1 the* expected effect of different control schemes is generalized, while in t*2* - an example of comparing the basic drive against the improved one on the layout.

Table 1. Comparison of excitation circuits

Scheme	Hysteresis (relative)	Stride stability	Complexity of implementation	Comment
Tension only	High	Average	Low	simple but frequency sensitive
Charge Only	Average	High	Average	More linear characteristic
Hybrid (charge + voltage)	Low	High	Average	Recommended in work

Table 2. Illustrative comparison of basic and advanced drives under the same conditions

Indicator	Base	Improved	Change
Average step, nm	120	95	−21%
Non-reproducibility (σ), nm	30	12	−60%
Speed, mm/s	2.0	2.8	+40%
Energy per step, μJ	1.0	0.7	−30%

Conclusions. A comprehensive improvement of the piezoelectric drive of the microrobot is proposed: hybrid excitation, automatic "pickup" of resonance and recommendations for electrode topology and elastic part.

MSC modeling of oscillation and resonance forms is directly integrated into the control settings, which increases the speed and repeatability of the step.

The technique is compatible with existing laboratory layouts on piezo tubes and disk bimorphs and can be scaled to micromanipulators and positioning platforms. The provisions are consistent with modern reviews and demonstrate practical applicability in microrobotics.

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RESEARCH ON THE INFLUENCE OF TECHNOLOGICAL MODES OF FORMING ANTI-REFLECTION COATINGS ON THEIR OPERATIONAL CHARACTERISTICS

Abstract. *The paper presents an approach to linking the performance indicators of anti-reflective thin layers with the modes of their production. On the basis of combined thermo-vacuum deposition followed by electron-beam treatment, the route of coating formation is proposed and how the selection of beam current, accelerating voltage and pulse duration affects homogeneity, microrelief, porosity and hydrophobicity are shown. For diagnostics, optical measurements, raster electronic and atomic force microscopy, which made it possible to correctly associate the microstructure with optical properties and wear resistance. An example of optimal parameters under which uniform thickness and reduction of porosity are achieved is given, and the procedure for validation on control samples is outlined. The results can be used to improve the transparency and durability of optical elements and functional coatings in observation and photonics instruments.*

Key words: *surface roughness, spectral transmittance, electron beam processing, atomic force microscopy, thermal vacuum deposition.*

Introduction. Optics illumination reduces reflection from surfaces and increases the light transmission of products due to the application of one or more thin films with selected refractive indices. Modern multilayer structures provide broadband reflection reduction throughout the visible range. Among the practical challenges, one of the promising ones is the management of microgeometry and defects in film formation, which directly affect optical loss and durability.

Global trends focus on multilayer dielectric systems (e.g., $TiO_2/Al_2O_3/MgF_2$) and the integration of protective or self-cleaning properties. Review and applied works of 2021–2024 show that the choice of technology and post-processing determines the mechanical resistance and abrasive endurance of AR coatings, but there is a lack of consistent "mode → microstructure → performance relationships" for specific parameter ranges.

The article is aimed at establishing reproducible dependencies between the technological modes of combined formation of anti-reflective layers and their optical and physical-mechanical characteristics on the example of a real vacuum installation and a standard set of measurements (optics, REM, AFM). For this purpose, the available methods are summarized and a comparative analysis of the obtained samples is performed.

The object of the study is the translucent layers on optical glass obtained by combined thermovacuum deposition; subject: dependence of performance characteristics on the modes of obtaining. Optical methods, REM and AFM were used for research; Reliability is ensured by comparison with theory, manufacture and testing of prototypes.

The deposition was performed in a vacuum chamber with subsequent electron beam modification, which made it possible to stabilize the film structure in one cycle. The equipment was modernized on the basis of the industrial UVN-71.

For example, we will give the operating values of processing, namely: beam current 89–93 mA, voltage 1.1–1.4 kV, pulse duration 0.8–3.3 μs. Under these modes, a coating with high uniformity in thickness, a decrease in porosity by 3–5%, a roughness of Ra ≈ 25–35 nm and an increase in hydrophobicity by 50–80% were obtained.

At the same time, experimental data indicate a nonlinear increase in the microhardness of CaF_2, YF_3, TiO_2 layers up to ~24% with a decrease in thickness from 10 to 2 nm. This approach allows you to evaluate multilayers under different modes.

Theoretical calculations and measurements of spectral transmittance use known thin layer interference models. Modern AR structures provide broadband reflection reduction compared to single-layer solutions, which is consistent with publications on multilayer systems based on $TiO_2/Al_2O_3/MgF_2$ and their implementation.

Research in recent years demonstrates an increased emphasis on durability (hydrophobicity and self-cleaning) and abrasion resistance in films on glass and silicon. The technological route is compatible with such modifications and can be integrated into multifunctional systems, Table 1.

Table 1. Electron beam processing parameters and obtained properties (range of optimal modes)

Mode	Beam current, mA	Accelerating voltage, kV	Pulse duration, μs	Uniformity of thickness	Porosity (change)	Roughness Ra, nm	Hydrophobicity	Comment
L (lower boundary)	89	1,10	0,8	High	↓ ~3%	35 ± 5	↑ ~50%	Delicate stabilization of the structure without overheating; suitable for thinner layers
N (nominal)	91	1,25	1,8	very high	↓ ~4%	30 ± 5	↑ ~65%	The best density-roughness-optics balance for most formulations
H (upper limit)	93	1,40	3,3	very high	↓ ~5%	25 ± 5	↑ ~80%	Maximum densification; monitor the thermal load on the substrate

For quick quality check, a minimum set of tests is offered, namely: control of thickness uniformity and defectiveness according to AFM / REM; measurement of spectral transmittance; evaluation of wettability/contact angles after post-processing. The use of AFM and profilometry is in line with the practice of the latest research on AR films.

Conclusions. The reproducible relationship between the modes of combined deposition, electron beam treatment and the operational properties of the anti-reflective layers is shown. Also, the above parameters provide uniformity and reduction of porosity along with an increase in hydrophobicity.

The use of a measurement package (optics, REM, AFM) allows you to correctly associate microstructure, micromechanics and optical functionality and is consistent with modern trends in the creation of durable AR coatings.

The proposed route is technologically compatible with multilayer solutions ($TiO_2/Al_2O_3/MgF_2$, MgF_2/SiO_2, etc.) and can be scaled into optical surveillance production processes.

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COMPARATIVE ANALYSIS OF CLASSICAL AND MODERN APPROACHES TO INFORMATION STEGANOGRAPHY

Abstract. *This article analyzes classical and modern approaches to information steganography. The main differences in data hiding methods, their advantages and areas of application are highlighted. The study emphasizes the growing role of machine learning in increasing the security and efficiency of steganographic systems.*

Key words: *steganography, covert data transmission, cybersecurity, artificial intelligence, adaptive methods.*

Introduction. In the context of rapid digital technology development, the problem of information protection is becoming increasingly important. Alongside cryptographic methods, the role of steganography – the science of concealing the very fact of message transmission – is growing. Classical steganographic methods were based on hiding data in images, audio, and text files, while modern approaches integrate machine learning, neural networks, and adaptive algorithms for information detection and protection (Fig. 1).

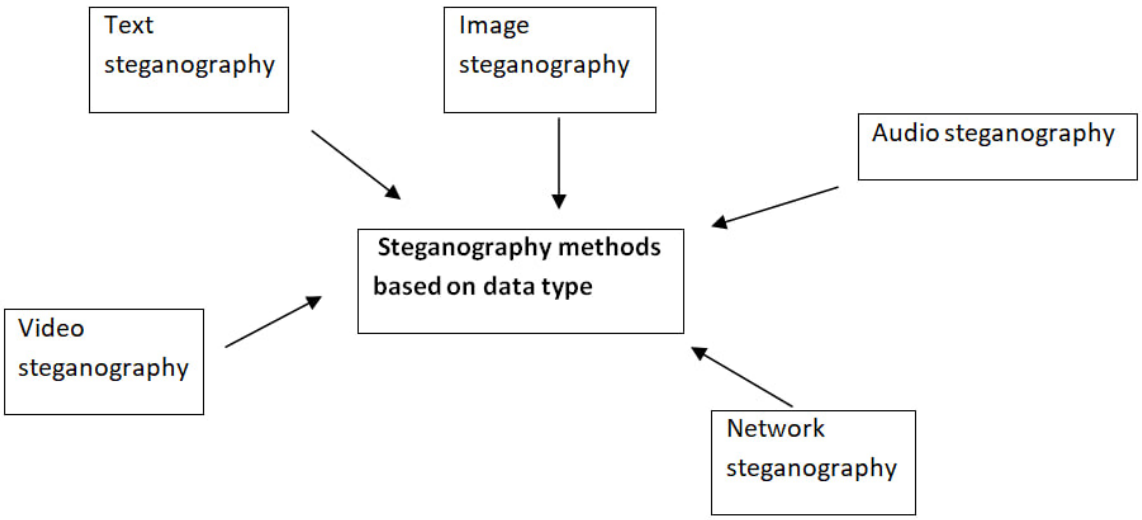

Fig. 1. Steganographic methods

Analysis of recent research and publications. The issues of information steganography have been studied by researchers such as N. Johnson, S. Jajodia, O. O. Kuznetsov, S. P. Yevseiev, O. H. Korol, and I. V. Shvidchenko. Traditional research concentrated on embedding data into the least significant bits (LSB) of digital images, as described in the works of Johnson and Jajodia, as well as Kuznetsov et al. and Shvidchenko. Modern studies, including those by K. Zhang, Zhou et al., and Tang et al., focus on the use of deep neural networks and image preprocessing frameworks for adaptive embedding, which significantly enhance resistance to detection attacks.

Table 1. The results compare analysis of classical and modern steganography approaches.

Criterion	Classical approach	Modern approaches
Principle	Data are hidden by modifying the least significant bits or pixels of an image.	Data are hidden using neural networks, deep learning, or adaptive algorithms.
Invisibility	Moderate – changes can be detected by statistical analysis.	High – deep learning improves invisibility and resistance to detection.
Capacity	Limited – suitable for small data volumes.	Higher – allows embedding larger data sets.
Complexity	Simple to implement and understand.	Requires computational resources and training data.
Security	Vulnerable to steganalysis attacks	Adaptive and intelligent embedding increases protection.
Application area	Educational, basic research, low-security communication.	Cybersecurity, confidential data transmission, AI-based systems.

Conclusions. The comparative analysis demonstrates that classical methods remain useful for educational and demonstration purposes but no longer meet the requirements of modern security systems. Modern AI-based methods provide higher resistance to attacks and open new perspectives for the development of adaptive information-hiding systems. Further research should focus on creating universal models capable of automatically optimizing the balance between capacity, imperceptibility, and robustness of steganographic methods.

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COMPARATIVE ANALYSIS OF STATE SECRET PROTECTION IN UKRAINE AND CANADA

Abstract. *The article conducts a comparative study of state secret protection systems in Ukraine and Canada. The legal, organizational and technological aspects of ensuring information security in both countries are considered. The main differences in the centralization of management, levels of classification of secret information and approaches to liability for disclosure are identified. The results obtained allow us to identify the advantages of the risk-oriented model of Canada and outline the directions for improving the Ukrainian system of state secret protection.*

Key words: *state secret, information security, cybersecurity, Ukraine, Canada, legal regulation, access control, criminal lability, organizational structure.*

Introduction. In modern conditions of growing cyber threats and hybrid warfare, the issue of protecting state secrets and ensuring the country's information stability becomes especially important. The effectiveness of the system for protecting classified information directly affects national security, government stability, and international trust.

Canada, as a strategic partner of Ukraine in the field of security and defense, has a well-developed information protection system based on a risk-oriented approach, interagency coordination, and modern cybersecurity technologies. Therefore, a comparative study of the Ukrainian and Canadian models is important for identifying effective practices and opportunities to adapt them to the Ukrainian context in order to improve the level of state information protection.

Purpose. To compare the systems of state secret protection in Ukraine and Canada to identify their similarities and differences in legal regulation, organizational structure, and practical approaches to information security. The study also seeks to highlight effective mechanisms and methods that could be applied in Ukraine based on Canada's experience as a strategic partner in the field of security and defense**.**

Results and Discussion. A comparative analysis of the state secret protection systems in Ukraine and Canada shows clear differences in legal regulation, organizational structure, and approaches to information security at the state level. Although both countries aim to safeguard classified information, the methods used vary in terms of centralization, technological development, and integration of cyber defense.

