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Post-Quantum Cryptography trends and perspectives

Abstract: This paper devoted to overview impact of quantum computing to modern cryptography and to analyze possible trends of cryptography development in the next years. Quantum computing became more popular these days and performance obtained using quantum computers promises to be extremely high. This trend causes to the security risks of current cryptographic algorithms usage without sufficient feasibility and analysis. It means that extremely high performance of quantum computers will be able to break some of existing cryptographic algorithm and produce the risk in security at all. To avoid such situation many cryptography specialists within whole world start research in the direction of so-called Post-quantum Cryptographic algorithms. Currently there are several projects performing research in this direction. Actuality of this topic is confirmed by many scientific papers in this direction. So, this paper contains overview of cryptography trends considering quantum computing coming in the nearest future.

Keywords: cryptography, postquantum, quantum computers, cybersecurity.

Abbreviations:

AES – Advanced Encryption Standard,
ECC – Elliptic Curve Cryptography,
DES – Data Encryption Standard,
KEM – key encapsulation mechanism,
LWE – learning-with-errors,
NIST – National Institute of Standards and Technology,
SIS – short integer solution.

Introduction

Cryptography is the science of mathematical methods for ensuring the confidentiality, integrity and authenticity of information. In recent decades, the scope of cryptography has expanded to include not only secret data transmission, but also methods for verifying message integrity, sender identification, authentication, digital signatures, interactive confirmations, and secure communication technologies. Widespread use of computer networks, in particular, the global Internet, development of electronic banking technologies, increases the amount of restricted information transferring of state, military, commercial and private data. This leads to development of new directions in cryptography, including public key distribution systems and electronic key distribution systems and electronic digital signature systems. Today it is difficult to find an information or telecommunication system, which would not use the mechanisms of cryptographic information security mechanisms. Today we are at the new step in cryptography development which is related with invention of quantum computers. Due to quantum computers performance cryptographic algorithms need to be improved or the new algorithms developed. The direction of cryptographic algorithms development that shall be reliable in the era of quantum computers is called post-quantum cryptography.

Cryptography history overview

Cryptography, as the science of protecting information from unauthorized access, has a long history. The beginnings of cryptography can be traced back to ancient civilizations that used various encryption methods to preserve significant data and communication confidentiality. However, an expanded description of cryptography as a modern science with mathematical and computer foundations began to develop in the 20th century with the advent of electronic devices and computers that required more sophisticated encryption methods to ensure data security. Thus, cryptography has become a key branch in cybersecurity and information security.

In ancient times, cryptography was already used to protect significant information and ensure the confidentiality of communications. One of the most famous examples is Caesar's cipher, where each letter of a text was replaced by another letter at a certain offset in the alphabet. Ancient cryptography methods also include the more complex Atbash cipher, which used the replacement of letters of the alphabet with their "reverse" letters, and other methods of replacing characters. Ancient civilizations such as Egypt, Greece, and Rome also played a significant role in the development of cryptography, using ciphers for communication and military purposes.

In the 20th century significant development in cryptography happened due to the emergence of new technologies and mathematical methods that have significantly increased the complexity of information security. During World War I, cryptography became a significant tool for military area, e.g., the German Enigma cipher was considered extremely difficult to decipher, but was cracked by British and Polish cryptanalysts, which significantly influenced the course of the war. In the 1970s and 1980s, the mathematical foundations of modern cryptography were developed, such as asymmetric ciphers and protocols based on complex mathematical problems such as the factorization of large numbers and the discrete logarithm. With the development of computers, new opportunities have occurred for the development and use of cryptographic algorithms. Computer cryptography has become a significant field, providing security for electronic communications and transactions (*Maqsood et al., 2017*; *Rathidevi et al., 2017*).

Starting from 1970s and 1980s, the first standards for cryptographic algorithms were created, such as DES. Later, other standards such as AES appeared, which are widely used around the world till these days.

At the beginning of the 21st century, the active study of quantum cryptography was started, which is based on the principles of quantum mechanics. This branch of cryptography has the potential to ensure absolute security of communications (*Bernstein et al., 2009*).

Quantum computing principles

Quantum computers began to appear on the horizon of science and technology in the second half of the 20th century, when scientists began to explore the possibilities of using the principles of quantum mechanics for computing. One of the key moments was the publication of the Shor`s factorization algorithm by Peter Shor in 1994, which demonstrated the potential of quantum computers in solving complex problems such as factorizing large numbers.

Since then, significant advances have been made in the development of hardware for quantum computing, such as qubits, quantum gates, and quantum computing devices. In addition, a variety of quantum algorithms have been created that can be used to solve a variety of problems, including cryptography, optimization, simulation of quantum systems, and many others (*Bernstein & Lange, 2017*; *Maqsood et al., 2017*).

Today, quantum computers remain at the early stages of development and their capabilities and limitations are still being studied. Nevertheless, they have the potential to become a promising technology for solving complex computing problems that currently require a large number of resources of traditional computers.

The principle of a quantum computer is based on the peculiarities of processing and storing information using qubits, the basic quantum analogues of classical bits. Qubits represent the states of a quantum system, which can be in a vertical or horizontal position, corresponding to the "0" or "1" values of classical bits. However, qubits can also be in a superposition of states, which allows them to store and process information faster and more efficiently than classical bits.

There are some other often used terms in quantum commuting: Quantum gates, Quantum algorithms and Quantum assembly. *Quantum gates* are similar to classical logic gates and perform operations on qubits such as rotation, superposition storage, state mixing, etc. These gates allow a quantum computer to perform computations and logical operations. *Quantum assembly* allows you to read information stored in qubits and convert this information into a classical output that can be interpreted by humans or other classical computers. Quantum computers use special *Quantum algorithms* that exploit the unique properties of quantum mechanics to solve complex computational problems such as significant for cryptography factorization of large numbers.

Quantum computing is based on the next three principles: superposition, entanglement and decoherence. Superposition, like in other scientific fields, means that adding two or more quantum states produces another valid quantum state. Quantum entanglement is phenomena when quantum state of two or more objects are described in relation to each other, even if the individual objects are separated in space. Finally, quantum decoherence is the loss of the quantum state in a qubit.

In general, the operation of a quantum computer is based on the use of quantum principles and algorithms to perform computations and process information, which can be much faster and more efficient (*Paquin et al., 2020*).

Impact of quantum computers to cryptographic algorithms

The impact of quantum computers on modern cryptography is a significant topic of discussion in information security. The main aspect of this impact includes breaking of existing cryptographic algorithms.

Some modern cryptographic algorithms, such as RSA and ECC, are based on complex mathematical problems, such as factorizing large numbers or calculating the discrete logarithm. Quantum computers can use algorithms that effectively break these mathematical problems, which leads to lose of security of such cryptographic systems. However, the development of quantum cryptography, which is based on the principles of quantum mechanics, may provide new methods of protecting information from quantum attacks, e.g., quantum cryptography can

use the principles of quantum key exchange to ensure absolute confidentiality of data transmission.

The introduction of quantum computers may cause to potential challenges to existing information security systems, as cryptographic algorithms previously considered secure may be vulnerable to quantum attacks. This may require a review and update of cryptographic protocols and algorithms to ensure resilience to quantum computing.

The purpose of post-quantum cryptography is to develop cryptographic methods and protocols that remain resistant to attacks that can be carried out using quantum computers. Since quantum computers can break some modern cryptographic algorithms, such as RSA and ECC, by using algorithms that effectively solve the complex mathematical problems on which these algorithms are based, post-quantum cryptography creates new methods of protecting information.

Post-quantum cryptography uses the principles of quantum mechanics to solve complex mathematical problems that form the basis of cryptographic algorithms. Post-quantum cryptography involves the development of new cryptographic protocols and algorithms that remain resistant to attacks by quantum computers. These algorithms can be based on other mathematical problems that are considered difficult for quantum computers or on quantum principles such as quantum key exchange. It is significant to note that some of existing cryptographic protocols can be adapted to protect against attacks by quantum computers by using longer keys or other security measures.

Considering this, the impact of quantum computers on modern cryptography creates not only both potential threats and also open new opportunities for the development of new methods of information protection. It is significant to continue researching these aspects and developing strategies to adapt to the new challenges.

Post-quantum projects overview

There are many projects in post-quantum cryptography that aim to develop and apply new methods of protecting information in the face of threats from quantum computers. Some of the most famous projects are mentioned and supported by NIST Post-Quantum Cryptography page. A project of the NIST aimed at creating post-quantum cryptography standards to protect information from quantum attacks. This project evaluates various candidates for post-quantum cryptography standards and develops recommendations for their use (*Moody et al., 2016*).

The most famous Post-Quantum Cryptography algorithms are: CRYSTALS-Dilithium, CRYSTALS-Kyber, Falcon. The information below is mostly taken from the official sites of these algorithms and contains some detailed explanation of these algorithms.

CRYSTALS-Dilithium is a digital signature scheme that is strongly secure under chosen message attacks based on the hardness of lattice problems over module lattices (*Cryptographic Suite …, 2018*). The security notion means that an adversary having access to a signing oracle cannot produce a signature of a message whose signature he has not yet seen, nor produce a different signature of a message that he already saw signed. Dilithium is one of the candidate algorithms submitted to the NIST Post-quantum cryptography project. The design of Dilithium is based on the "Fiat-Shamir with Aborts" technique of Lyubashevsky which uses rejection sampling to make lattice-based Fiat-Shamir schemes compact and secure. The scheme with the

smallest signature sizes using this approach is the one of Ducas, Durmus, Lepoint, and Lyubashevsky which is based on the NTRU assumption and crucially uses Gaussian sampling for creating signatures. Because Gaussian sampling is hard to implement securely and efficiently, we opted to only use the uniform distribution. Dilithium improves on the most efficient scheme that only uses the uniform distribution, due to Bai and Galbraith, by using a new technique that shrinks the public key by more than a factor of 2. To the best of our knowledge, Dilithium has the smallest public key + signature size of any lattice-based signature scheme that only uses uniform sampling. Performance overview is shown in the table of the Appendix (*Table 1*).

CRYSTALS-Kyber is an IND-CCA2-secure KEM, whose security is based on the hardness of solving the LWE problem over module lattices. Kyber is one of the finalists in the NIST Post-quantum cryptography project as well. The submission lists three different parameter sets aiming at different security levels. Specifically, Kyber-512 aims at security roughly equivalent to AES-128, Kyber-768 aims at security roughly equivalent to AES-192, and Kyber-1024 aims at security roughly equivalent to AES-256. The design of Kyber has its roots in the seminal LWE-based encryption scheme of Regev. Since Regev's original work, the practical efficiency of LWE encryption schemes has been improved by observing that the secret in LWE can come from the same distribution as the noise and also noticing that "LWE-like" schemes can be built by using a square (rather than a rectangular) matrix as the public key. Another improvement was applying an idea originally used in the NTRU cryptosystem to define the Ring-LWE and Module-LWE problems that used polynomial rings rather than integers. The CCA-secure KEM Kyber is built on top of a CPA-secure cryptosystem that is based on the hardness of Module-LWE.

Falcon is a cryptographic signature algorithm submitted to NIST Post-quantum Cryptography Project on November 30th, 2017 (*Fast-Fourier …, 2017*). Falcon is based on the theoretical framework of Gentry, Peikert and Vaikuntanathan for lattice-based signature schemes. It instantiates that framework over NTRU lattices, with a trapdoor sampler called "fast Fourier sampling". The underlying hard problem is the SIS problem over NTRU lattices, for which no efficient solving algorithm is currently known in the general case, even with the help of quantum computers. Falcon offers the following features:

- Security: a true Gaussian sampler is used internally, which guarantees negligible leakage of information on the secret key up to a practically infinite number of signatures (more than 264).
- Compactness: thanks to the use of NTRU lattices, signatures are substantially shorter than in any lattice-based signature scheme with the same security guarantees, while the public keys are around the same size.
- Speed: use of fast Fourier sampling allows for very fast implementations, in the thousands of signatures per second on a common computer; verification is five to ten times faster.
- Scalability: operations have cost O (n log n) for degree n, allowing the use of very long-term security parameters at moderate cost.
- RAM Economy: the enhanced key generation algorithm of Falcon uses less than 30 kilobytes of RAM, a hundredfold improvement over previous design such as NTRUSign. Falcon is compatible with small, memory-constrained embedded devices.

Performance of Falcon algorithm is shown in the table of the Appendix (*Table 2*).

Conclusion

Impact of quantum computers on modern cryptography creates not only both potential threats and also opens new opportunities for the development of new methods of information protection. It is significant to continue researching these aspects and developing strategies to adapt to the new challenges. Quantum computers can use algorithms that effectively break famous cryptographic algorithms like RSA and ECC, which leads to lose of security of such cryptographic systems. From another side, development of quantum cryptography, provides new methods of protecting information from quantum attacks, e.g., post-quantum cryptography can ensure absolute confidentiality of data transmission.

There are many projects in post-quantum cryptography that aim to develop and apply new methods of protecting information in the face of threats from quantum computers. The most famous projects are supported by National Institute of Standards and Technology and described on their web page.

Actuality of post-quantum cryptography is confirmed by many scientific papers related to this topic.

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Appendix

Table 1. Performance Overview of CRYSTALS-Dilithium algorithm

Dilithium2					
Sizes (in bytes)		**Skylake cycles (ref)**		**Skylake cycles (avx2)**	
		gen:	300751	**gen:**	124031
pk:	1312	**sign:**	1355434	**sign:**	333013
sig:	2420	**verify:**	327362	**verify:**	118412
Dilithium3					
Sizes (in bytes)		**Skylake cycles (ref)**		**Skylake cycles (avx2)**	
sk:		**gen:**	544232	**gen:**	256403
pk:	1952	**sign:**	2348703	**sign:**	529106
sig:	3293	**verify:**	522267	**verify:**	179424
Dilithium5					
Sizes (in bytes)		**Skylake cycles (ref)**		**Skylake cycles (avx2)**	
sk:		**gen:**	819475	**gen:**	298050
pk:	2592	**sign:**	2856803	**sign:**	642192
sig:	4595	**verify:**	871609	**verify:**	279936

(Source: *Cryptographic Suite …, 2018*)

Table 2. Performance Overview of Falcon algorithm

variant	keygen (ms)	keygen (RAM)	sign/s	verify/s	pub size	sig size
Falcon-512	8.64	14336	5948.1	27933.0	897	666
Falcon-1024	27.45	28672	2913.0	13650.0	1793	1280

(Source: *Fast-Fourier …, 2017*)

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Neuro-mathematical fusion for shot change detection in video sequences

Abstract: Shot change detection in visual media plays a pivotal role in various domains, including cinema, surveillance, and digital content organization. Traditional rule-based algorithms have shown limitations in handling the complexities of modern video content, prompting the exploration of computational intelligence approaches. This article presents a deep investigation of shot change detection, covering from traditional mathematical techniques to neural network methodologies. Through a series of experiments, we investigate the efficacy of a mathematical approach based on histograms and subsequently demonstrate the potential of integrating Long Short-Term Memory (LSTM) networks. Our findings reveal that combining mathematical precision with neural networks enhances shot change detection accuracy and efficiency, paving the way for practical real-time applications in domain of video processing and analysis. These improvements underscore the importance of adaptability and innovation in addressing the evolving challenges of visual media processing while emphasizing the importance of ethical considerations in algorithmic decision-making processes. Overall, this article invites researchers to explore the intersection of mathematical rigor and neural networks in the realm of shot change detection, offering insights into future directions and opportunities in visual perception.

Keywords: shot change detection, neural networks, Long Short-Term Memory (LSTM), video content analysis, shot change detection.

Introduction

In the vast landscape of visual media, the ability to determine subtle transitions between scenes is crucial for content-based analysis. Whether it is in the realms of cinema, surveillance, or digital content organization, the accurate detection of shot changes within video sequences holds significant importance. Shot change detection serves as the fundamental building block for various downstream tasks, including video summarization, content-based retrieval, and scene analysis.

Traditionally, shot change detection relied on rule-based algorithms, often incorporating simple mathematical techniques such as frame differencing or histogram analysis (*Lin et al, 2010*). While effective in some scenarios, these methods often falter in the face of complex visual dynamics, such as rapid camera motion, lighting variations, or intricate scene compositions.

This article explores the intersection of mathematics and neural networks within the field of shot change detection. It undertakes research that follows the historical progression of shot change detection methodologies, from traditional mathematical models to the forefront of contemporary research, which is characterized by advanced neural network techniques (*Soucek & Lokoč, 2020*). Throughout this exploration, we dissect the complexities of mathematical algorithms and scrutinize the architectural sophistication of neural networks, enhancing their individual capabilities and constraints.

Moreover, we dive into the inherent limitations and challenges in the domain, navigating through the complexities of lighting fluctuations, camera motions, and scene complexities

(*Abdulhussain et al, 2018*). Nevertheless, within these challenges, we discern promising trends and prospective routes.

Problem statement

Within the domain of visual media processing, the precise identification of shot changes within video sequences presents a notable challenge, carrying implications across numerous industries and applications. Conventional rule-based algorithms, grounded in elementary mathematical methodologies, frequently encounter difficulties in handling the complex characteristic of contemporary video content, including swift scene transitions, dynamic camera motions, and elaborate scene arrangements. While these traditional techniques may prove beneficial in specific contexts, their inherent limitations in adaptability and robustness often restrain their effectiveness in practical, real-world scenarios.

Moreover, with the escalating volume and diversity of video data across digital platforms, there is a growing demand for more advanced and scalable shot change detection solutions. In this context, development of neural network-based approaches signifies a new phase in computational intelligence, offering improved accuracy, flexibility, and generalization capabilities. However, the combination of mathematical and neural methodologies introduces its own array of challenges, encompassing algorithmic complexity, data accessibility, and computational resource demands.

Hence, the current challenge lies in the pursuit of ideal shot change detection methods that effectively combine mathematical precision with neural innovation. Solving this challenge requires a diverse strategy, including creation innovative algorithmic frameworks, investigation varied feature representations, and detailed examination of performance across diverse datasets and scenarios.

To summarize, the problem statement underscores the urgent necessity to push forward the frontier of shot change detection by harmonizing mathematical and neural methodologies. Addressing this challenge directly enables researchers to unlock novel routes in visual content analysis, enhancing applications spanning from video summarization and content retrieval to surveillance and beyond.

Proposed approach

To expedite and refine the detection of shot boundaries in videos, we propose employing mathematical algorithms to gather crucial information from each frame and utilize it for boundary detection (*Joyce & Liu, 2006*). This algorithm involves segmenting frames into blocks and generating visual representations in different color spaces, followed by histogram computation.

Let L denote the count of frames, B_i denote the i-th block in the frame, and C represent the number of blocks created during the splitting process, each block maintaining the same shape (*Figure 1*) (*Park et al., 2016*).

Subsequently, representations are generated for each block B_i in different color spaces. After experimentation, we determined that the optimal color spaces were grayscale and HSV (Hue, Saturation, Value). Notably, we found that utilizing only saturation and value from the

HSV spectrum sufficed. These representations are denoted as B_i^{gray}, $B_i^{saturation}$ and B_i^{value} respectively (*Zedan et al, 2016*).

Histograms are then computed for each block in each data representation, denoted as H_i^{gray}, $H_i^{saturation}$, and H_i^{value}. Each histogram compresses data counts into the range $[0; C_h]$ to manage data compression (*Mas & Fernandez, 2006*).

Additionally, for each B_i^{gray}, we calculate edges using the Sobel-Feldman operator, resulting in B_i^{sobel}, followed by histogram computation denoted as H_i^{sobel} (*Figure 2*) (*Huan et al., 2008*).

The distance between histograms is calculated as:

$$d(a,b) = \sqrt{\sum_{j=1}^{C_h}(a_j - b_j)^2}$$

where a and b represent histograms.

Subsequently, distances between histograms are combined into a single list:

$$d_i = d(H_i^{gray}, H_{i+1}^{gray}) \cup d(H_i^{saturation}, H_{i+1}^{saturation}) \cup d(H_i^{value}, H_{i+1}^{value}) \cap d(H_i^{sobel}, H_{i+1}^{sobel})$$

Thus, the difference between the same blocks in two frames can be calculated as:

$$D_i = \frac{1}{4C_h}\sum_{j=1}^{j=4C_h}(d_{ij})$$

yielding a single value denoting the distance (*Mohanta et al., 2012*).

Next, distances between frames are computed:

$$D_i^{frame} = \bigcup_{j=1}^{C}(D_{ij})$$

Distances between neighbouring frames can be calculated as:

$$D = \bigcup_{i=1}^{L}(D_i^{frame})$$

Anomaly detection techniques are applied to the histograms to identify deviations from the expected distributions. Let $\overline{D}$ represent the mean value of D and σ represent the standard deviation of D. This enables the identification of blocks between frames that deviate from the distribution:

$$D_{ij}^{map} = \begin{cases} 1: D_{ij} > \overline{D} + \sigma \\ 0: D_{ij} \leq \overline{D} + \sigma \end{cases}$$

Subsequently, deviations for all differences between frames based on deviated blocks are determined as:

$$A = \left\{ D_i \mid \sum_{j=1}^{C}(D_{i,j}) > \overline{D^{map}} + \sigma^{map} * k \right\}$$

where $\overline{D^{map}}$ and σ^{map} represent the mean value and standard deviation for distribution D^{map} respectively, and k is a coefficient determining anomaly detection threshold sensitivity.

This approach amalgamates block-based analysis, multi-view representation in different color spaces, histogram calculation, and anomaly detection to detect shot changes in video sequences.

To enhance the anomaly detection process, Long Short-Term Memory (LSTM) networks can be utilized (*Lindemann et al., 2021*). LSTM networks, a type of recurrent neural network (RNN), are adept at modeling sequential data and capturing long-term dependencies. In the context of shot change detection, LSTM networks can effectively analyze the temporal evolution of histogram features across consecutive blocks in the video sequence.

To train the neural network based on LSTM, we utilize D as input data where D_i represents timestamps and the number of features equals C. This allows us to replace the anomaly detection algorithm based on mean values and standard deviation with a neural network.

In conclusion, our proposed method for detecting shot boundaries in videos employs a comprehensive approach, leveraging mathematical algorithms and anomaly detection techniques. By segmenting frames into blocks and generating visual representations in grayscale, HSV, and Sobel-Feldman spaces, we enhance the accuracy of shot detection. Furthermore, our approach integrates histogram computation and anomaly detection to identify deviations between frames, thus effectively capturing shot changes. Moreover, by incorporating Long Short-Term Memory (LSTM) networks, we enhance the temporal analysis of sequential data, enabling more efficient shot change detection. This mix of techniques presents a robust framework for accurate and efficient shot boundary detection in video sequences, with potential applications in various domains.

Experiment 1

For our initial experiment, we utilized the SHOT dataset comprising 853 short videos, totaling 960,794 frames and containing 6,111 shots (*Zhu et al., 2023*). This dataset was selected due to its diverse range of videos and inclusion of challenging shot boundaries, including gradual transitions (*Figure 3*).

Algorithm 1. Compare results for the mathematical approach with TransNet V2, AutoShot@F1, AutoShot@Precision.

Input:

SHOT dataset.

Output:

Precision and F1 score.

Prosedure:

Step 1. Load dataset.

Step 2. For each video calculate prepare frames by splitting to blocks, converting to color spaces, calculating edges with Sibel-Feldman operator and calculating histograms.

Step 3. Calculate differences between neighboring frames.

Step 4. Determine deviating blocks and identify deviating transitions for each video.

Step 5. Calculate precision and F1 score.

During the experiment, we varied the number of blocks, color spaces, histogram sizes, and threshold coefficients, eventually settling on 64 blocks. These blocks were positioned as a grid to gather frame information without overlap.

We explored different combinations of color spaces, finding that the gray color space could effectively replace the RGB color space. Additionally, HSV proved valuable for detecting anomalies, although the Hue channel contained redundant information similar to the gray color space and was subsequently discarded.

Based on our experiments, we opted to reduce the histogram size to 64 bins, as the default size of 256 values yielded excessive information potentially lost during L2 distance calculation.

However, our findings indicated that the proposed mathematical approach using histograms for scene detection was ineffective and unreliable (*Table 1*). This experiment serves as an initial step towards developing more sophisticated shot change detection algorithms and applications in the realm of video processing and analysis.

Thus, our initial experiments on shot boundary detection utilizing the SHOT dataset and a mathematical approach yielded valuable insights into the complexities of scene transitions in videos. Despite our thorough exploration of various parameters such as block sizes, color spaces, and histogram sizes, our findings revealed limitations in the efficacy of the proposed method. While we successfully identified optimal configurations for certain elements like block size and color space selection, our approach utilizing histograms for scene detection proved inadequate compared to existing methods such as TransNet V2 and AutoShot@F1. These results underscore the need for further research and refinement in shot change detection algorithms, pointing towards the direction of leveraging more advanced techniques for improved accuracy and reliability in video processing and analysis.

Experiment 2

Building upon the initial experiment, we conducted a second experiment to assess the effectiveness of integrating Long Short-Term Memory (LSTM) networks for anomaly detection in scene change detection. This experiment aimed to showcase how LSTM-based anomaly detection enhances the accuracy and robustness of shot change detection compared to the solely mathematical histogram-based approach. The same algorithm was employed, but step 4 was replaced with training an LSTM-based neural network.

To train the neural network, we processed all videos using the algorithm from the first experiment, resulting in sequences with a size of (frame count, 64). Subsequently, we prepared short sequences with a length of 32 frames that ended with or without a scene change. To improve robustness against false positives, we included samples where the scene changes closely resembled model output (*Figure 4*)

We opted to minimize the size of the neural network to expedite the process and reduce overfitting. Consequently, our model consisted of one LSTM layer with 4 units, followed by a dense layer with 64 units and an output layer (*Figure 5*).

As a result, combination of mathematical approach with neural networks allowed us to achieve 88.9% precision and 88.8% F1 score accuracy (*Table 2*) which was 4.7% better then AutoShot@F1. We achieved comparable results with TransNetV2 and AutoShot architectures, but this approach also offers advantages in compact size and low computational requirements. The neural network we developed utilized around 1000 FLOPs per timestamp, making it suitable for real-time recognition.