The main distinction lies in how responsibilities for protecting state secrets are distributed. Ukraine has a centralized and hierarchical system, with the Security Service of Ukraine (SSU) responsible for overall control, granting access permissions, conducting personnel checks, and providing methodological guidance. This ensures consistent procedures and strict supervision but can lead to bureaucratic delays. Canada follows a decentralized approach, mainly regulated by the Security of Information Act, with responsibilities shared among agencies such as the Canadian Security Intelligence Service (CSIS), Communications Security Establishment (CSE) and Royal Canadian Mounted Police (RCMP). This model relies on a risk-based approach and gives agencies more autonomy in protecting their information assets, allowing faster responses to cyber threats and reducing the workload on central authorities.

Both countries use a comprehensive approach to protect information, including classification, access control, physical and technical security, and international cooperation. Ukraine has three levels of secrecy: Secret, Top Secret, and Especially Important. Access is managed through security clearances, special permits, and mandatory training. The system also monitors compliance, uses technical protections like cryptography and access control systems, and participates in international

knowledge exchange [1]. Canada has four levels of classification: Top Secret, Secret, Confidential, and Protected A, B, C. Protection measures include restrictions on storage, use, and transmission of information, security checks for personnel, physical and electronic security, and international collaboration under security agreements [2]. Overall, legal, organizational, and technological measures are combined, but Ukraine focuses more on formal procedures and physical safeguards, while Canada emphasizes cybersecurity, risk-based management, and flexible legislation.

Criminal liability exists in both countries for unauthorized disclosure of state secrets, but enforcement and interpretation differ. In Ukraine, the Criminal Code provides penalties of 2–5 years imprisonment for non-severe violations, along with possible restrictions on holding certain positions or performing specific activities for up to three years. More serious consequences can lead to 5–8 years imprisonment [3]. Canadian law allows fines, 2–14 years imprisonment, and in severe cases, life imprisonment, depending on the seriousness of the violation, its duration, and its impact on national security [4]. The Canadian system focuses on detecting and preventing espionage and ensuring personal accountability, whereas Ukraine applies a more formalized law enforcement approach, with investigative responsibilities mainly handled by the SSU.

Conclusions. The comparative analysis shows that Ukraine and Canada differ in legal frameworks, organizational structure, and approaches to state secret protection. Ukraine relies on a centralized, formalized system with strict control, while Canada uses a decentralized, flexible, risk-based approach with strong emphasis on cybersecurity. Both combine legal, organizational, and technical measures, but Canada demonstrates greater adaptability to modern threats. These findings can inform improvements in Ukraine's information security practices.

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WEAR CONTROL OF HIGH-PRECISION SLIDING ELECTRICAL CONTACTS IN LOW-SPEED APPLICATIONS

Abstract. *The article discusses approaches to increasing the durability and stability of electrical parameters of precision low-speed sliding contacts. The purpose of the work is to reduce wear and transient resistance while providing the required friction moment by optimizing coatings and the technology of their formation. The use of electrochemical gilding with alloying and nickel sublayer, as well as the procedure for running-in of the surface, is proposed; a test scheme is given (brush-ring bench, friction machine SRV) and evaluation criteria. It is shown that the correct selection of the composition and thickness of the coating layers, as well as treatment after application, can reduce the intensity of wear and stabilize contact resistance in operating modes. The results can be applied in current collectors of gyroscopic and other mechano-electrical devices.*

Key words: *coating, electrochemical gilding, transient resistance, coefficient of friction, current collector.*

Introduction. Sliding contacts provide reliable electrical communication in nodes where there is a relative movement of friction pairs (for example, "brush - ring"). Mechanical, thermal and electrical loads simultaneously act on them, which leads to degradation of surface layers, an increase in transient resistance and a decrease in the accuracy of the system.

World studies in recent years demonstrate the effectiveness of coating engineering and multilayer systems for sliding contacts: nickel sublayers, solid gold and composite layers with carbon components reduce wear and stabilize contact resistance; Test benches for brush-ring modeling and analysis of triboelectric behavior, including fretting-wear, are actively developing [1-5].

The article is aimed at substantiating and experimentally supporting technological solutions for the formation of wear-resistant coatings of sliding contacts (gold with alloying and/or nickel sublayer) and indicating how the selection of the structure of layers and running-in modes affects wear, friction moment and transient resistance in typical bench tests.

The object of research is the details of friction contacts of precision mechano-electrical devices; The subject is the formation of the coating structure and its effect on the wear resistance and current conductivity of working surfaces. The approach is based on the "composition – structure – properties" relationship and combines electrochemical layering with subsequent running-in, micromechanical tests and AFM control.

For low-speed contacts, it is advisable to use gold due to its high electrical conductivity and corrosion resistance; the nickel sublayer increases adhesion and wear resistance, and silver alloying or the formation of thin silver-carbon structures helps to stabilize resistance under load. Electrochemical gilding with adjustable thickness and alloying is proposed as an application technology: pure Au; Au-Ag (silver alloying in a bath); Ni/Au (hard nickel sublayer followed by gilding); Ni/Au-Ag. For individual options, the operating concentrations of the electrolyte components and the duration of the process are given; After application, running-in is used to form a stable contact layer, Table. 1.

Table 1. Coating options and their expected properties (qualitative assessment)

Coating option	Adhesion	Durability	Resistance stability	Complexity of technology	Note
Au (clean)	Average	Average	High	Average	Basic option
Au-Ag (alloying)	Average	Increased	High	Average	Improved conductivity
Ni/Au	High	Increased	High	Higher	better mechanical layer support
Ni/Au-Ag	High	High	High	Higher	Wear/Resistance Trade-Off

Friction processes are simulated on the SRV machine and on a special stand with geometry "4 brushes from PLI-25 - brass ring", which reproduces the "brush - ring" assembly, Table 2. Basic metrics: wear rate (mass flow rate or height reduction), friction coefficient, transient resistance/voltage drop, stability of parameters over time.

Table 2. Example of test modes

Stand	Load	Linear speed	Amperage / voltage	Duration	Main outputs
SRV Machine	10-50 N	0.05–0.5 m/s	up to 5 A / up to 24 V	30–120 min	coefficient of friction, mass loss
"Brush - ring"	5–20 N (per brush)	0.1-1 m/s	up to 10 A / up to 48 V	Year 10–50	transient resistance, parameter stability

The state of the surface before and after tests is monitored by atomic force microscopy (AFM). Thus, the formation of layers with a changed composition, in particular, silver-carbon structures up to hundreds of nanometers thick, which affect friction and conductivity, has been recorded.

According to the literature [3], solid gold on the nickel sublayer and other engineering solutions (including composite carbon-containing layers) reduce wear intensity and stabilize contact resistance in a slow-sliding mode consistent with the objectives [3].

Conclusions. The use of multilayer coatings (Au, Au-Ag on the Ni sublayer) for low-speed sliding contacts in order to reduce wear, stabilize transient resistance and ensure friction torque is substantiated. Technological options for electrolyte composition and post-processing, as well as a test scheme (SRV, "brush-ring") and evaluation criteria are given, which creates a practical basis for implementation in current collectors and adjacent units. Combination of nickel sublayer, solid gold and/or carbon-containing modifications provides a better compromise between wear resistance and electrical conductivity in precision units.

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ULTRASONIC AUTOMATED SYSTEM FOR CONTROLLING THE ORIENTATION OF DETAIL EDGES DURING LASER WELDING

Abstract. *The article proposes the architecture of an ultrasonic automated system for monitoring the orientation of edges during laser welding of thin-sheet and profiled metal products. The system uses non-contact (air-conjugated) sensing to determine the position of the edges and the angle of their mutual orientation in real time based on the estimation of the passage time and phase-amplitude signs of reflected waves. signal processing, correlation localization of responses and decision-making criteria for correction of the beam trajectory. Compared to visual methods that suffer from arc/splash and smoke flare, ultrasound is more resistant to such interference and can operate without lubrication thanks to the air acoustic channel. The issues of calibration, metrological verification and integration with the control of robotic complexes are considered. Recommendations are given for the selection of frequencies, input angles and sensor configurations for different types of joints and materials. The possibilities of combining with digital twins and methods of control of the welding bath based on phased grids are substantiated.*

Key words: *air-conjugate sensing, phased array, seam tracking, transit time, signal processing, closed control.*

Introduction. Ensuring accurate guidance of the laser beam at the joint requires reliable control of edge geometry in real time. Common visual methods of seam tracking are highly accurate, but significantly degrade due to arc illumination, smoke and changes in the reflective properties of the surface, which complicates work in real industries and with complex seam trajectories. Modern work demonstrates ways to increase the stability of vision methods, but the problem of interference remains critical for many welding modes, especially with thin gaps and closed circuits [1].

Ultrasonic approaches are an alternative. Air-coupled and laser-ultrasonic systems provide lubrication-free contactless inspection and can operate in optical interference environments. In recent years, [2-4] the effectiveness of such systems for diagnosing joints and thin-sheet structures, including the use of Lamb waves and phased arrays, has been shown, which reveals the potential of problems of preliminary beam guidance to the joint.

The purpose of the article is to propose a complete engineering concept of an ultrasonic system for monitoring the orientation of the edges of parts for laser welding and to describe methods of signal processing and integration with the control system for automatic trajectory correction. To substantiate the solutions, we rely on modern results of air-coupled converters, phased arrays and laser ultrasound [5].

During laser welding, the angle and shear of the edges affect the formation of the seam, penetration and the appearance of defects. Orientation control requires a stable geometric feature that can be measured independently of bright optical interference. Ultrasound gives the following sign, namely: the arrival time of reflected or refracted waves and their amplitude-phase characteristics, sensitive to the presence of edges, gaps and bevels. For thin sheets, it is advisable to use controlled input angles and directional waves (surface) to increase sensitivity to the geometry of the joint [1].

Such a system uses an emitter-receiver pair in the air with an oblique input. The orientation of the edge is determined by the time difference between the arrival of the two main responses (from the top surface and from the edge of the gap) and by the change in phase or spectrum in the group window. For thin-sheet steel, a range of hundreds of kilohertz – megahertz units is advisable, taking

into account attenuation in air and material; For more complex profiles, these are combinations with Lamb waves [2, 3].

Therefore, the paper proposes a compact module with two or three air-coupled channels located symmetrically relative to the axis of the laser head, Table 1.

Table 1. Comparison of Real-Time Docking Methods

Criterion	Vision sensor	Air-conjugate UZ	Laser-ultrasound
Resistance to bright obstacles or smokes	Low–medium	High	High
Lubrication or contact requirement	No	No	No
Sensitivity depth (subsurface)	Low	Average	Medium–High
Complexity of the equipment	Average	Average	Higher
Typical applications	Open seam area	Thin sheets, edges	Defects and orientation in complex nodes

For thicker parts, this is the option of a phased array with electronic scanning [1]. Synchronization is carried out by a real-time controller. Next, the data is transmitted to a PLC or a robot controller that corrects the beam trajectory with an advance of 1-2 steps of sampling the insured motion model, Table. 2.

Table 2. Configuration recommendations for typical joints

Type of joint or material	Frequency Response	Input angle	Comment
Stick 1-3 mm	200-800 kHz	20–35°	Gap sensitivity
Corner joint	500-1200 kHz	30–45°	Bevel estimation by phase characteristics
Profile elements	300-700 kHz	15–30°	Combine with a narrow polar pattern
High-alloy steels	300-900 kHz	20–35°	Take into account increased attenuation

The processing algorithms were as follows. Chain of interference suppression (averaging, bandpass filters), estimation of arrival time by correlation maximum or methods of pulse onset detection, feature formation (time differences, interference indices, energy indicators in the window), classification of the type of joint/edge position and estimation of the angle between edges. For complex scenes, it is possible to use small neural networks at the feature level [4].

Calibration includes the measurement of reference standards with controlled angle and clearance; Validation was compared to a coordinate measuring machine or vision system prior to arc ignition [1]. To assess quality, it is advisable to use the error in determining the shear angle, the frequency of lost determinations and the processing delay; For seam control, parallel application of phased arrays as a reference channel for process monitoring is possible.

Such vision methods give high spatial resolution, but are critically sensitive to light and thermal interference; Ultrasound is less sensitive to optical factors and works without lubrication (in air), but requires careful selection of frequency and geometry and may be inferior in scanning speed. Laser-ultrasound combines non-contact with accurate time estimates, but is more technologically complex [2].

The proposed subsystem can be built into laser welding heads for preliminary "aiming" to the joint, and in some tasks, it can be combined with monitoring of the bath or the root of the seam with

phased grids with a closure of the quality loop. A combination with digital twins of products and processes for simulated adjustment of sensor configurations and criteria is promising [6].

Conclusions. The proposed ultrasonic system provides non-contact control of edge orientation in real time and is resistant to typical optical interference of laser welding, which complements or replaces visual methods in difficult conditions.

The combination of air-coupled sensors, correlational estimation of arrival time, and phase-spectral features provides a suitable basis for closed beam path correction. For process monitoring, a combination with phased arrays is advisable.