Conclusions

The paper explores he dynamic landscape of shot change detection, traversing the realms of traditional mathematical approaches and cutting-edge neural network methodologies. Through a series of experiments and analyses, we have delved into the intricacies of scene change detection, highlighting the challenges, advancements, and potential future directions in this critical domain of visual media processing.

The initial experiment underscored the limitations of relying solely on mathematical techniques, particularly histogram-based approaches, for accurate and robust shot change detection. While foundational, these methods proved insufficient in handling the complexities inherent in modern video content, necessitating the exploration of more sophisticated solutions.

Building upon this groundwork, the second experiment showcased the transformative potential of integrating Long Short-Term Memory (LSTM) networks with mathematical algorithms. By leveraging the temporal dependencies in video sequences, LSTM-based anomaly detection achieved state-of-art accuracy and efficiency of shot change detection, exceeding AutoShot F1 score by 4.7% while offering advantages in model size and computational requirements.

With a streamlined architecture comprising one LSTM layer with four units, a dense layer with 64 units, and an output layer, our model demonstrated remarkable efficiency, requiring only around 1000 FLOPs per timestamp. This compact design not only facilitates real-time recognition but also reduces the computational burden, making it suitable for resource-constrained environments.

Our findings underscore the importance of combining mathematical rigor with the adaptability of neural networks, signaling a promising future for the field of shot change detection. As we continue to push the boundaries of research in this domain, the fusion of traditional methodologies with cutting-edge technologies promises to unlock new avenues for advancements in visual media processing and analysis.

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Appendix

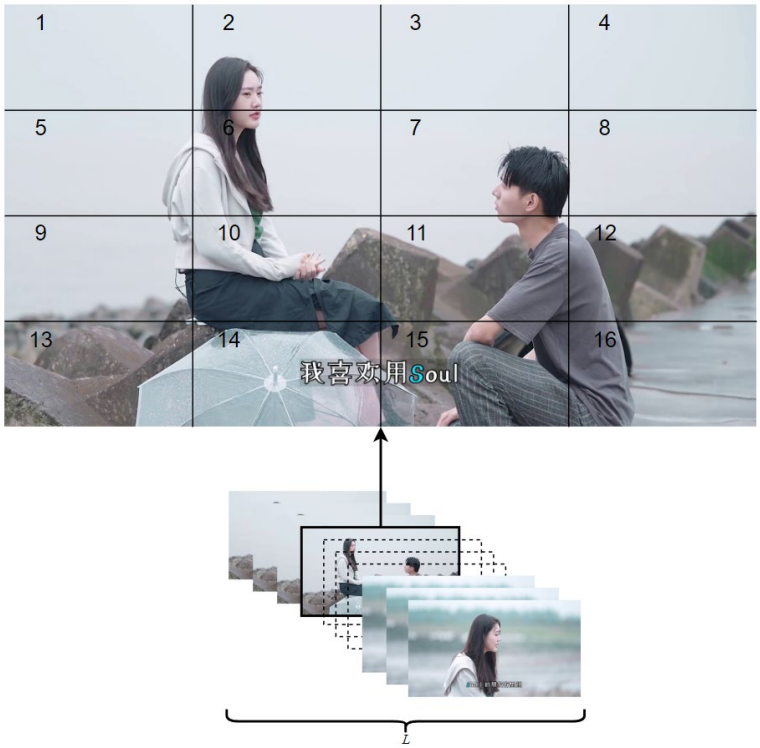

Figure 1. Example of splitting frame to blocks

Figure 2. Visualization of different color spectrums and edges

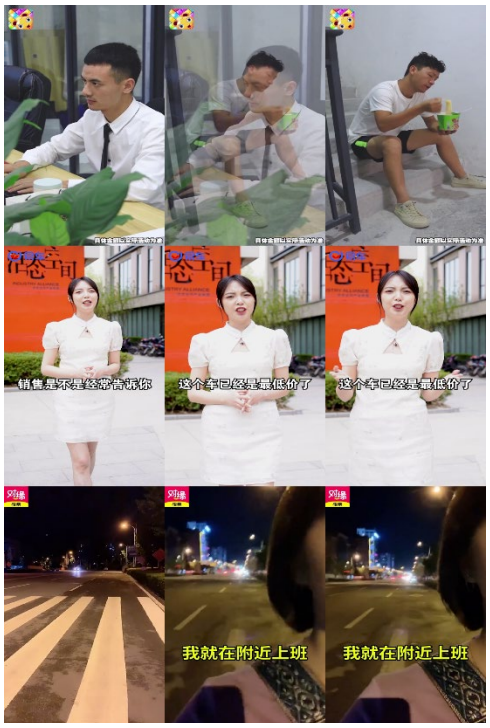

Figure 3. Example of SHOT dataset transitions

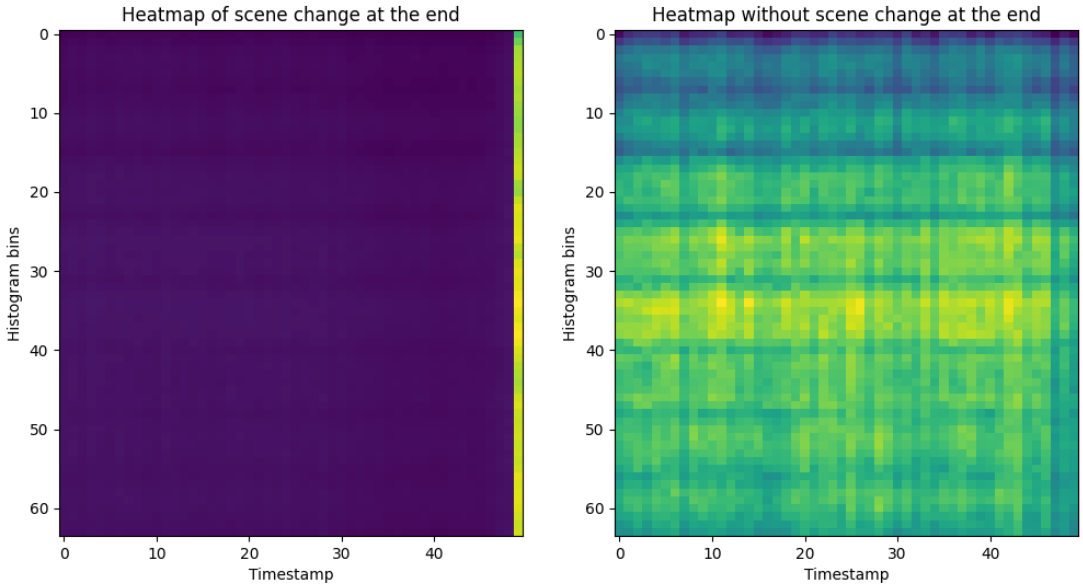

Figure 4. Heatmaps that accumulated train values for true and false labels respectively

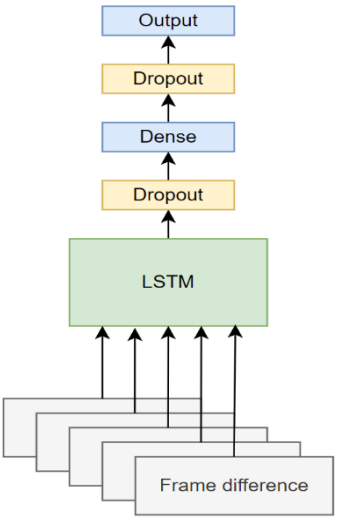

Figure 5. LSTM-base neural network architecture for shot boundary detection

Table 1. Comparison of mathematical approach with state-of-art models

Method	TransNetV2	AutoShot@F1	AutoShot@ Precision	Mathimatical approach
F1	0.799	**0.841**	0.826	0.473
Prec.	0.904	0.923	**0.939**	0.448

Table 2. Comparison between the mathematical approach and the mathematical approach enhanced with neural networks against state-of-the-art models

Method	TransNetV2	AutoShot@F1	AutoShot@ Precision	Mathimatical approach	Mathimatical with NN approach
F1	0.799	0.841	0.826	0.473	**0.888**
Prec.	0.904	0.923	**0.939**	0.448	0.889

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Quantum technologies in optical measurements

Abstract: The importance of light measurements from the point of view of ensuring accuracy and saving energy is considered. The study object is the quantum approach in the reproduction of optical units of measurement. The study subject is modern methodology in theoretical metrology, based on the concept of the New SI (2019). The purpose of the study is to analyze the current state of light measurements from the view point of ensuring accuracy and their energy efficiency. The analysis of quantum technologies of reproduction of optical units – candela, lumen is performed. The standards of Ukraine of candela and lumen, which were developed at the National Scientific Center "Institute of Metrology", Kharkiv, are analyzed. Practical aspects of realization of quantum effects on the example of modern light-emitting diodes which principle of action is based on quantum points are defined. Examples of the practical implementation of quantum photonics in the perspective of the next decade are identified. The opinion is expressed that the development of quantum technologies and practical achievements in the counting of individual photons bring us closer to the creation of devices of a new generation and to new achievements in precision and practical photometry.

Keywords: photoelectric effect, candela, lumen, photodetector, trap detector, standard of Ukraine, LED.

Introduction

The importance of light measurements is determined by the role played by vision in human life: about 80% of information about the world is one of the senses – sight.

The history of standards for light measurements begins in the 19th century, when the candle flame was used as a unit of light power. Over time, the technique of reproducing light quantities improved. The light intensity of all "flaming" standards largely depended on the purity of the fuel, the accuracy of maintaining the combustion regime, atmospheric pressure, air humidity, the percentage of carbon dioxide in it and a number of other factors. Taking into account all these conditions made it very difficult to assess the accuracy of the reproduction of the received light values.

In 1948, at the General Conference on Weights and Measures, a new name for the unit of light power was adopted – the candela. After a long discussion, in 1979, at the 16th General Conference on Weights and Measures, the following definition of the candela was adopted and is still valid: "The candela is equal to the power of light in a given direction of a source that emits monochromatic radiation with a frequency of $540 \cdot 1012\ Hz$, the energy power of which light in this direction is 1/683 W/sr".

The new definition of the candela opened the way to the development of new methods of its reproduction using not only a reference emitter (blackbody), but also a reference receiver. Today, two types of reference receivers are used: a cryogenic radiometer and a photoreceiver. The best metrological characteristics are provided by a cryogenic radiometer, but the use of new types of photodetectors in photodetectors – trap detectors with one hundred percent quantum efficiency – made them competitive in the creation of reference equipment.

The study object is the quantum approach in the reproduction of optical units of measurement.

The study subject is modern methodology in theoretical metrology, based on the concept of the New SI (2019).

The purpose of the study is to analyze the current state of light measurements from the point of view of ensuring accuracy and their energy efficiency.

Based on the purpose of the study, the following tasks were solved:

- analysis of the current state of optical quantum technologies, the principle of operation of which is based on the photo effect for the reproduction of optical blocks;
- research on the use of a precision radiometer based on a receiver to measure the power of light radiation from the point of view of accuracy;
- study of the metrological characteristics of the cryogenic radiometer during the practical implementation of the Ukrainian state standard of the unit of luminous intensity (candela);
- analysis of the accuracy of reproduction of a light flux unit (lumen) using the goniometric method and the ionizing sphere method;
- determination of ways of applied implementation of quantum effects in precision photometry, taking into account practical achievements in control and calculation of individual photons.

To achieve the set goal and solve research tasks, methods of such sciences as quantum physics, radiometry, photometry were used.

The research used the works and scientific sources of leading world scientists such as Barry N. Taylor, Christopher Chunnilall, Joanne C. Zwinkels, Shibu Saha, Ivano Ruo-Berchera, Giorgio Brida, Marco Genovese, Xiaobo Xue, Xiang Peng and Ukrainian scientists L. Nazarenko, P. Neyezhmakov, T. Timofeev, L. Grishchenko, M. Guriev, O. Kupko, V. Tereshchenko.

An analysis by the International Energy Agency showed that lighting costs 19% of the total energy budget. Therefore, it is important to create lighting technologies that provide not only high-quality lighting, but also energy conservation. Recently, the intensive development of light technology is noticeable not only in lighting, but also in medicine, biology, microelectronics, agriculture. Revolutionary advances in microelectronics have given impetus to new light sources – LEDs, which can be called light sources of the 21st century. Solar panels, photometric converters of solar energy are used not only in space, but also in everyday life. In this regard, in many countries' special programs for energy conservation and ecology in the field of lighting are formed and implemented, which cannot be implemented without metrological support, which would meet the challenges of the time (*Pavlenko et al., 2017*).

The results of the study

1. Quantum technologies and reproduction of optical units

The main quantum effect on which optical quantum technologies are based is the photoelectric effect.

The following three laws of external photoeffect are experimentally established:

(1) the maximum initial velocity of photoelectrons is determined by the frequency of light and does not depend on its intensity;
(2) for each substance there is a "red border" of the photoeffect, to wit the lowest frequency of light v_0, at which the photoeffect is still possible;
(3) the number of photoelectrons emitted from the cathode per unit time (saturation photocurrent) is directly proportional to the light intensity.

In addition, the practical inertia of the photo effect is established: it occurs instantly when illuminating the surface of the body, provided that the frequency of light $v = v_0$, i.e., the effect exists.