Matching frequencies, input angles and algorithms to a specific type of joint increases reproducibility and reduces the risk of defects. Integration with digital twins for pre-optimization of parameters is promising.

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CONTROLLED TWO-SIDED CONVECTIVE-BEAM GRAIN DRYING SYSTEM

Abstract. *The system works on the principle of "layer-by-layer": intense short warm-ups on both sides alternate with pauses of thermal equilibrium and blowing, which reduces temperature and humidity unevenness in the grain thickness. For feedback, radiofrequency (dielectric) estimation of flow humidity and infrared non-contact surface temperature measurement are used. The logic of mode control, the selection of sensors and safety requirements are described. Comparative analysis shows a reduction in drying time and specific energy consumption compared to traditional convection, while reducing the risk of cracking and overheating. The practical aspects of integrating the system into small-sized and modular post-assembly lines are considered. The compliance of the approach with modern trends in intelligent drying control is shown.*

Key words: *energy efficiency, intelligent control, radio frequency dielectric diagnostics, infrared emitters, simulation of heat and mass transfer.*

Introduction. Stabilization of grain moisture to values safe for storage remains one of the most resource-intensive agricultural processing operations. Classic convective drying provides reliable quality, but is often inferior in speed and specific energy consumption to hybrid methods where heat supply is combined (hot air + infrared radiation, etc.). Modern reviews [1-5] confirm that the combination of volumetric and surface heating speeds up moisture removal and improves process uniformity.

At the same time, the practical implementation of such solutions faces problems [1]: uneven temperature fields, risks of local overheating, lack of prompt, reliable assessment of humidity in the flow, and lack of adaptive control. A new wave of research offers intelligent systems with multidimensional data logging and real-time correction.

The purpose of the article is to substantiate and describe the system of controlled two-sided convection-beam drying with dielectric humidity control and IR pyrometry of surface temperature, to determine the requirements for sensors and algorithms, as well as to show the expected advantages in terms of speed, uniformity and energy consumption compared to basic convection. For this purpose, an analysis of the literature was performed, a functional scheme and a set of evaluation criteria were formed, control logic and typical settings were proposed.

The installation consists of a transport channel with a pseudo-layer or thin bulk of grain, two oppositely placed IR modules (top/bottom) with sectional power regulation, a ventilation circuit with heating and recirculation, a humidity measurement unit (RF dielectric probe in the channel wall or above the conveyor) and IR pyrometers or thermal chambers for surface temperature. The control system realizes alternation of short pulses of IR heating with blowing and "equalizing pauses".

The principle of two-way energy supply is as follows. Two-sided IR heating reduces the depth of the temperature gradient and accelerates the release of moisture to the surface, while controlled convection effectively removes evaporation. Compared to one-sided irradiation [2], this reduces the uneven heating, the risk of local overheating and the appearance of cracks. 1.

Table 1. Qualitative comparison of drying approaches for a batch of one crop

Approach	Cycle Duration	Specific energy consumption	Humidity uniformity	Risk of overheating
Convection (hot air)	medium / high	medium / high	Average	Low / medium
IR + convection (unilaterally)	Average	Average	Average	medium
IR (bilateral) + convection	**low / medium**	**low / medium**	**High**	**low**

Feedback on humidity and temperature is carried out as follows: humidity in the flow is estimated by the dielectric properties of the grain (radio frequency or microwave methods), sensitive to water content, the surface temperature is non-contact controlled by IR pyrometers. Such approaches provide efficiency and are suitable for closed control of air flow, conveyor speed and power of IR sections [3].

The logic of managing modes is based on a number of strategies. Thus, the basic strategy: a pulse of IR heating from above + below (5–20 s) to the maximum surface temperature; blowing and "resting" to equalize the temperature and diffuse moisture; estimation of the humidity trend; auto-correction of section power and air flow. To prevent overheating, restrictions on the maximum temperature of the shell, high-speed interlocks of fans and control of "hot spots" are used.

Due to the combination of surface and convective heat transfer, a reduction in drying time and specific energy is expected, which is consistent with the results for combined methods in cereals (hot air + IR; hot air + microwave/IR). Additionally, intelligent algorithms (adaptive or model-predictive) reduce the influence of variability in input humidity and fractional composition [4].

Dielectric humidity sensors, at the same time, need to be calibrated for the crop, bulk density range and temperature. IR pyrometers are used to correct the emissivity of the grain shell and background. Therefore, regular verification according to the laboratory standard of humidity is recommended.

Two-way IR heating allows you to reduce "unproductive" heating of air and metal structures, and recirculation allows you to reuse heat and evaporation. Review publications demonstrate significant energy saving potential for combination dryers with proper flow management [5].

Conclusions. Two-way IR heating in conjunction with controlled convection and dielectric humidity control forms a more uniform field of temperature and moisture, which increases the quality and shortens the drying time. The integration of fast sensors with adaptive control logic allows you to stabilize the process in case of changes in input parameters and reduce specific energy costs. The proposed architecture is consistent with modern trends in "smart" drying and is suitable for modular modernization of existing lines.

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AN INTELLIGENT PLATFORM FOR ULTRASONIC ASSISTED EXTRACTION OF PLANT RAW MATERIALS FOR PERSONALISED NUTRIENT SUPPORT

Abstract. *The project aims to create an intelligent ultrasonic extraction platform for plant-originated raw materials for producing multi-component functional beverages intended for personalized nutritional support of veterans and civilians with post-traumatic stress disorder (PTSD). The basis of the project is an ultrasonic platform with built-in sensors, signal processing, which allows for real-time optimization of the frequency spectrum, power, temperature, duration and degassing.*

Key words*: ultrasonic systems, intensification, extraction, functional beverages, post-traumatic stress disorder.*

Introduction. Post-traumatic stress disorder (PTSD) is defined as a widespread psycho-emotional disorder that affects both military personnel and civilians who have experienced traumatic events. Post-traumatic stress disorder in military personnel, veterans, and civilians has exacerbated the demand for safe, reproducible, and affordable nutritional support solutions in the practice of HEIs and partner rehabilitation facilities. The focus is on functional multinutrient beverages with high bioavailability of biologically active substances (BAS), due to their antioxidant, anti-inflammatory, and neuroprotective effects [1]. Not only food technologies, but also IT and electronic components of the treatment strategy are crucial for its success: sensor system architecture, algorithms and electronic means of adaptive control of ultrasonic transducers, built-in data acquisition and analysis tools, and digital traceability channels.

Conventional extraction approaches are still being deployed nowadays, even though being time-consuming, energy- and resource-intensive, costly, and difficult to scale up. In contrast, ultrasonic (US) extraction has been shown to reduce extraction time, increase BAS yield, and decrease energy and solvent consumption [2, 3].

Therefore, this project's ***goal*** is to improve the efficiency and safety of nutrient support through an intelligent platform for ultrasonic extraction with adaptive control, a sensor network, and optimized modes of production for functional beverages.

Materials and Methods. To achieve the goal of this study, we set up to solve the following problems and tasks:

- Requirements and architecture of the ultrasonic extraction platform.
- Prototype of a multi-frequency ultrasonic subsystem.
- Integration of the information and measurement system into the control platform.
- Recipes and personalization protocols.
- Analytical control and validation of methods.
- Equipment and process qualification (pilot project).

· Scaling and technology transfer.

Multifrequency excitation generates a combination of stable and transient cavitation events, enhances micro- and macroscopic fluid flows, disrupts cellular matrices, and facilitates solvent penetration; as a result, the extraction process flows faster and yields of target bioactive compounds increase. Controlled degassing stabilizes cavitation, reduces foaming and oxidative processes, and improves batch reproducibility. This process is treated as a controlled mass transfer phenomenon with critical parameters such as excitation frequency, amplitude, and power, as well as temperature, duration, hydrodynamics, and the degree of degassing. The hardware system includes multichannel ultrasonic drivers with matching networks, flexible spatial arrangements of piezoelectric transducers, and an optimized orientation of the working zone. Multifrequency and multipoint excitation make it possible to "tune" the spatial profile of the cavitation field for a specific raw material and solvent. The measurement electronics feature modular sensors of temperature, electrical conductivity, acidity, optical transparency, and acoustic cavitation indicators. The signals are amplified, filtered, synchronized by a hardware timer, and digitized with the required resolution and sampling rate. The data are then transmitted to a real-time controller running adaptive algorithms for power regulation and frequency pattern control.

Results. The expected result is an energy-efficient, scalable "sensors → data → solutions → quality" platform and standardised technology for producing stable multi-nutrient beverages with increased bioavailability of beneficial components. Technological indicators (yield of target substances, process duration, energy consumption) are supplemented by quality indicators (microbiology, organoleptics, stability over time).

Expected performance indicators: reduction of extraction time by 2–5 times, increase in the yield of target components by 15–35%, reduction of specific energy consumption by 20–30%.

Further research will be targeted at creating a technologically reproducible tool to produce functional multinutrient beverages with increased bioavailability for veterans, military personnel, students, and faculty at HEIs, i.e., groups prone to high stress levels.

Conclusions. The outcome of the present study is developing intelligent ultrasonic platform, technology, and experimental samples of multi-nutrient functional beverages to be introduced to the diet for treating stress disorders, particularly those caused by military actions.

Acknowledgements. The data presented in this study have been obtained as implementation of the experimental scientific and technical project titled "Development of an automated ultrasonic system for enhancing the nutritional properties of functional beverages for rehabilitation and preventing post-traumatic stress disorders" (national registration number: 0124U000740, 2024-2026) under development at Cherkasy State Technological University.

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IMPROVING THE EFFECTIVENESS OF ENVIRONMENTAL MONITORING AND PROTECTION OF WATER RESOURCES

Abstract. *Computer-integrated technologies using ion-selective sensors offer a modern and automated approach for real-time monitoring of water resource quality by accurately measuring specific ion concentrations. These systems combine miniaturized sensors, wireless data transmission, and computer integration for continuous, remote analysis and management of critical water parameters. The developed technologies enhance environmental protection efforts, optimize resource management, and support sustainable water quality control through improved data collection and decision-making processes.*

Key words: *ion-selective sensors, automated monitoring systems, sensor data processing, real-time water quality control, flow-injection system*

Introduction. Computer-integrated technologies for monitoring water resources using ion-selective sensors are a modern trend in environmental monitoring, leading to automated systems for collecting, processing, and analyzing data on the state of water objects. The use of ion-selective sensors allows for highly accurate and rapid measurements of ion concentrations in water, which is critical for assessing water quality and pollution.

The primary ***aim*** of work on computer-integrated technologies for monitoring water resources using ion-selective sensors is to enable real-time, accurate, and remote measurement of specific ion concentrations in water, supporting environmental protection, process control, and sustainable resource management. These technologies integrate miniaturized ion-selective sensors with wireless data transmission, cloud storage, and web-based interfaces, allowing for continuous, automated monitoring of water quality parameters such as nitrate, ammonium, potassium, and other critical ions

Methods and Materials. These technologies contribute to more effective monitoring by enabling continuous real-time control of water parameters, remote control systems, and integration with computer networks for centralized information analysis. The implementation of such complexes improves water resource management. It ensures greater efficiency in making management decisions on environmental protection.

There are two approaches to computer-integrated technologies for monitoring water resources. The first approach involves the use of combined ion-selective electrodes in monitoring (Fig. 1). The second involves the use of a flow-injection method with thin-film solid-phase electrode-active substances as ion-selective sensors.

A modern flow-injection ionometric water resource monitoring system consists of the following main components:

• An ion-selective sensor that continuously analyzes the concentration of ions in the water flow.
• A flow chamber or channel through which the water sample passes for analysis.

• An injection (introduction) system for standard solutions or reagents for calibration and measurement accuracy improvement.

• An electronic unit for processing signals from the sensor with a digital-to-analog converter.

• A computer-integrated system for collecting, processing, and visualizing data, allowing real-time monitoring of the state of the water body.

A graphical diagram of such a system shows: water inlet into the flow chamber, connection of an ion-selective sensor, injection system for calibration reagents, data transfer via a computer interface, where processing and output of results are performed.

Thus, the flow-injection ionometric system includes mechanical, electrochemical, and computer components for accurate control of the chemical composition of water resources.