First and second laws of the photoelectric effect contradict the electromagnetic theory, the propagation of light in space must occur in the form of separate portions of energy – photons. This interpretation of the nature of light allowed a new explanation of the laws of the external photoeffect, in particular, that the kinetic energy of the photoeffect depends on the frequency of light v and the output $A0$, and not on light intensity (the first law).

In addition, it turns out that the external photo effect is possible only at $hv > A_0$. From this formula, the lowest frequency of light at which a photoeffect is possible (red border) is calculated (the second law).

It is also substantiated that the number of photoelectrons that fly out of the metal every second is proportional to the intensity of light (third law).

On the basis of this effect the reference means of measuring equipment, and also the whole class of measuring photoelectric converters (sensors) are created. These include photoresistors, photodiodes, phototransistors, photothyristors. On the basis of these elements, a number of devices have been created, in particular, meters of optical quantities – photometer receivers.

The basic unit of SI in optical measurements (radiometry and photometry) is the candela, and the main method of its reproduction is the use of the photoelectric effect, which is realized with the help of a receiver – a photometer.

The photometer receiver uses photodiodes that convert light radiation into photocurrent. The circuit of the photodetector (photometer) is shown in Appendix (*Figure 1*), its essential components are a precision diaphragm, a filter adjusted for $v(X)$ function, and a photodetector. Consider the principle of measuring the intensity of light using a photodetector (*Saha et al., 2020*; *Zwinkels et al., 2010*; *Nazarenko, 2000*).

We pay attention to the correcting filter, the frequency response of which corresponds to the characteristics of the human eye (*Zwinkels et al., 2010*), shown at Appendix (*Figure 2*).

2. Light flow standards based on the receiver

Using a new definition of the candela (*Taylor & Thompson, 2008*; *Xiaobo et al., 2014*), in the UK it was possible to create a standard based on the receiver, which provided an error of reproduction of the candela at 0.1%. A precision radiometer (optical radiation power meter) with electrical replacement was used as a receiver. Of the existing radiometers of this type, cryogenic radiometers have the highest accuracy. The cryogenic radiometer is a unique device that provides accurate measurements of radiation power in a wide spectral range, which covers the ultraviolet, visible and infrared regions of the spectrum (*Fox, 1991*).

The cryogenic radiometer is now considered to be the most accurate means of reproducing radiometric scales, it heads the traceability chain and forms the absolute radiometric basis. Cryogenic radiometers, which are used to sell the candela, make it possible to reduce the expanded uncertainty to (0.2-0.4)%. But, despite the positive qualities, the cryogenic radiometer is an expensive and quite complex device to manufacture and operate. Therefore, in recent years, alternative methods and means of reproduction of candelas have been developed, and the highest precision devices – cryogenic radiometers – are mainly used as unique devices that provide several areas of optical and physical measurements.

An important metrological characteristic of the photodetector is quantum efficiency – the ratio of the number of photons, the absorption of which caused the formation of quasiparticles (electrons), to the total number of absorbed photons. The term "photodiode conversion factor" is also used. It is a measure of light sensitivity and the main characteristic of photon detectors. In the receiver, the scheme of which is shown in Appendix (*Figure 1*), it is quite limited, because part of the light is not absorbed, reflected and penetrates the output of the photometer.

Initially, these devices had to be calibrated separately for photodiodes, but later this approach acquired new properties due to the advent of "trap detectors" (trap detectors), which increase the efficiency of photodiodes, creating light traps by repeatedly reflecting light. These photometers have a predicted high quantum efficiency (PQED) of about 99.95% and do not require calibration. Trap detectors allow you to measure the intensity of light with an uncertainty of several units by 10^{-6}. For serial photodetectors on trap detectors, the typical measurement uncertainty is from $0{,}5 \cdot 10^{-3}$ to $1 \cdot 10^{-3}$.

On the basis of this technology, standards of chandeliers, lumens, just like precision laser power meters were created (*Pavlenko et al., 2017*). Please note that the meters of photometric units (candelas, lumens) have a corrective filter "visibility", and the power meter – no.

The use of trap detectors as absolute receivers has become common practice. The primary standards of Canada, New Zealand, Germany, and Turkey are based on this principle. Given this, the use of expensive and complex during operation cryogenic radiometers becomes economically impractical. In recent years, there has been the development of a new configuration of the trap detector, consisting of two large photodiodes forming a wedge (*Figure 3*).

This configuration can be used as at cryogenic temperatures (while the uncertainty of power measurements may be less $1 \cdot 10^{-6}$), and at room temperature (*Figure 4*) with an uncertainty of about 10^{-4}.

The use of such devices opens up the possibilities of a new version of candela reproduction based on a white LED as a light source and a receiver based on a trap detector.

The development of photodiode receivers and their latest developments allow us to say that there has been a qualitative leap in the accuracy of calculating the conversion factor of photodiodes, which allows them to be used as receivers with predicted quantum efficiency (Predictable Quantum Efficient Detector).

3. The primary standard of Ukraine's unit of light intensity is candelas

In 1996, the primary standard of Ukraine was built on the basis of an absolute cryogenic radiometer, which successfully performed its functions until 2015 (*Pavlenko et al., 2017*). In 2015, it was decided to create a standard based on a trap detector (*Fox, 1991*; *Nazarenko et al., 2012*).

As part of the work on improving the standard in the NSC «Institute of Metrology» was developed, created and studied photometer (*Figure 5*), based on a trap detector.

The primary standard of Ukraine, in addition to the unit of light intensity (candela), also reproduces the units of illumination (luxury) and illumination (candela per second).

The standard has the following metrological characteristics:

- light reproduction range $1 - 500\ cd$;
- light reproduction range $0.1 - 1000\ lux$;
- lighting playback range $10^{-3} - 500\ cd \cdot s$.

The relative errors (random S and non-excluded systematic error Θ) and the extended uncertainty (U) of the reproduction of units of light intensity, illuminance and illumination do not exceed:

- the power of light – candela
  $S = 0{,}15 \cdot 10^{-2}; \theta = 0{,}15 \cdot 10^{-2}; U = 0{,}3 \cdot 10^{-2}\ (k = 2);$
- lighting – luxury
  $S = 0{,}15 \cdot 10^{-2}; \theta = 0{,}15 \cdot 10^{-2}; U = 0{,}3 \cdot 10^{-2}\ (k = 2);$
- lighting – candelas for a second
  $S = 0{,}25 \cdot 10^{-2}; \theta = 0{,}35 \cdot 10^{-2}; U = 0{,}6 \cdot 10^{-2}\ (k = 2).$
  These values correspond to the world level.

4. Reproduction of a unit of luminous flux – lumen

Luminous flux, the unit of which is the lumen, has become the most important photometric quantity. In recent years, the international community of photometric photometrists has repeatedly raised the question of revising the basic unit of optics, namely the lumen instead of the candela. Therefore, one of the basic standards in the field of photometry, together with the standard of candela, is the standard of lumen. All developed countries of the world have such standards and are working to improve them.

There are two main methods of measuring total luminous flux, to wit lumen reproduction, on which the reference measurements are based:

(1) goniometric method;
(2) the method of integrating sphere.

It is the method of the integrating sphere, as more promising, that was chosen to create the primary standard of the lumen of Ukraine. The standard consists of a number of installations (*Figure 6*):

- installations for reproduction and transmission of a unit of light flux to radiation sources of small sizes;
- installations for reproduction and transmission of a unit of light flux to large radiation sources;
- systems of automatic control, registration and processing of information on the basis of computer technology;

- power supply systems for radiation sources.

The created standard has the following metrological characteristics (*Fox, 1991*; *Nazarenko et al., 2012*):

- range of luminous flux values $1 - 1500\ lm$;
- random error (SLE) – from $0.1 \cdot 10^{-2}$;
- unrecovered systematic error – from $0{,}25 \cdot 10^{-2}$;
- extended uncertainty – from $0.3 \cdot 10^{-2}$.

These characteristics are at the level of the corresponding characteristics of the national standards of economically developed countries.

Precisely due to the lack of reliable methods and means of manipulating individual photons, the redefinition of photometric units in quantum terms has not yet taken place.

Recent advances in the control and calculus of individual photons, just like in the creation of single-photon sources, look promising (*Xiaobo et al., 2014*). It is to be expected in the near future to create radiation sources with a precisely set number of photons per second, which will allow to obtain unprecedented precision of measurements. The ability to reliably manipulate individual photons will contribute to the development of new types of devices, which, in turn, require further development of metrology, the creation of new ones based on quantum phenomena, calibration methods and appropriate standards. For these reasons, sooner or later we should expect a redefinition of the candela in terms of photon units.

Currently, the international project "Quantum Candela" (*Neyezhmakov et al., 2013*), funded by the European Commission and aimed to review the basic unit of SI candela in terms of determining it by the number of photons, rather than optical power, thus linking to the Planck constant. It is also noted that this "will bridge the gap between macroscopic (optical power) and quantum quantities (photon), achieve greater consistency between the definitions of basic units and will promote the development of both quantum technology and classical radiometry" (*Xiaobo et al., 2014*).

5. Applied implementation

Today there are problems and even a crisis of modern semiconductor electronics. It has been found that integration in computing devices doubles every two years. However, at this time further integration is already difficult, heat dissipation increases significantly, parasitic quantum effects begin to appear, technologies become more expensive. Switching speeds and memory are also limited. All this leads to increased energy consumption, unprofitability and crisis. It is believed that semiconductor electronics has exhausted its capabilities.

According to the forecast, the basis of the new electronics, which replaces the semiconductor, are quantum principles and effects.

Modern quantum technologies and practical achievements in the control and calculation of individual photons promise new achievements in precision and practical photometry, the creation of new generation devices.

Separately it is necessary to talk about creation on the basis of quantum technologies of highly effective sources of illumination – light-emitting diodes which have made a kind of

revolution in lighting engineering. Modern directions of development include the use of quantum dots, which allow to obtain white light (*Neyezhmakov et al., 2017*).

The first white LEDs were expensive and inefficient. However, the light output of LEDs has increased exponentially. Recent research and development have been disseminated by Japanese manufacturers such as Panasonic and Nichia, just like Korean and Chinese manufacturers such as Samsung, Kingsun and others.

Experimental white LEDs were demonstrated in 2014 to produce $303\ lm/W$; some can last up to 100,000 hours. However, commercial LEDs have an efficiency of up to $223\ lm/W$. The previous record of 135 lm/W was set by Nichia in 2010. Now the light output of modern LEDs reaches $190\ lm/W$ (*Samsung Achieves…, 2023*). The theoretical limit of the technology is estimated at more than $300\ lm/W$ (*Cree…, n.d.*). Compared to incandescent lamps, this is a huge increase in electrical efficiency, and although LEDs are more expensive to purchase, the total cost is much cheaper than incandescent lamps (*The quantum candela, 2011*; *In new quantum-dot…, 2010*; *LED bulb…, 2016*).

EURAMET sees among the most promising practical implementations of Qu-Photonic for the next decade single-photon LIDAR (technology for forest structure and carbon monitoring at large spatial scales because it acquires 3D measurements of vegetation faster and more efficiently than conventional lidar instruments), Quantum illumination (a model for target detection that employs quantum entanglement between a signal electromagnetic mode and an idler electromagnetic mode, just like joint measurement of these modes), Sub-shot-noise imaging, amplitude-squeezed spectroscopy, NV-centre sensing, squeezing and entanglement for gravity wave detectors etc. (*Figure 7*) (*Chunnilall, 2022*; *Tang et al., 2016*; *Brida et al., 2010*).

6. On the prospect of quantum redefinition of light units

In the frequency range $0 - 108\ Hz$, the mathematical apparatus of electric circuits with concentrated parameters works. Above these frequencies, the apparatus of Maxwell's equations begins to operate, which is used up to frequencies of about $1015\ Hz$ and even higher. Next, there is a rather wide transition region where the classical approach must be supplemented by a quantum one, and it is in this region that the visible frequency range is located.

Quantities, the value of which is due to the number of photons, are quantities of optical radiation, which are expressed in terms of the number of photons or the photon flux. Due to the ambiguous (corpuscular-wave) nature of electromagnetic radiation, photometric and/or energy quantities can also be expressed in terms of the number of photons. The relationship between the energy value at a given wavelength ($\mathrm{X}_{e,\lambda}(\lambda)$) and the corresponding value, the value of which is determined by the number of photons ($\mathrm{X}_{p,\lambda}(\lambda)$), is expressed as

$$\mathrm{X}_{e,\lambda}(\lambda) = \frac{hC}{\lambda} \cdot n_a(\lambda)\mathrm{X}_{p,\lambda}(\lambda),$$

where:

h is Planck's constant,

c is the speed of light in a vacuum,

$n_a(\lambda)$ is the index of refraction in air at a wave of a given length (λ).

The practical implementation of the above units can be performed using a receiver (detector) or a source, just like using the conversion of radiometric values into values whose value is determined by the number of photons given in equation. However, it is also possible to use sources that generate individual photons at a known speed, and count the number of photons ("one-photon tunneling" method). This approach is called "conditional on the number of photons".

In other words, it is necessary to be able to create radiation sources with a precisely known number of photons per second, just like receivers whose sensitivity and resolution can be at the level of one photon.