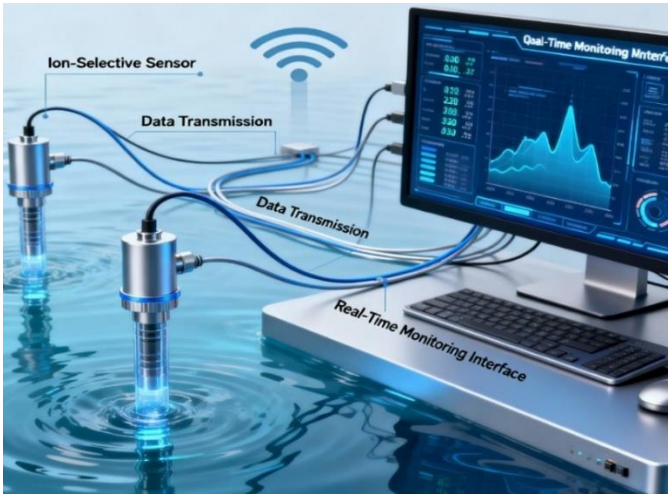

Fig. 1. Computer-integrated technologies for monitoring water

Conclusions. The conclusions of the work can be summarized as follows. Computer-integrated technologies represent a modern and effective approach to environmental monitoring, enabling automated collection, processing, and analysis of water quality data through the use of ion-selective sensors. The integration of miniaturized ion-selective sensors with wireless data transmission, cloud storage, and web interfaces allows continuous, real-time, accurate, and remote measurement of specific ions in water, which supports environmental protection, process control, and sustainable water resource management. Two main technical approaches are highlighted: the use of combined ion-selective electrodes and the flow-injection method with thin-film solid-phase electrode-active substances. A typical flow-injection ionometric monitoring system combines mechanical (flow chamber), electrochemical (ion-selective sensors), electronic (signal processing with digital-to-analog conversion), and computer-integrated components for real-time water quality control. These technologies improve monitoring effectiveness, enabling continuous real-time control, remote system management, centralized data analysis, and better-informed decisions for water resource management and environmental protection. Overall, this research confirms that computer-integrated ion-selective monitoring systems enhance the accuracy, responsiveness, and usability of water quality monitoring, contributing significantly to the protection and sustainable management of water resources

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ANALYSIS OF THE INFLUENCE OF EXTERNAL FACTORS ON THE ACCURACY AND RELIABILITY OF MEASUREMENTS OF LOW-INTENSITY ELECTRIC FIELDS USING AN INFORMATION-MEASUREMENT SYSTEM

Abstract. *This study focuses on developing and validating an information-measurement system for low-intensity electric fields. It examines the impact of external factors such as temperature, humidity, and mechanical stress on measurement accuracy and reliability. Advanced experiment planning using Sobol's LP_τ-sequences enabled precise data collection with an atomic force microscope sensor. Regression models were built and statistically validated to predict field characteristics under varying environmental conditions. The results demonstrate high measurement stability and metrological compatibility, highlighting the system's potential for industrial and educational applications.*

Key words: *low-intensity electric fields, measurement system, atomic force microscope, regression modeling, external factors influence, Sobol`s LP_τ-sequences, measurement accuracy and reliability.*

Introduction. During the study of accuracy and reliability in measuring low-intensity electric fields amid external disturbances, a key challenge is the predictive monitoring of the spatiotemporal state of a microelectronic device's quasi-static electric field. This involves extrapolating past patterns of field characteristic changes to forecast future values. A highly effective method for this task is developing a regression model that quantitatively captures how input variables affect measurement outcomes. Particular emphasis must be placed on experiment design and the careful selection of test points within a multidimensional space, as the model's quality and reliability heavily rely on the input data structure.

The primary ***aim*** of the work is to develop and analyze an information-measurement system for accurately and reliably studying static and quasi-static low-intensity electric fields, particularly by investigating the influence of external factors (such as temperature, humidity, and electromechanical effects) on the measurement results. This involves creating regression models using advanced experiment planning methods (like Sobol's LP_τ-sequences) to quantitatively describe these influences, ensuring high accuracy and repeatability of measurements conducted with an atomic force microscope equipped with a proprietary sensor. The work also includes statistical validation of these models, assessment of measurement stability, robustness under varying environmental conditions, and demonstration of practical applications in industrial and educational settings

Methods and Materials. In the study of the accuracy and reliability of measuring low-intensity electric fields, particularly under the influence of external factors influence, a critical task is the predictive monitoring of the spatial-temporal state of the quasi-static electric field of a microelectronic device. This task involves extrapolating past patterns of change in the field's characteristics to predict future values. A highly effective method to address this is the construction of a regression model that quantitatively captures the effect of input variables on measurement outcomes. Careful consideration must be given to methods of designing experiments and the selection of test points in a multidimensional environment, as the robustness and accuracy of the model heavily depend on the input data structure. This approach ensures reliable forecasting of field behavior and improves understanding of measurement influences.

This section presents research devoted to analyzing the influence of external factors on the accuracy and reliability of measurements of low-intensity electric fields using a developed information and measurement system. Given the high sensitivity of electric fields to environmental

conditions such as temperature, humidity, and mechanical stress, experiments were conducted to assess their impact on measurement characteristics.

A methodology for constructing and analyzing regression models to describe the influence of external factors (temperature, humidity, electromechanical impact) on the force (electric field strength) and energy (electric potential) characteristics of low-intensity electric fields is presented. Sobol's LP_τ-sequences were used to form the experiment plan, ensuring uniform filling of multidimensional space and high sample informativeness. Measurements were performed using an NT-206 atomic force microscope equipped with a proprietary sensor under controlled environmental conditions. Statistical analysis was performed in the Statistica Data Miner environment using various types of models, including decision trees, support vector methods, artificial neural networks, MARS, and classical multiple regression. The best models for predicting responses Y_1 and Y_2 were selected, their adequacy was confirmed using Fisher's criteria, t-criteria, and residual analysis, and the models were deployed to evaluate new data. The results of the experiments showed that an increase in temperature from 10°C to 40°C (Table 1) causes an increase in electric field tension by 22% for the measured values and by 20.4% for the reference values. At the same time, the relative measurement error did not exceed 1.4%. For relative humidity, it was found that an increase in this parameter to 70% causes a decrease in electric fields intensity by 39.89%, which is explained by an increase in the electrical conductivity of the surface of the studied samples. In addition, mechanical impact within the range of up to 1500 Pa showed that at pressures above 1106 Pa, there is a significant decrease in the charge on the surface of the sample due to a change in its mechanical properties.

To assess the accuracy of the measurements, the root mean square error was used, the value of which varied from 0.018 V/m to 0.050 V/m, indicating high stability of the results. The probability of failure-free operation of the information-measurement system was at least 0.945 under optimal research conditions. The reproducibility of the results was assessed by the standard deviation, which was 0.056 V/m, and the reproducibility limit did not exceed 0.155 V/m, confirming the high metrological compatibility of the obtained data.

Table 1. Change in electric field strength with temperature [1]

T, (°C)	Field intensity, (V/m)		Relative error, (%)
	Average reference value	Average measured value	
10	9.55	9.65	1.04
15	9.88	10.01	1.32
20	10.20	10.36	1.56
25	10.53	10.72	1.80
30	10.85	11.06	1.94
35	11.18	11.43	2.24
40	11.50	11.78	2.44

Conclusions. A software-implemented mathematical model and corresponding algorithm were developed to accurately and promptly determine the distribution of force and energy characteristics of ultra-low intensity electric fields. This model takes into account their temporal dynamics, spatial parameters, and the effects of external influences. An information-measurement system utilizing an atomic force microscope was created to investigate low-intensity electric fields generated in microelectronic devices during operation, enhancing the precision and consistency of measuring these characteristics.

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DETERMINING EFFECTIVENESS BASED ON THE ACCURACY CRITERION OF THE OPTIMIZATION METHOD FOR RECONSTRUCTING PROFILES IN THE PCA SPACE

Abstract. *This study presents a method for simultaneously reconstructing the electrical conductivity and magnetic permeability profiles of planar conductive objects using surface eddy current probes, leveraging surrogate optimization with deep neural network metamodels in reduced PCA-dimensional spaces. The approach addresses the computational complexity of inverse problems by incorporating apriori information and applying dimensionality reduction, achieving high accuracy in profile reconstruction as demonstrated in comprehensive numerical experiments. The results confirm the effectiveness and potential of this method for nondestructive testing and material characterization in various industrial applications.*

Key words: *electrical conductivity, magnetic permeability, profile reconstruction, inverse problem, surrogate model, PCA space, surface eddy current probes*

Introduction. The electrical conductivity and magnetic permeability of materials are fundamental electrophysical properties that inform us about their structural and functional characteristics. Accurate reconstruction of these profiles is crucial in nondestructive testing and material diagnostics, particularly using surface eddy current probes. The inverse problem of determining such profiles from measurement data is computationally challenging due to high dimensionality and complex interactions affecting probe signals. This study employs surrogate modeling and dimensionality reduction techniques to enhance reconstruction accuracy and computational efficiency.

The primary ***aim*** of this work is to develop a computationally efficient method for reconstructing electrical conductivity and magnetic permeability profiles of planar metal objects using surrogate optimization techniques. The study focuses on reducing the dimensionality of the optimization problem by applying advanced dimensionality reduction methods such as PCA, thereby enhancing the accuracy and efficiency of the reconstruction process. Additionally, the method aims to incorporate apriori information into neural network-based surrogate models to improve predictive accuracy in diverse operational conditions. This approach addresses the challenges of high computational cost and complexity inherent in inverse problems related to electromagnetic property profiling.

Methods and Materials. The study focuses on reconstructing the electrical conductivity (EC) and magnetic permeability (MP) profiles of planar metal objects using surface eddy current probes (ECPs). The method employs surrogate optimization techniques with reduced-dimensional metamodels built by deep neural networks. The original high-dimensional design space is reduced using principal component analysis (PCA), which preserves the majority of the variance while minimizing computational complexity. Data for metamodel training were generated through a design of experiments based on Sobol's quasi-random sequences to uniformly fill the factor space.

The electrodynamic model follows the Uzal-Cheng-Dodd-Deeds analytical formulation, modified to consider multilayer subsurface zones representing varying material properties. The model accounts for excitation coil geometry, uniform current density, and the layered nature of the test

object. Output signals of the ECP are computed by summing the coil field in air and the perturbations caused by conductive layers. Computational experiments include variations in EC, MP, frequency, and probe lift-off distance to comprehensively capture their effects on output signals.

Neural network metamodels are separately trained for real and imaginary components of the ECP signal, using architectures with multiple hidden layers and activation functions such as hyperbolic tangent. Training is performed using advanced algorithms like Levenberg-Marquardt with normalization of input feature scales for stability. Model accuracy is validated via root mean square error (RMSE), mean absolute error (MAE), and relative mean absolute error (RMAE) across training, cross-validation, and test datasets.

Experimental profiles cover a wide range of EC and MP values, scaled to represent realistic surface and subsurface variations. The PCA-space dimensionality was tested for multiple values, ultimately selecting dimensions that balanced metamodel accuracy and computational efficiency. The inverse problem is formulated as an optimization to minimize the discrepancy between measured and surrogate-predicted ECP signals. Final reconstructed profiles demonstrate high accuracy with errors below 5%, validating the effectiveness of the surrogate-based inverse solution.

This approach reduces the “curse of dimensionality” typical of direct optimization in the full design space, enabling practical and efficient material characterization. The developed framework integrates physical modeling, statistical design, neural network learning, and global optimization for robust profile reconstruction. Future work may extend this methodology to multifrequency sensing and more complex geometries.

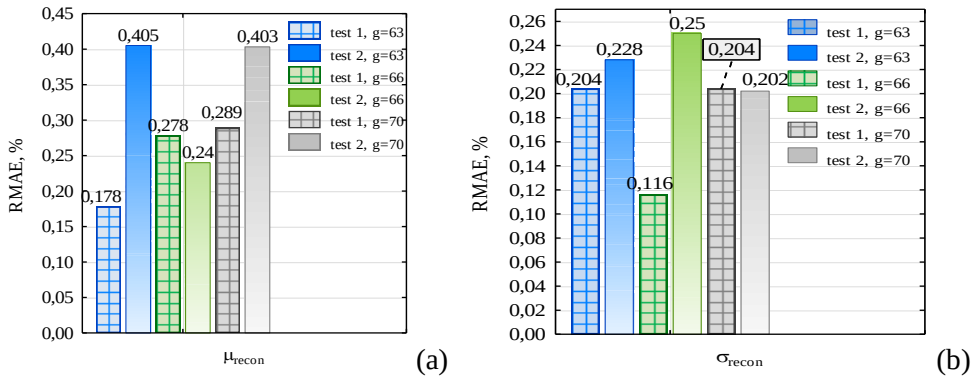

Fig. 1. Errors in determining the RMAE profiles (expressed as percentages) are presented for two separate test measurements conducted at different PCA space dimensions: (a) for magnetic permeability profiles and (b) for electrical conductivity profiles

Conclusions. To enhance the accuracy of profile reconstruction, it is essential to consider information from all significant factors influencing the formation of the combined VSP signal, all of which were accounted for in this study. The precision of solving the inverse problem for reconstructing magnetic permeability and electrical conductivity profiles is also affected by the accuracy of the developed metamodels. This work demonstrates that excessively reducing the PCA space dimension by discarding basis vectors linked to important eigenvalues leads to difficulties in creating metamodels with satisfactory mean squared error performance. Conversely, incorporating more information by increasing the PCA space dimension allows obtaining highly accurate metamodels. Minor changes in PCA space dimensions caused by eigenvalues below the 10^{-3} order did not significantly improve reconstruction accuracy, while expanding the search space dimension complicates finding the extremum due to the "curse of dimensionality", ultimately decreasing profile search accuracy. Therefore, selecting the smallest possible PCA dimension that ensures compact, accurate surrogate models and facilitates effective optimization is advisable.