Since each photon can be thought of as a frequency-dependent quantum of energy, it is conceptually easy to relate the number of photons to the amount of energy or power.

For example, the light flux Φ can be represented by the number of photons n:

$$\Phi = \frac{n \cdot h \cdot f}{t},$$

where:

h is Planck's constant,

f is the frequency of light radiation ($540 \cdot 1012\ Hz$).

In turn, if we know Φ, we can calculate the photon flux:

$$\frac{n}{t} = \frac{\Phi}{h \cdot f}.$$

The energetic power of the radiation corresponds to the photon power (intensity)

$$(683 \cdot 540 \cdot 10^{12} \cdot 6.62603896 \cdot 10^{34})^{-1}$$

photons per second per steradian.

At this time, there are already experimental single-photon sources, just like detectors capable of counting individual photons (photomultipliers, single-photon avalanche diodes, superconducting nanowire detectors, etc.).

Today, it is still too early to talk about a reliable practical implementation of the "one-photon tunneling" method and photometric units determined by the number of photons. but single-photon sources and photon number detectors as experimental models already exist.

As in the "one-electron tunneling" method, there are, first of all, technological problems in practical implementation. However, research in this direction is actively continued, especially since one of the tasks of modern metrology is the creation of the "quantum candela" (and other photometric units).

Conclusion

The new definition of candela paved the way for the development of new methods of its reproduction using not only the reference emitter (black body), but also the reference receiver. Today, two types of reference receivers are used: cryogenic radiometer and photodetector. The best metrological characteristics are provided by a cryogenic radiometer, but the use of new types of photodetectors in photodetectors – trap detectors with 100% quantum efficiency – has made them competitive in the creation of reference equipment. One of the areas of research in fundamental radio and photometry is the search for ways to redefine photometric quantities through the number of photons, binding to the Planck constant. It is expected that this will

achieve greater consistency between the basic SI units and promote the further development of optical measurements in general.

Research on quantum measurement technologies has contributed to the development of a number of applied optical quantum technologies and related devices: solar electricity sources – using the photo effect, thermal imagers and night vision devices – using the conversion of infrared radiation into visible light, photodiode lighting sources – using the quantum conversion of electricity into light.

Modern quantum technologies and practical achievements in the control and counting of individual photons promise new achievements in precise and practical photometry, the creation of new generation devices, the redefinition of photometric quantities through the number of photons, i.e., binding to Planck's constant. It is expected that this will allow for greater consistency between the basic SI units and contribute to the further development of optical measurements in general. Recent advances in the control and counting of single photons, just like in the creation of single-photon sources, look promising.

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Appendix

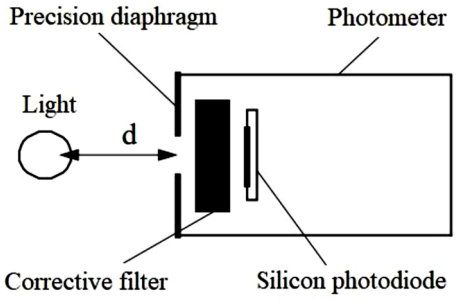


Figure 1. Optical scheme of the photodetector

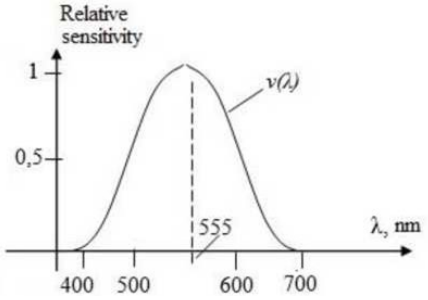


Figure 2. Characteristics of the spectral sensitivity of the human eye (curve of "visibility")

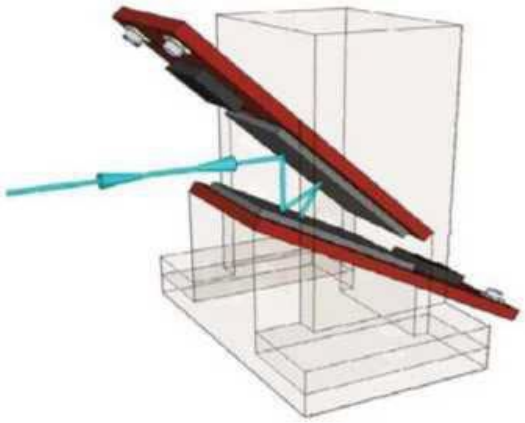


Figure 3. Optical circuit of a two-diode trap detector with 7-fold reflection

Figure 4. Industrial device with predicted quantum efficiency

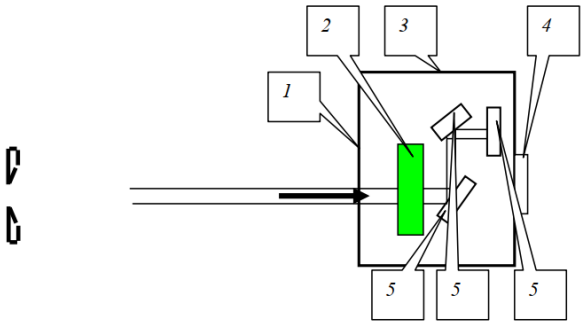
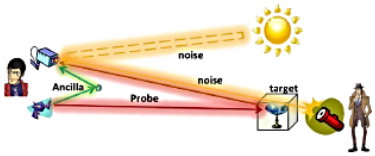


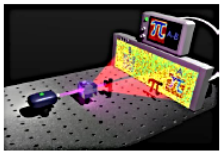
Figure 5. Scheme of a photometer based on a trap detector:
1 – diaphragm; 2 – filter V (λ); 3 – housing; 4 – a mirror; 5 – photodiodes S1337

Figure 6. Appearance of the standard unit of luminous flux

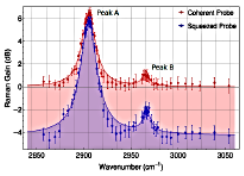
Single-photon LIDAR



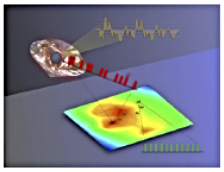
Quantum illumination



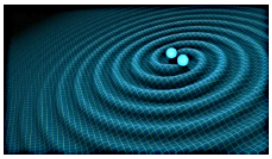
Sub-shot-noise imaging



Amplitude-squeezed spectroscopy



NV- centre sensing



Squeezing and entanglement for gravity wave detectors

Figure 7. Some photonics applications (*Chunnilall, 2022*)

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Prospects for developing the technical supply system of the leading NATO member countries' armed forces

Abstract: The experience of the use of troops (forces) in wars and armed conflicts of the late twentieth and early twenty-first centuries has shown that the advantage in armed struggle will belong to armies that are sufficiently trained, armed and comprehensively provided. The most significant role in solving the problems of comprehensive support of troops (forces) is played by technical support – one of the main types of logistics of troops (forces). According to leading Western military experts, strategy and tactics are the basis for planning and conducting operations and combat operations, and the relevant components of the technical support system ensure their implementation, ie the scope and timing of operational plans depend on the ability of the technical support system to meet needs. troops (forces) in serviceable samples of armaments and military equipment, necessary stocks of military-technical property and other material and technical means. The study subject is the system of material and technical support of the leading NATO member countries' armed forces. The study object is the technical support of the leading NATO member countries' armed forces. The study's purpose is to determine the trends and prospects for further developing the technical support of the leading NATO member countries' armed forces. To achieve the purpose and solve the tasks, the authors used such scientific methods as primary methods for the purpose of gathering information and studying sources; secondary methods for the purpose of processing and analyzing the received data – quantitative and qualitative data analysis, their systematization; logical-analytical such as methods of deduction and induction. The authors used works and scientific sources of leading scientists, such as Vladyslav Yemanov, Oleksandr Sysoev, Oleksiy Kolomiytsev, Oleg Mysyura, Serhiy Kovalishyn, Oleksiy Pavlovsky, Serhii Shevchenko. The authors conclude that (1) trends and prospects for the development of air attack means of the armed forces of the leading countries of the world, their capabilities for defeating air defence forces and means must be thoroughly studied and considered during the organization and implementation of TS in all branches of management of the Air Force of the Armed Forces of Ukraine; (2) the main characteristics of the modern TS of the armies (forces) of the leading countries of the world, the directions of their development are a kind of foundation, based on which it is necessary to improve the TS of the Armed Forces of the Armed Forces of Ukraine; (3) as part of further research in this direction, it is advisable to analyze the possibilities and prospects of developing the WME system maintenance according to the technical state in the world-leading countries.

Keywords: technical support system, armament, military equipment, maintenance, repair.

Introduction

The analysis of the experience of the use of troops (forces) of the leading NATO member countries' armed forces in local wars and armed conflicts of the late 20th and early 21st centuries showed (*Ashirmetov, 2023*; *Kolomiitsev et al., 2023*; *Kovalishin & Halturin, 2014*; *Pavlovskyi & Sysoiev, 2010*; *Pro skhvalennia…, 2017*; *Safonov et al., 2023*; *Shevchenko & Bezdielnyi, 2021*) that the advantage in armed struggle will belong to armies that are sufficiently trained, armed and comprehensively equipped. The most important role in solving the tasks of comprehensive support of troops (forces) is played by technical support (TS) – one of the main types of material and technical support (MTS) of troops (forces). According to the leading Western military experts, strategy and tactics are the

basis of planning and conducting operations and hostilities, and the corresponding components of the TS system ensure their implementation, i.e., the scope and timing of the implementation of the developed operational plans depend on the ability of the TS system to meet the needs of the troops promptly (forces) in serviceable samples of weapons and military equipment (WME), necessary stocks of military-technical property (MTP) and other material and technical means (MTM) (*Ashirmetov, 2023*; *Sysoiev, 2004*; *Yemanov, 2023*).

The study subject is the system of material and technical support of the leading NATO member countries' armed forces.

The study object is the technical support of the leading NATO member countries' armed forces.

The study's purpose is to determine the trends and prospects for further developing the technical support of the leading NATO member countries' armed forces.

Based on the study's purpose, the following tasks were solved:

- conduct an analysis of trends and prospects for the further development of the technical support of the leading NATO member countries' armed forces;
- derive analytical dependencies to determine ways of development of technical support of the leading NATO member countries' armed forces;
- establish the influence of technical support components on indicators of the system of material and technical support of the leading NATO member countries' armed forces.

To achieve the purpose and solve the tasks, the authors used such scientific methods as primary methods for the purpose of gathering information and studying sources; secondary methods for the purpose of processing and analyzing the received data – quantitative and qualitative data analysis, their systematization; logical-analytical such as methods of deduction and induction.

The authors used works and scientific sources of leading scientists, such as Vladyslav Yemanov, Oleksandr Sysoev, Oleksiy Kolomiytsev, Oleg Mysyura, Serhiy Kovalishyn, Oleksiy Pavlovsky, Serhii Shevchenko.

Materials and methods

The current stage of the development of military science in the world requires taking into account the latest trends in the development of WME, which have manifested themselves in local wars and armed conflicts of our time, just like an analysis of the functioning of the TS of the armies (forces) of the world-leading countries, ensuring the conduct of these operations (combats). Therefore, the issue of determining the trends and prospects for the further development of the systems of TS, armed forces WME of the leading NATO member countries based on the results of the analysis of their support in local wars and armed conflicts of the late 20th and early 21st centuries remains relevant (*STANAG 1406*; *STANAG 2182*; *STANAG 2406*; *STANAG 7166*).

Results

1. Trends in the WME development of the leading NATO member countries

The fundamental difference of modern military conflicts is the leap-like renewal of various types of WME and methods of their use. Thus, there were nine previously unknown weapon types in the Korean War (1950-1953), already 25 such types in Vietnam (1964-1975), about 30 ones in the conflicts in the Middle East (1967, 1973, 1982, 1986), 50 ones in the Persian Gulf

war (1990), and more than 100 samples and weapons systems during the hostilities in the Balkans in 1999 that had not been used anywhere before. Military and political leadership of the leading NATO member countries, in particular the USA, among the latest technologies, pays special attention to aerospace and missile technologies, as evidenced by the analysis of the experience of military actions of the last decades in which the US armed forces took part.

The main trends in developing the world-leading countries armed forces WME are based on:

- expanding the scope of scientific knowledge and achievements realized in samples, complexes and systems of WME;
- increasing their manoeuvrability and the degree of automation through the use of artificial intelligence and robotics;
- increasing the ability of WME samples to act autonomously in different environmental conditions and on a real-time scale;
- simplifying the operation of air defence systems and reducing, on this basis, the number of crews and the amount of military work;
- creating special means for peacekeeping activities to neutralize armed conflicts, including the creation of non-lethal weapons;
- increasing the role and importance of guided weapons, first of all, high-precision weapons in WME systems;
- shortening the time of transfer of samples, complexes and systems of WME to combat readiness;
- increasing the security, survivability and reliability of the functioning of samples, complexes and systems of WME;
- implementation of the modular principle of construction, new forms of standardization and unification of samples, complexes and systems of WME;
- increasing the importance of modernization of existing samples, complexes and systems of WME in the general system of creation of WME.

The technical base for implementing the WME development trends consists of the latest technologies, based the latest achievements in microelectronics, informatics, optoelectronics, robotics, etc.