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ADAPTIVE OPTIMIZATION OF INDUSTRIAL VENTILATION SYSTEM ENERGY CONSUMPTION BASED ON MODEL PREDICTIVE CONTROL (MPC)

Abstract. *This paper addresses the critical need for improving energy efficiency in industrial ventilation systems by proposing an advanced control strategy: Model Predictive Control (MPC). The study analyzes the dynamic correlation between air quality (CO_2 concentration), airflow rate, and energy expenditure. A unique mathematical model is developed to forecast the system's thermal and pneumatic response, enabling the MPC controller to continuously minimize fan speed while maintaining pre-set air quality standards. Simulation results demonstrate that this adaptive approach reduces energy consumption by up to 25% compared to traditional PID control systems operating on fixed setpoints, thus ensuring optimal energy utilization without compromising air quality or operational stability.*

Key words: *Model Predictive Control (MPC), industrial ventilation, energy efficiency, air quality, VFD, automation*

Problem Statement and Relevance. Industrial heating, ventilation, and air conditioning (HVAC) systems are among the most energy-intensive consumers in the industrial sector, frequently accounting for over 40% of a facility's total electricity usage. Traditional automation systems rely on fixed setpoints or rudimentary PID controllers, reacting to current deviations without factoring in future demands or load dynamics. This deficiency leads to excessive energy consumption due to the continuous operation of fans at unnecessarily high speeds. The relevance of this work lies in the necessity of developing intelligent control systems that ensure minimal energy expenditure (and subsequently, less equipment wear), while strictly maintaining the required air quality parameters, such as CO_2 concentration, in dynamic manufacturing environments.

Literature Review and Unresolved Problem. Recent research confirms the effectiveness of integrating variable frequency drives (VFD) into ventilation systems for improved efficiency. However, achieving comprehensive energy saving requires a shift from reactive control to a predictive methodology. Model Predictive Control (MPC) is a recognized advanced control method, utilizing a dynamic model of the system to optimize control actions over a prediction horizon. A gap exists in the availability of easily integratable MPC controllers for industrial ventilation that simultaneously optimize energy use (fan speed) and air quality, accounting for delays in pollutant dispersion and fluctuating production schedules. A need remains for developing a simplified yet effective predictive model suitable for real-time microprocessor implementation.

Methods and Materials. To develop and model an adaptive control system for an industrial ventilation unit based on Model Predictive Control (MPC), the scheme of which is presented in Fig. 1, to ensure maximum energy savings (target goal: over 20%) while strictly adhering to air quality standards we use next methods:

- **Mathematical Modeling:** Creation of a simplified dynamic model linking fan speed (ω), airflow inertia, CO_2 dispersion dynamics, and electrical energy consumption ($P_{fan} \infty \omega^3$).
- **MPC Algorithm Development:** Designing a control algorithm that minimizes the cost function (energy consumption) at each step, while simultaneously predicting system behavior over the control horizon and respecting constraints (maximum CO_2 concentration).
- **Simulation:** Comparative simulation of the MPC controller against a traditional PID regulator under conditions of variable pollutant load using MATLAB/Simulink.

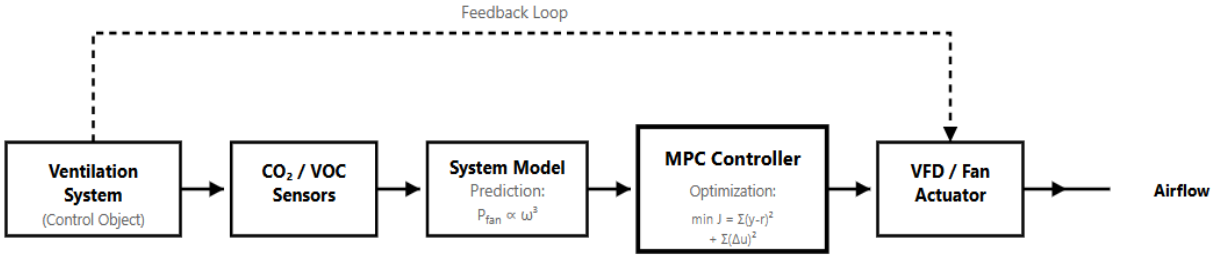

Fig 1. Block diagram of MPC control system for industrial ventilation

Presentation of Main Material and Unique Results. First of all we do system modeling and cost function. The core principle exploits the cubic relationship between fan power ($\boldsymbol{P_{fan}}$) and fan speed ($\boldsymbol{\omega}$), where minor speed reductions yield major energy savings. The control objective is defined by the following cost function (J), which minimizes the deviation from the $\boldsymbol{CO_2}$ setpoint ($\boldsymbol{r}$) and penalizes excessive changes in the control signal ($\boldsymbol{\Delta u}$):

$$J = \sum_{k=1}^{N_p} \|y(k) - r(k)\|_Q^2 + \sum_{k=1}^{N_u} \|\Delta u(k-1)\|_R^2$$

Where N_p is the prediction horizon, $y(k)$ is the predicted CO_2 concentration, $r(k)$ is the reference setpoint, N_u is the control horizon, Δu is the change in the fan speed, and Q and R are weighting matrices. After that, we analyze and compare the results. Simulation tests were performed comparing MPC against traditional PID control, configured to maintain air quality near the allowed CO_2 threshold. The results of the comparison of key indicators are presented in Table 1.

Table 1. Comparison of Control System Energy Efficiency

Criterion	Traditional PID Control	MPC Control (Predictive)
Average Energy Consumption (Relative, %)	100%	75%
Energy Saving	0%	25%
Response to Peak Load	Delayed response, potential setpoint overshoot	Predictive speed increase before constraint violation
Quality of Regulation	Maintains constant setpoint (high fan speed)	Dynamic regulation, near setpoint limit (minimal fan speed)

The MPC controller significantly outperformed the PID system by employing its predictive model to keep the fan speed at a minimum baseline level, initiating controlled increases only when the critical CO_2 limit was projected to be exceeded. This proactive approach resulted in an overall 25% reduction in energy consumption compared to the reactive PID system (Fig. 2).

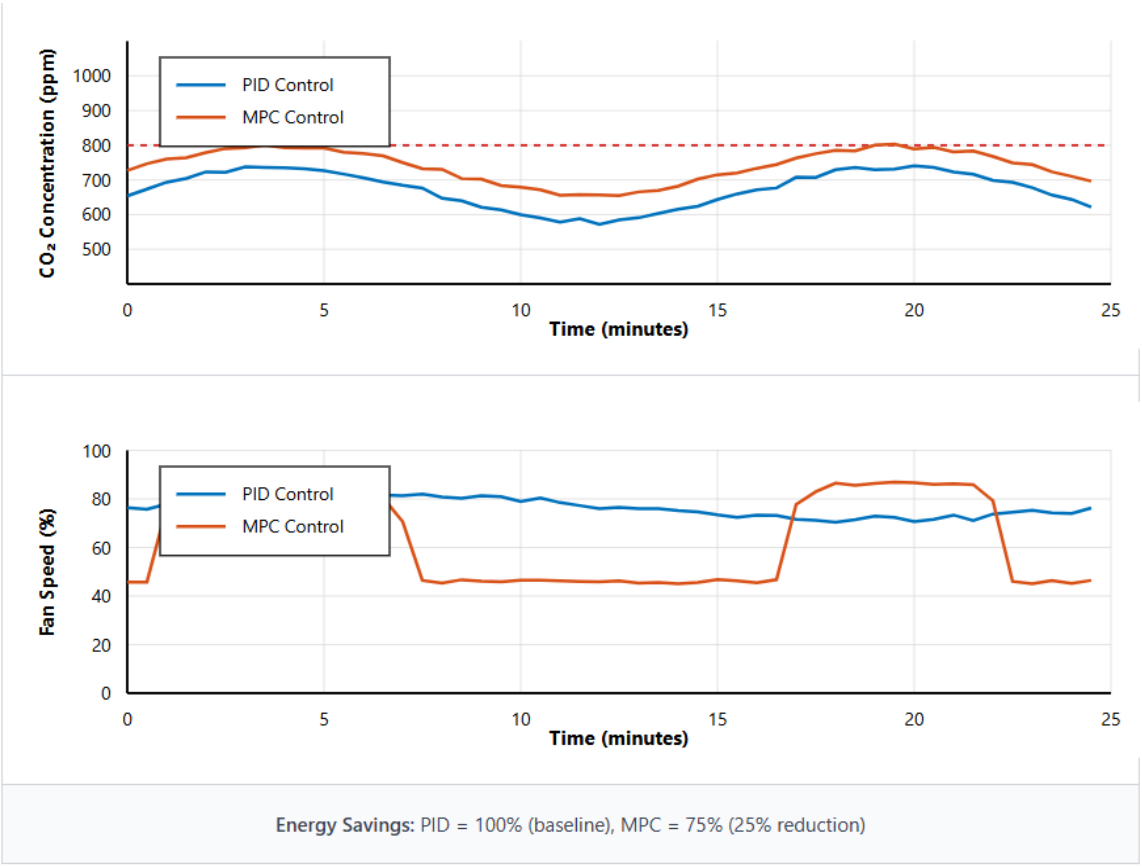

Fig.2. Comprasion of Energy Consumption: PID vs MPC Contollers

Conclusions. The developed methodology utilizing Model Predictive Control (MPC) is a highly effective tool for optimizing the energy consumption of industrial ventilation systems. Simulation confirmed that MPC achieves significant energy savings of up to 25% by leveraging the predictive model and the cubic relationship between fan power and speed. Predictive control ensures smoother and more precise compliance with air quality standards CO_2 while minimizing actuator wear. Further research will focus on adapting the MPC algorithm to handle nonlinear models and integrating machine learning methods for automated, real-time model parameter refinement (system identification). This will enhance the system's robustness against unforeseen changes in the manufacturing environment.

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ROBUST PARAMETRIC DESIGN OF EDDY CURRENT PROBES FOR ACCURATE MEASUREMENT OF MAGNETIC PERMEABILITY IN MOVING FERROMAGNETIC STRIPS USING TAGUCHI OPTIMIZATION

Abstract. *This work focuses on the development and optimization of eddy current probes for precisely measuring the magnetic permeability of ferromagnetic strips under dynamic conditions. By employing the Taguchi robust design approach, the study aims to maximize the signal-to-noise ratio and minimize signal variability caused by uncontrollable design and operational factors. The resulting probe design enhances measurement accuracy, stability, and reliability in real-world industrial applications, ultimately improving the quality control processes for ferromagnetic materials.*

Key words: *eddy current measurement, magnetic permeability, ferromagnetic strips, Taguchi optimization, signal-to-noise ratio (SNR), robust parameter design*

Introduction. The measurement of magnetic permeability in ferromagnetic strips via the eddy current method represents a challenging metrological task, largely because the precision depends heavily on how well signals caused by cross-sensitivity in the probes are suppressed. These interfering signals arise from multiple factors, including local fluctuations in the material's electrical conductivity, variations in the distance between the probe and the test object, and inconsistencies in sample thickness. Accurate determination of magnetic permeability requires the application of compensation techniques aimed at minimizing the impact of these influences, thereby reducing measurement inaccuracies. Additionally, incorporating advanced models that reflect the complex interactions among these influencing parameters is crucial for interpreting the probe output correctly. By employing such integrated strategies, measurement reliability is significantly enhanced under practical industrial conditions.

The primary **aim** of this work is to develop a robust parameter design method for eddy current probes measuring magnetic permeability in moving ferromagnetic metal strips. Using the Taguchi optimization algorithm, the aim is to maximize the signal-to-noise ratio and reduce output signal variation caused by uncontrolled noise factors without eliminating these disturbances. This method enables more accurate and stable measurements, ensuring reliable assessment of magnetic permeability in real production conditions.

Methods and Materials. The experimental setup included a series of eddy current probes designed to measure the magnetic permeability of ferromagnetic strips during dynamic conditions. For calibration, probes were initially characterized in a controlled environment by measuring impedance components at a specified excitation frequency. A mathematical model of an ideal filamentary coil was employed to determine the equivalent parameters and sensitivity coefficients. Various samples with known conductivities and permeabilities were used to validate the probes'

responses, ensuring the accuracy of the model. During testing, probes were mounted close to the moving strips, and impedance measurements were taken at multiple frequencies to assess the influence of different operational parameters. The probes' signals were processed using specialized filtering techniques to eliminate parasitic noise and cross-sensitivity effects. Spatial variations in the strip's surface and thickness were systematically introduced to evaluate probe robustness. Temperature effects were simulated to analyze their impact on measurement stability, and compensatory algorithms were implemented accordingly. The measurements accounted for the distance between probe and strip, as well as for the velocity of the moving sample. Data acquisition was synchronized with the strip's motion to ensure real-time monitoring. A combination of statistical design of experiments (DOE) and finite element modeling facilitated the optimization of probe parameters. The experimental results were statistically analyzed using ANOVA to identify significant factors affecting measurement accuracy. All tests were repeated multiple times to ensure reproducibility and to quantify measurement uncertainties.

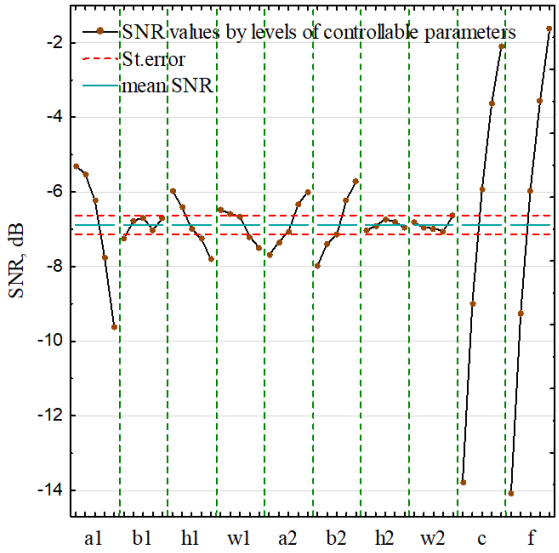

Fig. 1. Graph of dependence of SNR values on controlled parameter levels: a1 is the width of the excitation coil, m; b1 is the length of the excitation coil, m; h1 is the height of the excitation coil cross-section, m; w1 is the width of the excitation coil cross-section, m; a2 is the width of the pick-up coil, m; b2 is the length of the pick-up coil, m; h2 is the height of the pick-up coil cross-section, m; w2 is the width of the pick-up coil cross-section, m; c is the axial distance between coils, m; f frequency, kHz.

Conclusions. The study demonstrated that the application of the Taguchi robust design method significantly improves the accuracy and stability of eddy current probes for measuring magnetic permeability in moving ferromagnetic strips. The optimized probe design effectively reduces the impact of uncontrollable environmental and operational factors, resulting in higher signal-to-noise ratios and consistent measurement results. The proposed approach enables reliable real-time monitoring on conveyor lines, enhancing quality control in industrial metal processing. Additionally, the method provides a framework for further probe development under varying dynamic conditions. Overall, the research contributes valuable insights into optimizing eddy current measurement systems for complex metrological challenges.

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REVIEW OF METHODS AND PROSPECTS FOR POST-PROCESSING OF METAL 3D-PRINTED PARTS

Abstract. *Additive manufacturing, particularly selective laser melting (SLM), enables the fabrication of complex metal components but often results in surfaces with high roughness and structural nonuniformity. Traditional post-processing methods are limited in treating intricate geometries and may introduce additional defects. This study evaluates electrochemical polishing (ECP) as an effective finishing technique for SLM-produced AISI 316L parts. Experimental results show that ECP reduces surface roughness in a geometry-dependent manner while causing minimal mass loss. Owing to its ability to uniformly treat hard-to-reach areas without thermal or mechanical impact, ECP demonstrates strong potential as a versatile and reliable post-processing method for metal additive manufacturing applications.*

Key words: *Selective Laser Melting (SLM); additive manufacturing; electrochemical polishing; surface roughness; post-processing; AISI 316L; complex geometry; anodic dissolution.*

Additive manufacturing technologies, primarily selective laser melting (SLM), are rapidly expanding the capabilities for producing complex metal structures. Owing to the layer-by-layer melting of metal powder by a laser beam, it is possible to achieve high dimensional accuracy and reproduce intricate geometries that are unattainable using traditional processing methods. However, the surface of such components – formed by numerous local melt pools and powder layers – is often characterized by increased roughness, structural nonuniformity, manifestations of anisotropy, and residual defects. As experimental data obtained from SLM-fabricated samples indicate, surface roughness is one of the key parameters influencing both functional and visual properties of the final part [1].

Improving the surface quality typically requires the application of post-processing, which may include mechanical, chemical, thermal, or combined methods. Mechanical grinding or polishing is among the most common approaches, yet the effectiveness of such methods is significantly limited by part geometry. Components with complex spatial structures – typical for additive technologies – often contain numerous internal cavities, channels, or undercuts that are physically inaccessible to conventional tools. Moreover, mechanical treatment is associated with the risk of inducing micro-scratches, generating residual stresses, and producing locally nonuniform material removal.

Thermochemical methods involving surface smoothing through localized remelting or interaction with a reactive gaseous environment can markedly reduce roughness, but they also induce structural changes in the material. Particularly undesirable are microdefects caused by overheating, which can alter mechanical properties or lead to deformations in thin-walled regions. Additionally, ensuring uniform treatment is challenging because thermal fields in parts of complex geometry are inherently nonuniform.

Chemical etching offers more delicate removal of micro-irregularities without mechanical loads on the surface. However, this method is strongly dependent on the microstructural uniformity of the

material, which in the case of SLM parts is often unstable: regions of local overheating, altered track morphology, and variations in melt-pool density may cause the etchant to dissolve the surface unevenly. Thus, chemical post-processing may yield good results on typical surfaces, but its effectiveness is significantly reduced when dealing with the complex micro-geometry characteristic of SLM components [2].

Against this background, electrochemical polishing (ECP) emerges as one of the most promising post-processing methods. This process is based on controlled anodic dissolution of surface micro-irregularities, where protruding areas dissolve faster than recesses. Due to the nature of the electrochemical mechanism, ECP demonstrates the ability to treat both external and internal surfaces with equal efficiency, including hard-to-reach channels, provided that electrolyte access is ensured.

In [3], it is shown that electrochemical polishing of AISI 316L samples in a phosphoric-acid–glycerin solution altered surface roughness differently depending on local geometry and cross-sectional area. The smallest effect was observed in regions with the largest cross-sectional area, whereas areas with reduced section thickness exhibited roughness reduction by approximately one-third. This pattern is explained by the distribution of current density: narrower regions receive higher local anodic dissolution rates, accelerating the polishing process. At the same time, the overall mass loss of the samples after six minutes of ECP was relatively small – about 1.5%, indicating a sufficiently gentle and controlled treatment regime.

Analytical comparison of the methods shows that the main advantages of electrochemical polishing lie in its ability to process components with complex geometries, ensure high surface uniformity, and avoid thermal or mechanical loads. This is particularly relevant for SLM technology, where internal defects and track structures may have complex configurations. The study also demonstrated that ECP not only reduces roughness but also increases surface gloss and uniformity, which is important both for aesthetic considerations and for functional requirements (e.g., in biomedical or corrosion-resistant applications).

Although the experiment revealed a certain degree of polishing nonuniformity across different cross-sectional regions, this does not diminish the method's potential. On the contrary, these results highlight the need for further research aimed at optimizing process parameters—current density, electrolyte composition, polishing duration, and part orientation relative to the electrodes. Appropriate equipment configuration and adaptation of parameters to specific geometries can equalize polishing intensity and ensure highly efficient treatment even for complex structures.

Conclusions. Electrochemical polishing is among the most promising post-processing methods for components produced via SLM and other metal 3D-printing technologies. It combines technological versatility, high surface quality, and scalability for industrial applications. Based on the analysis of experimental results, it can be asserted that ECP has the potential to become the standard finishing method for stainless-steel and other corrosion-resistant alloy components, particularly in fields that impose stringent requirements on dimensional accuracy and surface cleanliness.

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ETHICO-LEGAL ASPECTS OF DEVELOPING AN ALGORITHM FOR THE OPERATION OF INDIVIDUAL INTELLECTUAL MEDICAL DEVICES – "LAST RESORT" DEVICES IN TACTICAL MEDICINE

Abstract. *The influence of changes in the conduct of hostilities on the requirements for haemostatic agents in tactical medicine, ethical and legal aspects of the introduction of individual medical devices with elements of artificial intelligence as «last resort» devices are considered.*

Key words: *tactical medicine, haemostatic tourniquets, haemostatic tourniquets, massive limb bleeding, medical ethics, medical law, individual medical devices.*

Introduction.

Extensive and large-scale studies by foreign scientists on injuries and losses among US military personnel as a result of military operations in Afghanistan and Iraq have convincingly demonstrated the importance and effectiveness of using tactical medicine haemostatic agents to preserve the life and health of personnel. Among these agents, the most common are haemostatic tourniquets (ligatures). These agents are recommended for use in tactical medicine documents, and experience with their use has been taken into account in the development of a number of standards, programmes, and protocols for the provision of medical care [1-4].

However, after the start of hostilities in 2022 in Ukraine, there have been calls for a change in international standards of tactical medicine. According to Ukrainian medical instructor Izhytska – «In the current conflict, participants are suffering a completely different type of injury, with fewer gunshot wounds and more internal injuries» [5].

The growing and predominant role of unmanned aerial vehicles should also be taken into account. The widespread use of drones has led to the emergence of a so-called «kill zone», where it is extremely difficult to carry out logistics tasks, provide medical assistance, and evacuate the wounded. According to the Commander-in-Chief of the Armed Forces of Ukraine, Syrsky – «At the current stage of the war, the realities of the battlefield are determined by strike drones, and the «kill zone» already reaches 10 km. Under such conditions, the capabilities of our logistics and military medicine are of great importance for the rapid evacuation of the wounded.». The emergence of the "kill zone" predictably increases the time required to provide medical assistance and evacuate the wounded, or makes it impossible altogether [6].

Therefore, the use of traditional means of tactical medicine no longer solves the problem of preserving the life and health of personnel. One of the possible ways to solve the problem of providing medical care in the conditions under consideration is the use of telemedicine and individual intelligent medical devices (IMDs).

However, the use of IMDs in autonomous mode involves this device making decisions and performing actions, as well as inaction, which can have critical and irreversible consequences for the

life and health of the wounded. For example, an intelligent haemostatic tourniquet in autonomous mode must make a decision – to suspend or restore blood flow – taking into account the risks of tissue necrosis due to lack of blood supply and the risk of continued blood loss and haemorrhagic shock.

Therefore, developers of algorithms, software (SW), and artificial intelligence (AI) elements for IMDs are tasked with complying with medical law and ethics requirements, which are generally decided by medical professionals when providing assistance directly to the victim.

The issue of AI use in the context of human rights compliance is the focus of attention for lawyers, doctors, scientists, and government officials. According to Rossilna – «there are no reasonable grounds to hope that domestic legislation will be able to adapt to the pace of the spread and penetration of artificial intelligence elements into the healthcare sector in general and personalized medicine in particular... especially in a state of martial law.» [7].

A publication prepared as part of the EU4DigitalUA project in collaboration with the Ombudsman's Office and the Ministry of Digital Transformation emphasizes that «if AI systems are used to make conclusions about people, then it is necessary to ensure that the system has sufficient statistical accuracy for such purposes.», «Legislation requires security measures to be put in place when processing personal data for automated decisions that have legal or similar significant effects on individuals. These measures cover the right of individuals to: y request human intervention; y express their point of view; y challenge a decision made about them; y obtain an explanation of the logic behind the decision» [8].

In 2024, the World Health Organization issued another guideline on the ethics and regulation of large multimodal models (LMMs) in healthcare. The document reviews the state of development and application of generative AI technologies and proposes more than forty recommendations for governments, technology development companies, and healthcare providers [9, 10].

Thus, for developers of algorithms, software, and AI for IMDs, there are guidelines and established recommendations that can and/or should be taken into account to comply with ethical and legal considerations and requirements, optimize risks and responsibilities, and protect the rights and interests of affected individuals. The conditions for the use of IMDs, the «price» of error, and the degree of responsibility complicate the task of developing such algorithms.

Conclusions. Changes in the conduct of hostilities and the widespread use of unmanned aerial vehicles pose new challenges and requirements for medical devices, protocols, and tactical medicine standards to ensure timely and effective medical care for victims. The development of and compliance with ethical and legal requirements for algorithms, software, and artificial intelligence elements for individual intelligent medical devices for stopping bleeding – the «last resort» of tactical medicine – is a complex and urgent task.