According to their specialists, implementing the specified trends in the leading NATO member countries' WME development can lead to significant changes in the forms and methods of conducting combat operations by troops (forces) and their comprehensive support.

2. Analysis of the existing system of leading NATO member countries' armed forces technical support

Technical support is organized and performed to maintain the combat readiness of the troops (forces) by:

- providing them with WME and other MTS;
- maintaining them in working condition and readiness for combat use;
- restoring WMEs when they fail.

According to the assessment of military experts, the combat readiness of troops (forces),

the combat capability of units, WME, is directly dependent on the degree of TS management system readmess, just like the quantitative and qualitative composition of the forces and means of the TS.

Technical support, as a type of MTS of troops (forces), includes:

- maintenance of WME;
- repair of WME;
- introduction of constructive changes to WME;
- collection, evacuation and restoration of damaged WME;
- preservation and storage of WME.

Maintenance of WME in the NATO member countries' armed forces is performed based on standards developed in each country. The version of the maintenance system adopted by the US Army is given in Appendix (*Table 1*).

In connection with the adoption of modern types of WME, the US armed forces are transitioning to WME maintenance system in a state that, according to military experts, will make it possible to reduce the costs of its implementation by up to 30% (*Kolomiitsev et al., 2023*; *Kovalishin & Halturin, 2014*; *Pavlovskyi & Sysoiev, 2010*; *Pro skhvalennia…, 2017*).

In NATO, next to the national management bodies of TS, joint bodies have been created, which are responsible for developing the general policy and requirements for the TS system, the organization and performing of repair and restoration works of WME.

The core management bodies of the MTS system, which organize and carry out TS activities, include the NATO Advisory Council on Armaments, the Infrastructure Committee, the Committee on Rear Management Pipelines of the International Joint Staff of the Military Committee. The main body that directly deals with the issue of the maintenance of troops (forces) is the NATO agency for the supply of spare parts, maintenance and repair. In addition, NATO has created bodies that organize the maintenance and repair of specific types of WME.

When planning and implementing the TS, the management bodies adhere to the following principles:

- national responsibility for the TS of units, military units (subunits), transferred to NATO;
- centralized TS;
- minimum duration of repair of WME.

It is believed that the criterion for evaluating the effectiveness of the TS is the ability of the military administration bodies (departments, services), military units and units to perform the WME restoration directly in the troops in a short period.

Now there is a process of some reduction of the total volume of MTP stocks, stored in the warehouses of the Ministry of Defense, with the simultaneous optimization of its possible use. According to the American press, the process of reorganization of strategic stocks began in the 1990s. They ceased to be attached to some commands in the zones, but became general. It ensures the implementation of a new US strategy, providing for the possibility of the country's participation in two regional military conflicts, simultaneously conducted in any region of the globe.

Materiel in the NATO member countries' armed forces is divided into five classes (*Kolomiitsev, 2023 et al.*; *Kovalishin & Halturin, 2014*; *Pavlovskyi & Sysoiev, 2010*; *Pro skhvalennia…, 2017*):

- class I – personal hygiene food and items, consumed in approximately the same of quantities in any conditions of the environment and terrain. They are allocated based on data on the number of personnel.
- class II – standard weapons, military equipment, engineering and medical property, spare parts and tools necessary for maintenance and repair.
- class III – fuel and lubricants of all kinds, liquid gases, coolants and coal.
- class IV – items of supply that do not belong to the standard (table) set of weapons, military equipment and equipment, construction and fortification materials, special machines and additionally allocated items of supply of class II.
- class V – ammunition of all kinds, explosives, detonators, poisonous substances.

A single system of MTS codification has been introduced to simplify and unify the accounting, storage and requisitioning of supplies in the NATO armed forces. According to it, each item is assigned a 13-digit number and a short description, which facilitate the selection of identical and interchangeable MTS.

The created reserves of MTS are divided into basic ones, needed in the initial period of the war – for about 30 days, and long-term ones, needed in the subsequent period. The created reserves of MTS are graded as follows. In the rear areas of the division, before the start of the operation, reserves are created for 10-12 days of hostilities, during the operation, the reserves are maintained in the division at the level of 3 days. In total, it is expected to have supplies for 7-10 days of combat operations in the operation course in the rear area of the army corps and warehouses.

It is worth emphasizing that one of the most significant TS tasks is to restore the maximum possible amount of WME in the shortest possible time. According to the estimates of NATO specialists, WME losses, including armored ones, during the Arab-Israeli war exceeded the indicators of the Second World War by an average of four times.

When organizing the repair of WME in combat conditions, the US troops (forces) repair bodies' specialists adhere to the following principles:

- for the restoration of damaged equipment located near the front edge, the time of repair work should not exceed 20 minutes;
- equipment, which requires about one hour to restore (including towing time), must be evacuated to the nearest shelter 2-4 km away from the line of contact of the troops;
- repair works lasting up to 12 hours are expected to be performed in the rear areas of battalions, 12-36 hours – in the rear brigade areas, 36-120 hours – in the rear areas of divisions and corps;
- equipment that requires a longer time to restore must be evacuated further to the rear or dismantled for spare parts;
- in the event of a threat of capture by the enemy, weapons and military equipment are subject to destruction.

Regulatory and repair and restoration works in NATO countries armed forces are organized and performed in a single repair system, including military (current), field (medium) and basic (capital) repairs. The main types of WME repair of the leading NATO member countries' armed forces are listed in the Appendix (*Table 2*).

Military (current) repairs are performed by the forces of combat services (crews), just like the personnel of repair units (battalions and companies). It includes operations to replace nodes, aggregates and eliminate malfunctions, the labor intensity of which does not exceed six man-hours per equipment unit.

Field (average) repair, performed by the forces of repair division bodies, army corps, is divided into direct and general. Direct average repair is performed in the interests of a specified unit, military unit (subdivision) and involves the work performance, the degree of labour intensity of which does not exceed 24-36 man-hours per unit of equipment. General average repair is performed in the interests of the entire WME supply system. It assumes the implementation of works on the restoration of the WME with a labour intensity of 72-96 man-hours per equipment unit.

Basic (capital) repairs are carried out by civilian contractor companies from the USA, just like NATO member countries if there are relevant agreements.

3. Trends and prospects for developing the technical support system of the leading NATO member countries' armed forces

The appearance of new modern types of WME has always necessitated the development of new forms and methods of using troops (forces) in operations (combat operations) and new approaches to their comprehensive support, too. This concerns (1) the structure of the TS system itself and (2) the organization of the restoration of WME, considering its possible losses during operations (combat operations), thirdly, the norms of WME reserves and their echeloning both in peacetime and in a specific period, fourthly, of direct management of the TS of troops (forces) in operations (combats).

Discussion

Because the task of ensuring the combat readiness of troops (forces) has turned into one of the most significant problems of increasing their effectiveness in combat use, it is worth assuming that developing the TS system will be performed in this direction. In addition, the development of WME, operational art and tactics of combat operations causes changes in the structural construction and functioning of the TS system.

The analysis of the experience of organization and implementation of TS activities of troops (forces) in operations (combat actions) based on the experience of local wars and armed conflicts confirms this conclusion and determines the main trends and directions of development of TS systems of the armed forces of the leading NATO member countries, listed below.

(1) Automation of technical support management. First, this concerns creating an automated management system (AMS), which should cover all management processes, related to TS. To date, in the armed forces of the leading NATO member countries, the TS management system is fully automated in the brigade-division-corps link. In particular, befitting automated material accounting centres have been created in the tactical management chain (brigade). Thus, in the operation "Desert Storm", the troops TS planning was already performed with the help of a system that made it possible to perform all calculations for determining the need for material resources, their distribution and supply to the troops.

Space communication systems were already used in Operation "Iraqi Freedom" under the control of TS.

(2) The ability of the TS system to carry out repair and restoration works of WME systems in modern conditions of armed conflict. It is due to the use of new types of weapons, in particular, high-precision weapons (HPW), which led to a change in the structure of combat damage of WME in the direction of an increase in severe damage and irreversible losses. Thus, the irreversible MAW losses reached 50% in Afghanistan, the losses of the Taliban's anti-aircraft guns reached 50-80% in the anti-terrorist operation "Unshakable Freedom", the vast majority of the damaged anti-aircraft guns were severely damaged in the operation "Iraqi Freedom". Therefore, it is likely that developing the TS system will be performed in the direction of increasing the capacities for military (medium) and basic (capital) repairs, i.e., strengthening the tactical and strategic link repair systems.

(3) Early preparation of the TS system of troops (forces) in operations (combat operations). Thus, to ensure the combat operations of the armed forces troops in the Persian Gulf zone, 30 daily MTS supplies were created two years before the operation. Six months before the operation, these supplies were doubled and before the start of the operation satisfied 60 daily needs of the troops. The technical support of the troops (forces) in the operations "Unshakable Freedom" and "Iraqi Freedom" was performed by a system that was deployed in advance and functioned in peacetime.

(4) An increase in MTS number and weight, consumed by one serviceman in modern conditions of conducting operations (combat operations). If earlier this norm in the initial period was 70-100 kg (of which up to 70% belongs to the MTS of the TS system nomenclature), then already in the war in the Persian Gulf, it exceeded 110 kg and, according to Western experts, has a steady tendency to increase. Thus, according to the results of the analysis of military specialists on TS issues, the division's daily need for material resources was (will be):

- in the First World War – up to 100 tons;
- during the Second World War – 700-800 tons;
- in the Vietnam War – more than 1,000 tons;
- in the war in the Middle East – 2,000-2,100 tons;
- in modern local wars and armed conflicts – 2,700-2,800 tons.

This factor makes it necessary to determine expedient options for the echeloning of MTS in various branches of managing the TS of the troops (forces).

(5) Increasing readiness degree of military units (subunits) and TS institutions in operations (combat actions). For example, in the war in Chechnya, at the end of the operation, some military units of the TS armed forces of the Russian Federation had a readiness level corresponding to combat military units.

(6) Development of the weapons system and military equipment. Changes in views on methods and methods of repairing the latest weapons systems are provided for in this direction. It is quite likely that the entire complex (systems) of weapons will be immediately repaired (restored) when its elements fail. At the same time, the means of repair will develop in the direction of the development of diagnostic systems and the aggregate method of repair.

Conclusions

The conducted analysis of the functioning of the existing system of TS of the leading NATO member countries armed forces and its capabilities to support the troops (forces) of WME, MTP and other MTS in operations (combat actions) makes it possible to draw the following conclusions:

(1) Trends and prospects for the development of air attack means of the armed forces of the leading countries of the world, their capabilities for defeating air defence forces and means must be thoroughly studied and considered during the organization and implementation of TS in all branches of management of the Air Force of the Armed Forces of Ukraine.

(2) The main characteristics of the modern TS of the armies (forces) of the leading countries of the world, the directions of their development are a kind of foundation, based on which it is necessary to improve the TS of the Armed Forces of the Armed Forces of Ukraine.

(3) As part of further research in this direction, it is advisable to analyze the possibilities and prospects of developing the WME system maintenance according to the technical state in the world-leading countries.

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Appendix

Table 1. The existing system of maintenance of WME of the US Armed Forces

Type of maintenance	Periodicity		Duration	
	Tanks, IFV, etc (1 group)	Cars, etc (group 2)	Group 1	Group 2
Overview 1	Before each exit		30 min	15 min
Overview 2	At short stops		15 min	3 min
Plan type ”A”	Every day after running the machine		1,2 hours	20 min
Plan type ”B”	Weekly	In two weeks	4-6 hours	1 hours
Plan type ”C”	Monthly or after 400 km mileage	Monthly or after 1,600 km of mileage	up to 24 hours	16-17 hours
Plan type ”D”	Quarterly or after 1200 km mileage	Quarterly or after 9,600 km of mileage	1-2 days	1-2 days
Seasonal	When switching to the summer (winter) period of operation		3-5 days	3-5 days

Table 2. Types of the leading NATO member countries' armed forces WME repair

Repair	Echelon of repair	Content, duration of repair	The place of repair, who performs it
Military	First	Current repair	company, driver, crew
	Second	Current repair (2-6 man-hours per sample)	company, brigade, special rem. groups
Field	Third	Repair of WME with replacement or repair of nodes, aggregates (24-36 man-hours per sample)	brigade, division, repair company
	Fourth	Repair of WME with replacement or repair of nodes, aggregates (up to 96 man-hours sample)	division, army corps, repair battalion
Base	Fifth	Overhaul of WME. Restoration of operational resource by 70%	field army, stationary repair enterprise

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Device for measuring the blood oxygenation considering the concentration of carboxyhemoglobin

Abstract: The general method of assessing the level of arterial blood oxygenation is pulse oximetry. However, in known pulse oximeters, blood oxygen saturation is determined only by functional fractions of hemoglobin, reducing the accuracy of the devices and is unacceptable in some clinical cases. The purpose of the study was to increase the accuracy of measuring the arterial blood oxygenation level by the pulse oximetric method by considering the concentration of carboxyhemoglobin and developing a device. To achieve this purpose, the authors used Simulation computer modelling methods to build a model and assess the accuracy of a pulse oximeter. The purpose was achieved by using an additional LED. Its light wavelength choice was justified under the condition of maximizing the contribution of carboxyhemoglobin to the optical density of the measurement object. The theoretical provisions for measuring the blood oxygenation level, considering carboxyhemoglobin concentration and the structural diagram of the pulse oximeter, have been developed. Computer models of the known pulse oximeter and pulse oximeter with an additional LED were developed, simulation studies were conducted based on the developed models, and the device accuracy for measuring blood oxygenation level, considering carboxyhemoglobin concentration, was evaluated. The authors conclude that simulation studies based on the developed models proved that the proposed pulse oximeter, unlike the known one, allows you to detect and evaluate the decrease in blood oxygenation level caused by an increase in the concentration of carboxyhemoglobin in the patient's blood.