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TECHNOLOGIES FOR APPLYING LUBRICANTS AND COOLANTS AND THEIR POTENTIAL IMPACT ON THE WEAR RESISTANCE OF THE WORKING SURFACE OF THE TOOL

Abstract. *This work examines technologies for the application of Lubricant-Coolant (L-C) fluids to the working surface of the workpiece or tool, as well as their influence on the wear resistance of the tool's working surface. Modern application methods are analyzed, namely: flooding, wiping, spraying with tribostatic powder charging, pneumatic spraying, airless spraying, and solid coating application. Based on the literature review, it is determined how the correct selection of application technology and L-C fluid parameters can reduce friction, lower the temperature in the cutting zone, improve chip removal, and thus increase tool life and processing quality.*

Future work is planned to include modeling the interaction of L-C fluid with the tool's working surface, with an emphasis on changing the wear mode and tool longevity.

Key words: *lubricant-coolant fluid, cutting fluid, application technologies, tool wear, working surface, material processing*

Introduction. Material processing with metal-cutting tools is accompanied by intense friction and heating in the tool-workpiece contact zone. Improper management of the cutting zone leads to accelerated wear, deterioration of surface quality, and increased cost. The most promising direction for reducing tool wear is the use of L-C fluids to extend the tool's service life in the processing zone. Modern L-C fluid application technologies are designed to mitigate these negative phenomena, enhance the tool's working surface wear resistance, and improve productivity [1, 2].

An L-C fluid is a complex homogeneous and heterogeneous system that possesses various physicochemical dispersed phases (ionic, molecular, colloidal, and suspension). Ionic dispersion refers to a fluid containing solutions of inorganic salts in water. Molecular dispersion is when low-molecular-weight polymers are present in the fluid. Colloidal dispersion is a fluid system with high-molecular-weight and polymeric substances. Suspension dispersion represents a water-oil emulsion (foam, suspension, aerosol).

One of the key stages in developing L-C fluid application technology is selecting the method of its application to the working surface of the workpiece or tool during various machining operations.

Flooding is the most common, traditional delivery method, where a large volume of pressurized fluid is continuously supplied to the cutting zone.

- *Advantages:* High cooling capacity, effective chip removal, simple implementation.
- *Disadvantages: High L-C fluid consumption, significant environmental risks, oil mist formation.*

Wiping (Rubbing): This method is widely used for applying L-C fluids during metal forming, particularly for lubricating various types of dies in small-batch production. The greatest effect can be achieved in these processes.

Pneumatic Spraying with Tribostatic Charging: This method involves the application of fine powder materials with tribostatic charging. The essence of the method is that the particles of the powdered lubricating substance become electrified upon friction against the insulating layer of the atomizer. The ionized air-powder mixture exiting the atomizer forms a uniform powder cloud that settles on the grounded workpiece in the die.

Pneumatic Spraying (General): This is the most common method for applying all types of L-C fluids (suspensions, emulsions).

- *Advantages: Simple implementation, better penetration into the cutting zone.*
- *Disadvantages: High non-productive L-C fluid consumption (necessity of equipping the work zone with powerful ventilation equipment).*

Airless Spraying (Airless Atomization)*:* This is an advanced method of applying fluid to the tool surface during pressure processing. In airless spraying, the fluid is delivered under high pressure through a special atomizer or nozzle. Since no air is used, the fluid is atomized with minimal aerosol formation, which reduces loss and contamination.

- *Advantages: Higher accuracy of fluid application, which reduces consumption and increases efficiency. Enhanced tool cooling reduces wear and increases service life.*
- *Disadvantages: Overly complex design.*

Spraying in an Electric Field (Electrostatic Spraying): This is a crucial process used in metalworking. It involves using special atomizers that deliver fluid under pressure to the surface being machined. The electric field can be used to improve fluid distribution, increase its penetration into microcracks or pores of the material, and enhance fluid adhesion to the surface.

- *Advantages: Reduces the risk of material overheating, which increases processing accuracy. Reduces tool wear, extending their service life.*
- *Disadvantages: Complexity of spraying systems. May create additional risks associated with electric shock or short circuits.*

Solid Coatings: Solid L-C substances are applied to the tool surface in the form of coatings to provide a lubricating effect at high temperatures. These solid particles create an additional lubricating layer that reduces friction and wear between surfaces.

- *Advantages: Solid particles provide an additional lubricating effect. Simultaneously reduces wear on tools and materials.*
- *Disadvantages: Possible contamination of machined parts. Solid particles may settle, complicating cleaning and equipment maintenance.*

Conclusions. The results of the analysis of L-C fluid application methods show that the transition from traditional flooding to progressive technologies, such as various forms of spraying and the use of L-C fluids in the form of solid coatings, is a key direction for increasing processing efficiency. The choice of application method must be based on a balance between the necessary cooling and lubricating capacity, surface quality requirements, and environmental and economic criteria.

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INVESTIGATION OF THE INFLUENCE OF FUEL OZONATION ON FUEL ACTIVATION

Abstract. *This study investigates the effect of preliminary ozone treatment of gasoline fuels on their reactivity and combustion intensity. Theoretical aspects of fuel activation through ozone-induced chemical modification are reviewed, and a mathematical model of combustion kinetics is developed with ozone considered as an additional oxidizing component. Numerical simulations were performed in GNU Octave for four ozone concentrations: 0, 0.2, 0.4, and 0.8 g O_3 per kg of gasoline. The aim of the study is to determine the optimal ozone concentration that provides the highest combustion efficiency with minimal energetic impact. The use of GNU Octave, fully compatible with MATLAB, ensures transparent and license-free computational experiments.*

Key words: *ozone-assisted combustion, gasoline activation, reaction kinetics, numerical modeling, fuel oxidation.*

Introduction. Improving energy efficiency and reducing harmful emissions of internal combustion engines remains a critical challenge in modern energy systems. One of the promising approaches is fuel activation via ozone treatment, which implies introducing ozone (O_3) directly into liquid fuel before combustion [1, 2].

Ozone, being a strong oxidizer, can react with hydrocarbon molecules prior to ignition, generating reactive fragments and radicals. This reduces the activation energy of oxidation reactions and promotes more complete combustion, which decreases emissions of CO, unburned hydrocarbons, and partially NO_x. Since the efficiency of ozone treatment strongly depends on its concentration in the fuel, determining optimal dosing is an important scientific task.

Research Objective and Tasks. The objective of the study is to evaluate how ozone concentration influences gasoline combustion kinetics and to determine the optimal level that ensures the highest reactivity and combustion completeness.

The tasks include:

- analyzing the chemical mechanism of gasoline activation by ozone;
- constructing a combustion kinetics model incorporating ozone-enhanced oxidation;
- performing numerical simulations in GNU Octave [3] for four ozone concentrations;
- identifying the concentration that ensures the most efficient combustion behavior.

Methods. The combustion process is represented as a first-order reaction between fuel (Fuel) and the combined oxidizer ($O_2 + O_3$):

$$Fuel + \nu \cdot Oxidizer \xrightarrow{k} Products,$$

where the reaction rate constant k depends on ozone concentration:

$$k = k_0(1 + \alpha \cdot C_{O3})$$

The temporal evolution of concentrations is described by the system of equations relates the change in the concentrations of fuel, oxidant, and combustion products, taking into account thermal processes during the combustion of the fuel mixture.

Numerical integration was performed using the fourth-order Runge–Kutta method implemented in GNU Octave. Simulations were carried out for ozone concentrations of 0, 0.2, 0.4, and 0.8 g O_3/kg fuel, with time-dependent profiles of reactants and temperature obtained for each scenario.

Results and Discussion. The numerical experiments demonstrate that even small additions of ozone significantly influence combustion kinetics. Concentrations of 0.2 and 0.4 g/kg notably accelerate the reaction and reduce the duration of the main oxidation stage.

The strongest effect was observed at 0.4 g O_3 per kg of gasoline, indicating the most favorable balance between radical formation and effective acceleration of oxidation chains. Increasing the dose to 0.8 g/kg does not result in proportional improvement. This saturation effect is consistent with referenced experimental and numerical studies.

The obtained results confirm that ozone promotes faster and more stable reaction propagation and improves the overall completeness of gasoline combustion.

Conclusions

1. Ozone treatment is an effective method of chemical activation of gasoline, accelerating oxidation reactions and improving combustion completeness.
2. The developed ODE-based kinetic model adequately represents the influence of ozone concentration on combustion intensity.
3. GNU Octave provides a fully open and reproducible platform for numerical simulations, ensuring compatibility with MATLAB tools.
4. The optimal ozone concentration based on numerical results is 0.4 g O_3 per kg of gasoline. Higher concentrations do not yield proportional benefits.
5. Future research should focus on experimental validation and development of practical ozone dosing systems for fuel supply pipelines.

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RESEARCH OF THERMAL COMPENSATION IN OPTOELECTRONIC MODULE

Abstract. *This paper examines the influence of temperature fluctuations on the stability of parameters in optoelectronic systems and proposes a structural solution for compensating thermal deformations. A calculation of the change in distance between the lens and the photodetector for different module housing materials is presented, and the effectiveness of using Invar rods as elements of passive thermal compensation is analyzed. The obtained results demonstrate a significant increase in the thermal stability of the system without complicating its design.*

Key words: *optoelectronic module, thermal compensation, Invar, focal distance, temperature stability.*

Introduction. In recent years, optoelectronic devices have become widely used in scientific research, industrial control systems, measurement complexes, and specialized equipment. Their reliability and accuracy largely depend on the stability of optical parameters under varying environmental conditions. One of the key factors influencing the performance of such devices is temperature.

In real operating conditions, temperature may change within a very wide range – from −50 °C to +50 °C or even more. Without special compensatory measures, these variations cause a noticeable deterioration of system characteristics: loss of image sharpness, focus shift, measurement errors, and a general decrease in reliability.

Main Causes of Optical Degradation. Temperature fluctuations affect both the materials and geometry of optical system components. First, the refractive index of the glass lenses changes. The curvature of lens surfaces, lens thickness, and the air gaps between them vary as well. Simultaneously, thermal expansion of the housing occurs. Altogether, these factors cause a shift of the focal plane and degradation of image quality.

To compensate for such effects, optical materials with different thermal expansion coefficients are selected and lens thicknesses and distances between optical elements are optimized during design. However, this is insufficient because geometric changes occur not only in the lens assembly but also throughout the entire optoelectronic module, which includes the housing, optical system, and photodetector.

Influence of Housing Material. Calculations show that even with relatively small geometric changes, temperature significantly affects focusing.

If the housing is made of aluminum alloy (linear expansion coefficient 22.5×10^{-6} m/°C) and the focal length of the lens is 150 mm, a temperature change from −50 °C to +50 °C results in a 0.37 mm shift in the photodetector position. Such deviation leads to noticeable defocusing and image distortion.

If the housing is made of titanium (linear expansion coefficient 8.6×10^{-6} m/°C), the shift is reduced to 0.13 mm, which is better, but manufacturing such housings is technologically complex and expensive.

A stainless-steel housing (linear expansion coefficient 11.8×10^{-6} m/°C) produces an intermediate result—a shift of approximately 0.19 mm. Even these values indicate that the thermal stability of the system remains insufficient.

Need for Thermal Compensation. The examples above show that for optical systems operating over a wide temperature range, additional design measures must be implemented to maintain the stability of the distance between the lens and the photodetector. Simply using materials with low thermal expansion is not enough, especially for systems with long focal lengths.

Design Solution. In the developed thermally compensated optoelectronic module (utility model patent No. 159784 dated 03.07.2025), Invar rods are proposed as passive thermal-compensation elements.

Invar has an extremely low linear expansion coefficient—about 1.5×10^{-6} m/°C. The rods are positioned so that one end is fixed near the lens and the other is attached to the photodetector platform.

The platform is mounted through a metal diaphragm at the bottom of the module, enabling compensation for housing expansion independent of the housing material (aluminum, steel, titanium, brass, etc.).

Calculations show that using Invar rods reduces the change in the lens–photodetector distance to only 0.023 mm over the −50…+50 °C range. This is more than ten times smaller than without a thermal compensator and ensures stable focusing and high image quality.

Practical Advantages. The proposed design provides several advantages:

- maintains optical focus despite temperature fluctuations;
- does not require expensive housing materials;
- can be used in various devices (thermal imagers, laser rangefinders, sensors);
- does not complicate assembly technology.

Thus, the use of Invar thermal compensators enhances the stability of optoelectronic module parameters without significantly increasing device cost or mass.

Future Research. For longer focal lengths (800–900 mm), even small housing elongation can cause a focus shift comparable to the depth of field. Therefore, systems with such parameters require additional analysis and possibly new structural solutions, such as:

- using composite materials,
- applying active thermal stabilizers (heating or cooling),
- implementing adaptive mechanical compensators.

Conclusions. The study confirms the necessity of accounting for temperature effects during the design of optoelectronic modules. The application of Invar rods as thermal compensators is an effective and technologically simple method for stabilizing the distance between the lens and the photodetector. For a focal length of 150 mm, the change is only 0.023 mm within the −50…+50 °C range, ensuring stable image quality regardless of housing material.

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MODELS AND METHODS FOR ANALYSIS OF MONITORING DATA OF ELECTRON BEAM PROCESSING OF OPTICAL COMPONENTS

Abstract. *The paper considers models and methods for analysis of monitoring data of electron beam processing (EBP) of optical components. It is shown that, under conditions of growing requirements for the quality of optical surfaces and their metrological characteristics, traditional approaches to setting EBP modes based on limited series of experiments become insufficiently efficient. The proposed approach is based on the formation of a structured information environment for EBP, which provides registration of time series of technological parameters, diagnostic signals and results of surface quality measurements. An information model of the process, stages of data acquisition and pre-processing, as well as the use of statistical methods, regression analysis and machine learning algorithms for identifying informative parameters, building predictive models of surface quality and classifying processing modes are described. The application of such models makes it possible to reduce the scope of full-scale tests, improve the reproducibility of quality indicators of optical components and create preconditions for the transition to adaptive control of EBP processes.*

Key words: *electron beam processing; optical components; process monitoring; data analysis; machine learning models; surface quality.*

Introduction. Electron beam processing (EBP) is currently one of the key tools of surface engineering for optical elements, sensor substrates and components of photonic systems [1–2]. Due to the high energy density and accurate control of the spatio-temporal distribution of the electron beam power, it becomes possible to smooth microrelief, form micro- and nanostructures, modify the near-surface layer and deliberately change the optical characteristics of the surface. At the same time, optical components (quartz and optical glass, special dielectric materials, composite structures) are highly sensitive to surface defects, nanoscale roughness, residual stresses and structural inhomogeneity. Even minor fluctuations in beam parameters or the state of the vacuum system can lead to significant changes in the microrelief distribution, appearance of local defects, degradation of transparency or loss of stability of optical characteristics.

The traditional strategy for improving EBP technology for optical components is usually based on series of experiments with stepwise variation of process modes and subsequent evaluation of the resulting roughness, microrelief and optical parameters. This approach is labour-intensive, requires considerable time and resources, and does not always make it possible to separate the influence of individual factors and their interactions. As the design of optical systems becomes more complex, the range of materials expands and the list of controlled quality indicators grows, the need becomes evident to move from “manual” tuning of the technology to systematic processing of monitoring data and the use of predictive models of surface quality [1-2].

A number of studies have shown that the application of EBP makes it possible to significantly improve the quality of optical surfaces, in particular to reduce roughness parameters down to a few nanometres, increase microrelief uniformity and control the characteristics of the near-surface layer [1–2]. The regularities of the influence of strip and focused electron beams, scanning parameters and thermal cycles on the optical and metrological properties of the element base of information systems are investigated in. At the same time, the main focus is placed on separate series of experiments and analysis of final results, whereas the potential of using full sets of technological data (time series of parameters, diagnostic signals, intermediate measurements) remains only partially realised.

In parallel, methods of quality monitoring, production data analysis and application of machine learning for prediction of surface roughness and other quality indicators are actively developing in machining and related processes. The effectiveness of using structured data attributes, various types of sensor information, dimensionality reduction methods and hybrid “data + physics” models has been demonstrated. However, the specifics of EBP of optical components – a combination of vacuum technology, electron-optical systems, highly sensitive dielectric materials and complex surface metrology – make it necessary to adapt these approaches to the conditions of micromachining with strip and focused electron beams [2–4].

The aim of this work is to develop and justify models and methods for analysis of monitoring data of electron beam processing of optical components, which ensure:

– identification of informative process parameters;

– construction of predictive models of surface quality indicators;

– support of technological decision-making when setting EBP modes.

To achieve this aim, it is proposed to form an information model of the EBP process for optical components and a classification of monitoring parameters; develop approaches to acquisition, pre-processing and unification of experimental data; propose and investigate regression and machine learning models for predicting surface quality indicators; assess the informativeness of separate groups of features and their suitability for classification of processing modes; and formulate recommendations on integration of the developed models into an information technology for decision support in EBP.

Within this framework, the process is described by three groups of parameters: controllable EBP mode parameters (beam current, accelerating voltage, scanning speed, trajectory type and parameters, focus position, irradiation duration), diagnostic signals and time series (vacuum level, secondary emission current, beam stabilisation signals, temperature indicators of unit elements), and surface quality indicators and functional characteristics (roughness parameters obtained by profilometry or atomic force microscopy, microrelief characteristics, local defects, optical coefficients and metrological characteristics of sensor structures).

Monitoring data acquisition provides synchronous registration of technological parameters and diagnostic signals with a sampling rate sufficient to represent the process dynamics, as well as storage of post-processing surface measurements in a unified format. To reduce data fragmentation, a unified description scheme is used, in which each experiment (or series of experiments) is represented as a structured record with a unique identifier, a set of input parameters, time series of signals, measurement results and metadata (material, component type, pre-processing, measurement conditions).

At the pre-processing stage, outlier removal, time synchronisation of heterogeneous signals, normalisation and scaling of features, and extraction of aggregated indicators (means, variances, spectral characteristics of signals, integral energy parameters) are performed. Further analysis involves correlation analysis to identify relationships between mode parameters, signal characteristics and surface quality indicators, as well as construction of regression models of varying complexity (multifactor linear regression, polynomial models, decision trees, ensemble methods) for prediction of roughness and other quality indicators. For classification of processing modes (for example, “quality meets requirements / does not meet requirements”), methods of logistic regression, decision trees, random forests or gradient boosting are considered, followed by evaluation of accuracy and robustness of the models on test datasets.

Works devoted to the development of electron gun designs and investigation of ribbon-shaped electron flows complement the above research and emphasise the importance of detailed monitoring of beam parameters and their spatial distribution. These results, together with data-driven approaches to surface quality prediction in precision and additive manufacturing [3, 4], indirectly support the chosen direction of developing integrated models and methods for analysis of monitoring data in EBP of optical components.

Conclusions. The analysis shows that the transition from fragmentary tuning of electron beam processing modes to systematic analysis of monitoring data using statistical and machine learning models is well justified for optical components. The proposed information model of the process, together with the approaches to data acquisition, pre-processing and unification, enables the construction of predictive models of surface quality and classification of processing modes. This, in turn, reduces the scope of full-scale experiments, improves the reproducibility of quality indicators of optical components and creates preconditions for the further implementation of adaptive control in electron beam processing systems.

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INTELLIGENT SYSTEM FOR THE SMART SORTING OF METALS: A GENERATIVE ADVERSARIAL APPROACH TO SOLVING THE INVERSE PROBLEM

Abstract. *This work presents a new intelligent system for the fully automated sorting-classification and identification-of ferrous and non-ferrous metals with the purpose of overcoming the critical limitations of the traditional sorting methodologies by reframing the task in question as a data-driven inverse problem. For this, we employ a truly advanced machine learning architecture, namely a Conditional Generative Adversarial Network (cGAN), in order to map raw, high-dimensional Eddy Current (EC) signals directly to their corresponding intrinsic physical properties, specifically electrical conductivity and magnetic permeability. This generative approach spares no effort in moving beyond simple classification for the quantitative material characterization. The system is trained on a dataset of EC responses with the aim of learning the complex nonlinear mapping of sensor signals back to the physical parameters. This approach assures great accuracy and, what is most critical, inherent robustness against real-world noise in the signal, like sensor lift-off or sample tilt, which are the chief causes of failure of the conventional systems. The implementation is done via the PyTorch and TensorFlow frameworks.*

Key words: *metal sorting, eddy current testing (ECT), machine learning, Generative Adversarial Networks (GANs), inverse problem, material characterization, data augmentation, deep learning, conductivity.*

Problem statement and its relation to important research or practical tasks. The automated sorting of metallic materials represents a task of significant industrial and environmental importance; it forms the cornerstone of the modern recycling industry1 and is important for quality control in manufacturing. Whereas classic Eddy Current systems are widely used for separation, that is, deflecting non-ferrous metals from non-metallic waste, their use for high-fidelity classification or identification, for example, distinguishing between aluminum and copper, or sorting specific alloys, is a far greater challenge.

The first challenge is again the complexity of the EC signal: The sensor's response is not only a function of the material's intrinsic properties-electrical conductivity and magnetic permeability-but also highly sensitive to confounding variables such as sensor lift-off (distance) and sample tilt. These physical perturbations introduce significant non-linear distortions that plague traditional feature-based methods, leading to high classification error. Although standard ML models can handle this, they involve enormous amounts of data, which must be diverse and well-labeled. Such data are extremely expensive and time-consuming to create, because of which the deployment of robust intelligent systems becomes economically unviable.

Analysis of the latest sources of research and publications. Literature confirms these challenges. Conventional sorting algorithms are based on hand-crafted features (e.g., the so-called "characteristic phase") providing a good separation for nontilting metals but failing under real-world conditions and hence requiring sophisticated hardware compensation, such as secondary photoelectric sensors, to achieve even 95% sorting accuracy. Other approaches focus on extracting signal parameters from PEC signals, including rising points or zero-crossings.

These features are brittle; therefore, various ML approaches have been tried: ANN, support vector machines, and CNNs. Yet, all of these models suffer from exactly the same fundamental weakness: scarcity of data. The lack of training data is one part of this problem that has not been previously addressed. GANs have been proposed for data augmentation in analogous fields as a way

to generate synthetic LIBS spectra of scrap metal for identification or as a way to generate synthetic training images for robotic sorting of waste.

This, however, only solves the data-scarcity problem at the level of simple classification. The more fundamental problem, to which this diploma work is dedicated, consists in finding an object's intrinsic physical parameters, such as conductivity and permeability directly from its sensor response. While literature exists on using GANs to solve complex inverse problems and for material-property-conditioned design, the application of a generative model as a direct inversion tool for ECT-based material characterization is a significant and novel research gap.

The purpose of this research is to formulate and demonstrate a new intelligent system reframing the metal sorting problem as a data-driven inverse problem. In the course of this work, we will propose and develop a machine learning architecture, using a cGAN specifically designed to map raw, high-dimensional eddy current signals directly to a vector of their corresponding intrinsic physical parameters-e.g., σ, μ. We go beyond simple classification ("this is aluminum") to the quantitative characterization ("this material has a conductivity of 37.7 MS/m"). Our main goal shall be to prove that this approach is highly accurate and inherently robust to the signal variations (lift-off, tilt) undermining the current systems.

The proposed methodology represents a two-stage process. First, a training dataset is generated by combining sensor data with known material properties. This can be done via a smaller, high-precision experimental setup or through validated FEM simulations-a common practice in solving the forward problem for EC.

Second, a cGAN architecture is implemented using the PyTorch and TensorFlow libraries. The network consists of two components:

The Generator (G): the network is trained to solve the inverse problem, conditioned on the raw EC signal (as a 1D time-series or 2D impedance plot); it predicts a vector of the physical parameters σ, μ hypothesized to have produced that signal.

The Discriminator (D): his network plays the role of critic, taking as input (Signal, Property) pairs from two sources: (a) "real" pairs from the training dataset and (b) "fake" pairs where the signal is real but the property vector is the output of the Generator. The Discriminator is trained to be able to make the distinction between real and fake pairs.

In the process of adversarial training, the Discriminator becomes an expert at spotting physically inconsistent matching of signal and property pairs. The only way that the Generator can "fool" the Discriminator is by learning the true, complex, nonlinear mapping from the signal back to its physical source; thus, it effectively becomes a robust solver for the EC inverse problem. This generative approach differs from simple data augmentation in that it learns the underlying physical relationship rather than just the signal distribution.

Initial validation will be performed comparing this GAN-based inversion system against two baselines: (1) a traditional classifier using hand-crafted features, and (2) a standard CNN classifier trained on a GAN-augmented dataset. We hypothesize that the GAN-inverter will demonstrate superior accuracy and, critically, near-total invariance to lift-off and tilt noise.

Conclusions. This work introduces a new paradigm for intelligent metal sorting. Framing the task as an inverse problem and using a cGAN as a generative solver, we can make a leap from simple, brittle classification to robust, quantitative characterization. This system is able not only to identify a material's fundamental properties with far greater precision and resilience to real-world noise but also to provide much richer data for industrial processes.

The most promising direction for future work involves upgrading this model to a Physics-Informed GAN. This will inherently encode the physics of the problem-which, in this case, involve the Maxwell equations-directly into the loss function of the network. It will further constrain the

model to only physically-plausible solutions, with which it can be trained on even less data to achieve unparalleled accuracy, effectively making it a real-time non-contact metrology device.

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