Keywords: pulse oximeter, oxygenation, carboxyhemoglobin, simulation, saturation.

Пристрій для вимірювання оксигенації крові з врахуванням концентрації карбоксигемоглобіну

Анотація: Основною методикою оцінки рівня оксигенації артеріальної крові є пульсова оксиметрія, перевагами якої є швидкість, проста, надійність та неінвазивність процедури. Проте в відомих пульсоксиметрах сатурація крові киснем визначається лише за функціональними фракціями гемоглобіну, що зменшує точність приладів і є неприйнятним в певних клінічних випадках. Методом дослідження є підвищення точності вимірювання рівня оксигенації артеріальної крові пульсоксиметричним методом шляхом врахування концентрації карбоксигемоглобіну, а також розробка відповідного приладу. В ході дослідження застосовувалися методи імітаційного комп'ютерного моделювання для побудови моделі і оцінки точності пульсоксиметра. Мету досягнуто застосуванням у відомому пульсоксиметрі додаткового світлодіоду, обґрунтовано вибір довжини хвилі його світла за умовою максимізації внеску карбоксигемоглобіну в оптичну густину об'єкта вимірювання. Розроблено теоретичні положення вимірювання рівня оксигенації крові з врахуванням концентрації карбоксигемоглобіну і структурну схему пульсоксиметра, що реалізує дане вимірювання. Розроблено комп'ютерні моделі відомого пульсоксиметра і пульсоксиметра з додатковим світлодіодом, проведено імітаційні дослідження за розробленими моделями і оцінено точність апарату для вимірювання рівня оксигенації крові з врахуванням концентрації карбоксигемоглобіну. Автори зробили висновок що дослідження за розробленими моделями довели, що запропонований

пульсоксиметр, на відміну від відомого, дозволяє виявити і оцінити зниження рівня оксигенації крові, яке викликане підвищенням концентрації карбоксигемоглобіну в крові пацієнта.

Ключові слова: пульсоксиметр; оксигенація; карбоксигемоглобін; моделювання; сатурація.

Вступ

Існує велика кількість патологій функціонування організму людини, перебіг яких супроводжується гіпоксією, а рівень оксигенації крові пацієнта потребує постійного спостереження.

Основною методикою безперервної оцінки сатурації киснем гемоглобіну артеріальної крові є пульсова оксиметрія (*Pole, 2002*). До її переваг можливо віднести швидкість, просту, надійність та неінвазивність, що дозволяє виявити низький рівень кисню в крові до того, як стануть помітні його клінічні ознаки. Медичним приладом, призначеним для вимірювання концентрації кисню в крові, є пульсовий оксиметр (пульсоксиметр). Портативні пульсоксиметри, що працюють від первинних гальванічних елементів, доступні для транспортування і домашнього моніторингу рівня оксигенації крові (*Black ma in., 2023*).

Важливість контролю рівня насичення крові киснем суттєво зростає в сучасних умовах пандемії COVID-19 (*Rosic ma in., 2022*), коли у пацієнтів відзначаються значні ураження легеневої тканини. Тому підвищення точності відомих пульсоксиметрів, а також розробка апаратів для вимірювання рівня оксигенації крові при патологічних станах організмів пацієнтів є актуальним завданням.

В відомих пульсоксиметрах сатурація гемоглобіну артеріальної крові киснем визначається за рівнянням (*Tremper i Barker, 1989*):

$$SpO_2 = \frac{C_{HbO_2}}{C_{HbO_2}+C_{HbH}}, \quad (1)$$

де:

C_{HbO_2} – концентрація оксигемоглобіну, моль/л;

C_{HbH} – концентрація дезоксигемоглобіну, моль/л.

Величина SpO_2 має назву функціонального насичення крові киснем. Її числове значення показує частку гемоглобіну артеріальної крові, що з'єднаний з киснем, (оксигемоглобіну, HbO_2) від загальної концентрації функціонального гемоглобіну, який може приймати участь в перенесенні кисню.

Визначення SpO_2 в пульсоксиметрах здійснюється оптичним двоспектральним методом (*Von Chong ma in., 2018*), а в якості джерел світла зазвичай застосовуються два світлодіоди: червоний і інфрачервоний з орієнтовними довжинами випромінюваних хвиль $\lambda_1 = 660$ та $\lambda_2 = 940$ нм відповідно.

Монохроматичне світло, з довжиною хвилі λ_j і інтенсивністю $I_{0,j}$, при проходженні крізь шар артеріальної крові частково поглинається. Інтенсивність світла на виході становитиме I_j і визначається за законом Бугера-Ламберта-Бера:

$$\log\frac{I_{0,j}}{I_j} = l \cdot \sum_{i=1}^{n}(\varepsilon_{j,i} \cdot C_i), \quad (2)$$

де:

C – мольна концентрація похідної гемоглобіну в крові, моль/л;

l – товщина шару артеріальної крові, см;

n – кількість похідних гемоглобіну в крові;

ε – коефіцієнт екстинкції, л/(моль·см).

В формулі використано наступні індекси:

i – порядковий номер похідної гемоглобіну,

j – порядковий номер довжини хвилі світла.

В (1) сатурація крові киснем визначається за двома похідними гемоглобіну, тому n в (2) дорівнює 2.

Проте товщина l шару артеріальної крові змінюється внаслідок зміни кровонаповнення судин, яке відбувається періодично і зумовлюється пульсом. Окрім цього, випромінюване світло поглинає не тільки артеріальна, а й венозна кров разом зі шкірою.

Тому в розрахунки сатурації вводиться допоміжна величина R, яку визначають за відносною зміною інтенсивності світла кожної довжини хвилі (*Рисунок 1*), що пройшло крізь тканину тіла, за один кардіоцикл:

$$R = \frac{\log\left(\frac{I_{min,1}}{I_{max,1}}\right)}{\log\left(\frac{I_{min,2}}{I_{max,2}}\right)}, \tag{3}$$

де:

I_{max} – постійна складова інтенсивності світла, яке пройшло крізь об'єкт вимірювання;

I_{min} – мінімальна інтенсивність, яка обумовлена пульсовою зміною наповнення судин об'єкта артеріальною кров'ю.

При використанні (3) враховується поглинання світла лише шаром артеріальної крові, що додатково створюється під час кровонаповнення судин. Товщина такого шару періодично змінюється від 0 до деякого максимального значення, що становить d_{max}. Тоді згідно з (2) інтенсивність світла на виході об'єкта при застосуванні червоного світлодіода:

$$I_{min,1} = I_{max,1} \cdot 10^{-d_{max}\left(\varepsilon_{1,HbO_2}C_{HbO_2}+\varepsilon_{1,HbH}C_{HbH}\right)}. \tag{4}$$

Інтенсивність світла на виході об'єкта при застосуванні інфрачервоного світлодіода:

$$I_{min,2} = I_{max,2} \cdot 10^{-d_{max}\left(\varepsilon_{2,HbO_2}C_{HbO_2}+\varepsilon_{2,HbH}C_{HbH}\right)}. \tag{5}$$

Підстановкою (4) і (5) в (3) одержуються вираз для розрахунку величини R:

$$R = \frac{\varepsilon_{1,HbO_2}C_{HbO_2}+\varepsilon_{1,HbH}C_{HbH}}{\varepsilon_{2,HbO_2}C_{HbO_2}+\varepsilon_{2,HbH}C_{HbH}}, \tag{6}$$

і взаємозалежність концентрацій похідних гемоглобіну:

$$C_{HbO_2} = C_{HbH}\frac{R\varepsilon_{2,HbH}-\varepsilon_{1,HbH}}{\varepsilon_{1,HbO_2}-R\varepsilon_{2,HbO_2}}. \tag{7}$$

Підстановкою (7) в (1) одержується відомий вираз для розрахунку функціональної сатурації SpO_2 крові киснем за допоміжною величиною R (*Kusznier i Wojtkowski, 2019*):

$$SpO_2 = \frac{\varepsilon_{2,HbH}-\varepsilon_{1,HbH}}{R\left(\varepsilon_{2,HbH}-\varepsilon_{2,HbO_2}\right)+\varepsilon_{1,HbO_2}-\varepsilon_{1,HbH}}. \tag{8}$$

Технічно задача визначення рівня оксигенації крові реалізується в пульсоксиметрі шляхом вимірювання постійної і промодульованої пульсом компонент світла, яке пройшло крізь тканину в червоному та інфрачервоному діапазонах, для подальшого обчислення співвідношення R (6) і сатурації (8) (*Mehrabi ma in., 2018*; *Zhuk i Datsok, 2013*).

Однак, окрім функціональних фракцій в артеріальній крові людини присутні і дисфункціональні, які не змозі приєднати до себе кисень чи вже поєднані з іншими газами. До них належать карбоксигемоглобін ($HbCO$), метгемоглобін ($HbMet$) та сульфгемоглобін ($HbSulf$).

Карбоксигемоглобін є з'єднанням гемоглобіну з чадним газом (*Hullin ma in., 2017*). Надлишок $HbCO$ в крові призводить до кисневого голодування, запаморочення, нудоти, втрати свідомості або, навіть, смерті, оскільки чадний газ, що зв'язаний з гемоглобіном, позбавляє його можливості приєднувати до себе кисень. В нормі концентрація $HbCO$ в крові складає 0,5-1,5% від усього гемоглобіну. Проте при певних умовах і обставинах дані значення є більшими. Так, висока концентрація карбоксигемоглобіну (до 9%) може спостерігатись у курців, мешканців великих міст та високогір'я, а також у новонароджених (*Hampson, 2018*). Окремим випадком, коли концентрація $HbCO$ суттєво перевищує свої нормальні значення, є отруєння чадним газом (*Onodera ma in., 2016*; *Hampson, 2015*). Підвищення концентрації карбоксигемоглобіну в артеріальній крові спостерігається і у пацієнтів з COVID-19 (*Scholkmann ma in., 2020*).

Карбоксигемоглобін поглинає світло при вимірюванні рівня оксигенації оптичним методом, що вносить похибки в результати вимірювання (*Sheikus i Prasol, 2022*). Високі концентрації $HbCO$ в артеріальній крові збільшують його внесок в оптичну густину об'єкта вимірювання, що впливає на точність визначення сатурації лише за функціональними фракціями. Крім цього, зміни концентрації $HbCO$ не позначаються на величині функціональної сатурації крові киснем і даний показник втрачає свою діагностичну цінність, наприклад, у випадку гіпоксії, що викликана отруєнням чадним газом (*Sebbane ma in., 2013*).

Тому вимірювання рівня оксигенації крові, особливо при патологічних станах організму людини, а також підвищення точності діагностики неможливе без врахування концентрації карбоксигемоглобіну в артеріальній крові пацієнта.

Завдання роботи:

(1) Розробка теоретичних положень вимірювання рівня оксигенації крові з врахуванням концентрації карбоксигемоглобіну, а також структурної схеми і математичного забезпечення пульсоксиметра, що реалізує дане вимірювання.

(2) Розробка комп'ютерних моделей відомого пульсоксиметра і пульсоксиметра з додатковим світлодіодом, який вимірює рівень оксигенації крові з врахуванням концентрації карбоксигемоглобіну і в якому застосовується розроблене математичне забезпечення.

(3) Проведення імітаційних досліджень за розробленими моделями пульсоксиметрів з визначення впливу вмісту карбоксигемоглобіну в артеріальній крові на очікувані показання приладів і оцінка точності апарату для вимірювання рівня оксигенації крові з врахуванням концентрації карбоксигемоглобіну.

Матеріали і методи

З врахуванням концентрації карбоксигемоглобіну сатурація крові киснем визначається за рівнянням:

$$SpO_2(HbCO) = \frac{C_{HbO_2}}{C_{HbO_2}+C_{HbH}+C_{HbCO}}. \quad (9)$$

Рівняння (9) містить три невідомі, тому визначення сатурації потребує додаткового інформаційного каналу. Задача вирішується застосуванням додаткового світлодіода з довжиною хвилі, яка відмінна від довжин хвиль світла двох основних світлодіодів.

Введемо допоміжні величини R_j:

$$R_j = \log\frac{I_{max,j}}{I_{min,j}}, j = 1, 2, 3. \quad (10)$$

Тоді відповідно до закону Бугера-Ламберта-Бера можливо скласти систему рівнянь:

$$R_j = d_{max} \cdot \sum_{i=1}^{3}\left(\varepsilon_{j,i} \cdot C_i\right), j = 1, 2, 3. \quad (11)$$

Система з трьох рівнянь містить 4 невідомі величини: концентрації похідних гемоглобіну C_i і максимальний приріст шару артеріальної крові за один кардіоцикл d_{max}. Тому введено позначення α_i для добутку концентрації i-ої похідної гемоглобіну на d_{max}:

$$\alpha_i = d_{max} \cdot C_i. \quad (12)$$

Після підстановки (12) в (11) система рівнянь вирішується методом Гауса відносно α_i. Введемо наступні позначення:

$$a = \varepsilon_{1,HbH} - \frac{\varepsilon_{1,HbO_2}}{\varepsilon_{2,HbO_2}} \cdot \varepsilon_{2,HbH}; \quad (13)$$

$$b = \varepsilon_{1,HbCO} - \frac{\varepsilon_{1,HbO_2}}{\varepsilon_{2,HbO_2}} \cdot \varepsilon_{2,HbCO}; \quad (14)$$

$$c = \varepsilon_{1,HbH} - \frac{\varepsilon_{1,HbO_2}}{\varepsilon_{3,HbO_2}} \cdot \varepsilon_{3,HbH}; \quad (15)$$

$$d = \varepsilon_{1,HbCO} - \frac{\varepsilon_{1,HbO_2}}{\varepsilon_{3,HbO_2}} \cdot \varepsilon_{3,HbCO}; \quad (16)$$

$$e = r - \frac{\varepsilon_{1,HbO_2}}{\varepsilon_{2,HbO_2}} \cdot R_2; \quad (17)$$

$$f = R_1 - \frac{\varepsilon_{1,HbO_2}}{\varepsilon_{3,HbO_2}} \cdot R_3. \quad (18)$$

$$m = R_1 \cdot (b \cdot c - a \cdot d) - \varepsilon_{1,HbH} \cdot (b \cdot f - e \cdot d) - \varepsilon_{1,HbCO} \cdot (e \cdot c - a \cdot f) \quad (19)$$

Тоді величини α_i визначаються за рівняннями:

$$a_{HbO_2} = \frac{m}{\varepsilon_{1,HbO_2} \cdot (b \cdot c - a \cdot d)}; \quad (20)$$

$$a_{HbH} = \frac{b \cdot f - e \cdot d}{b \cdot c - a \cdot d}; \quad (21)$$

$$a_{HbCO} = \frac{e \cdot c - a \cdot f}{b \cdot c - a \cdot d}. \quad (22)$$

Для визначення сатурації в рівняння (9) замість концентрацій можливо підставити розраховані величини α_i:

$$SpO_2(HbCO) = \frac{d_{max}}{d_{min}} \cdot \frac{C_{HbO_2}}{C_{HbO_2}+C_{HbH}+C_{HbCO}} = \frac{a_{HbO_2}}{a_{HbO_2}+a_{HbH}+a_{HbCO}}. \quad (23)$$

Підстановкою (20), (21) і (22) в (23) одержується формула для розрахунку сатурації $SpO_2(HbCO)$ з врахуванням концентрації карбоксигемоглобіну:

$$SpO_2(HbCO) = \frac{m}{m+\varepsilon_{1,HbO_2}\cdot(f\cdot(b-a)-e(d-c))}. \quad (24)$$

А підстановкою (20) і (21) в (1) одержується формула для розрахунку функціональної сатурації SpO_2 з врахуванням концентрації карбоксигемоглобіну:

$$pO_2(HbCO) = \frac{a_{HbO_2}}{a_{HbO_2}+a_{HbH}} = \frac{m}{m+\varepsilon_{1,HbO_2}\cdot(f\cdot b-e\cdot d)}. \quad (25)$$

Розроблено структурну схему найпростішого пульсоксиметра, який вимірює рівень оксигенації крові з врахуванням концентрації карбоксигемоглобіну.

Схема передбачає застосування трьох світлодіодів: червоного, інфрачервоного і додаткового, які вмикаються по черзі. Світло проходить крізь об'єкт вимірювання ОВ, частково поглинається і сприймається світлоприймачем. Сигнал від приймача посилюється операційним підсилювачем ОП, перетворюється в цифровий сигнал аналого-цифровим перетворювачем АЦП і надходить до мікроконтролера. Мікроконтролер виконує операції обробки сигналу, розрахунку значення рівня оксигенації і його індикації, а також виконує функції керування роботою світлодіодів за каналом зворотного зв'язку (*Ganesh ma in., 2022*). Розроблена структурна схема містить лише визначальні компоненти пульсоксиметра і дозволяє виконати побудову комп'ютерної моделі апарату.

Моделювання проведено із застосуванням пакету прикладних програм MATLAB і середовища графічного моделювання *Simulink*. Модель пульсоксиметра з додатковим світлодіодом складається з підсистем, що є моделями окремих компонентів розробленої структурної схеми: трьох світлодіодів, об'єкта вимірювання з генератором пульсових імпульсів (*Bhowmick ma in., 2016*; *Shyshkin, M. ma in., 2018*), світлоприймача, підсилювача і мікроконтролера з функцією індикації розрахованих значень сатурації. Точність вимірювання оцінюється шляхом порівняння очікуваних показань пульсоксиметра з початковими даними, для чого модель доповнена блоками для розрахунку і індикації величин сатурації за заданими при моделюванні значеннями концентрацій похідних гемоглобіну.

Для врахування концентрації карбоксигемоглобіну при вимірюванні сатурації запропоновано застосування додаткового світлодіоду, вибір довжини хвилі випромінювання якого потребує обґрунтування. Так як коефіцієнт екстинкції $HbCO$ приймає менші числові значення порівняно з коефіцієнтами екстинкції інших похідних гемоглобіну (*Rusch ma in., 1996*), то важливо, щоб на обраній довжині хвилі внесок карбоксигемоглобіну в загальну оптичну густину об'єкта вимірювання був би найвищим. Тому в якості функції цілі обрано вираз:

$$q(\lambda) = \frac{\varepsilon_{\lambda,HbCO}C_{\%,HbCO}}{\varepsilon_{\lambda,HbO_2}C_{\%,HbO_2}+\varepsilon_{\lambda,HbH}C_{\%,HbH}+\varepsilon_{\lambda,HbMet}C_{\%,HbMet}}\cdot 100\%. \quad (26)$$

Графік функції (26) представлений в Додатку (*Рисунок 2*).

Внесок карбоксигемоглобіну в оптичну густину об'єкта вимірювання в нормі не перевищує 0,4%. Такий незначний відсоток пояснюється незначною концентрацією карбоксигемоглобіну в артеріальній крові, а також низькими значеннями його коефіцієнта екстинкції.

Залежність має три екстремуми, проте два з них припадають на світло з довжинами хвилі 520 і 565 нм. Таке монохроматичне світло суттєво поглинається об'єктом

вимірювання і не може використовуватись в пульсоксиметрах. Тому в якості третього, додаткового світлодіоду обрано світлодіод з довжиною хвилі 610 нм, на яку припадає третій екстремум залежності функції цілі від довжини хвилі. Світло з обраною довжиною хвилі має бурштиновий колір.

Модель мікроконтролера розроблено на основі блоку "*S-Function Builder*" із застосуванням мови *C++*.

Для усунення впливу зовнішнього світла на показання пульсоксиметрів в черзі імпульсів, що відповідають роботі кожного із світлодіодів, присутній додатковий, 4-й імпульс U_4, що одержується при виключених світлодіодах. Обробка сигналів в мікроконтролері розпочинається з розділення імпульсів, що відповідають роботі окремих світлодіодів і зовнішньому світлу.

При одержані чергового набору імпульсів виконується розрахунок інтенсивностей світла I_j, які позбавлені складових, що спричинені зовнішнім засвітленням. Для проведення розрахунків пропонується використання наступної формули:

$$I_j = \frac{\log\left(\left(\frac{U_j}{U_4}\right)^{I_2-I_1}\right)}{\log\left(\frac{i_2}{i_1}\right)},\ j = 1,2,3. \tag{27}$$

де:

U_j – розділені сигнали від світлоприймача, що відповідають роботі відповідного світлодіоду;

$(I_1; i_1)$ і $(I_2; i_2)$ – дві довільні точки усередненої нелінійної статичної характеристики світлоприймача.

Залежність (27) враховує нелінійність статичної характеристики світлоприймача.

Визначаються екстремальні значення інтенсивностей світла I_j. Для відсіювання локальних мінімумів і максимумів, а також низькоамплітудних шумів сигналу світлоприймача, кожне визначене максимальне чи мінімальне значення інтенсивності світла не задіюється в розрахунках, якщо висота даного піку на часових діаграмах з обох сторін менша за деяке значення, що задається заздалегідь і є параметром моделі. На екстремальність при цьому досліджується сигнал, що відповідає роботі одного світлодіоду з трьох. Якщо на обраній часовій діаграмі досягається екстремум, то він досягається і на двох інших, так як даний періодичний процес обумовлюється одним і тим же явищем – кровонаповненням судин.

По завершенні чергового кардіоциклу за визначеними значеннями $I_{max,j}$ і $I_{min,j}$ за формулою (10) розраховуються допоміжні величини R_j, після чого за формулами (13)-(19), (25) і (24) розраховуються функціональна сатурація і сатурація з врахуванням карбоксигемоглобіну.

Для підвищення точності вимірювань рівень оксигенації крові і частоту серцебиття необхідно розраховувати як середні значення за декількома кардіоциклами:

$$SpO_2 = \frac{\sum_{k=1}^{nc} SpO_{2,k}}{nc}; \tag{28}$$

$$SpO_2(HbCO) = \frac{\sum_{k=1}^{nc} SpO_2(HbCO)_k}{nc}; \tag{29}$$

$$Pr = \frac{60\cdot(nc-1)}{\sum_{k=2}^{nc}(t_{min,k}-t_{min,k-1})}, \tag{30}$$

де:

nc – кількість кардіоциклів, за якою здійснюються розрахунки;

Pr – частота серцебиття;

k – порядковий номер кардіоциклу.

Результати

Вихідними величинами моделі пульсоксиметра є його очікувані показання функціональної сатурації і сатурації з врахуванням карбоксигемоглобіну, частоти серцебиття і часу вимірювання.

Перелік усіх вхідних величин, із збуреннями на процес вимірювання включно, а також параметрів моделі, числові значення яких необхідно задати для розрахунків, представлені в Додатку (*Таблиця 1*). В моделі враховано основні збурення на процес вимірювання, які полягають в різних концентраціях метгемоглобіну в артеріальній крові пацієнтів, різних значеннях максимального приросту товщини шару артеріальної крові за один кардіоцикл, а також в змінах інтенсивності зовнішнього світла (*Yeroshenko ma in., 2022*; *Prasol ma in., 2022*; *Prasol i Yeroshenko, 2023*). Вказано умовні позначення величин і їх номінальні числові значення. Частота серцевих скорочень прийнята 60 уд/хв. Кількість кардіоциклів, за якими проводились вимірювання, $nc = 5$. Відстань від світлодіоду до світлоприймача $r = 1$ см. Частота роботи пульсоксиметра $f = 2000$ Гц. Довжини хвиль випромінювання світлодіодів: $\lambda_1 = 660$ нм; $\lambda_2 = 940$ нм; $\lambda_3 = 610$ нм.

При врахуванні наявності в артеріальній крові інших похідних гемоглобіну є необхідність у визначенні фракційної сатурації крові киснем, яка розраховується як відношення концентрації оксигемоглобіну до загального вмісту гемоглобіну в крові:

$$SpO_2(Hb)_{in,\%} = \frac{C_{HbO_2}}{C_{HbO_2}+C_{HbH}+C_{HbCO}+\sum C_{Hb}} \cdot 100\%, \quad (31)$$

де:

$\sum C_{Hb}$ – сума концентрацій інших дисфункціональних фракцій гемоглобіну, в тому числі і метгемоглобіну;

in – індекс позначає дійсні значення величин, що розраховуються.

Для розрахунку сатурацій можливо використовувати концентрації похідних гемоглобіну, що виражені у відсотках від його загального вмісту:

$$SpO_{2,in,\%} = \frac{C_{HbO_2}}{C_{HbO_2}+C_{HbH}} \cdot 100\% = \frac{C_{Hb} \cdot C_{HbO_2,\%}}{C_{Hb} \cdot C_{HbO_2,\%} + C_{Hb} \cdot C_{HbH,\%}} \cdot 100\% = \frac{C_{HbO_2,\%}}{C_{HbO_2,\%}+C_{HbH,\%}} \cdot 100\% \quad (32)$$

Тоді з врахуванням того, що сума усіх відсоткових концентрацій похідних гемоглобіну дорівнює 100%, фракційна сатурація крові киснем дорівнює відсотковій концентрації оксигемоглобіну в артеріальній крові пацієнта:

$$SpO_2(Hb)_{in,\%} = C_{HbO_2,\%}. \quad (33)$$

За розробленими комп'ютерними моделями проведено дослідження впливу концентрації карбоксигемоглобіну в артеріальній крові на показання запропонованого і відомого пульсоксиметрів. Концентрацію метгемоглобіну прийнято рівною 0,5%, дезоксигемоглобіну – 2,5%, а зміна концентрації $HbCO$ здійснювалась за рахунок

відповідної зміни концентрації оксигемоглобіну. Результати представлені в Додатку (*Таблиця 2*).

Залежності очікуваних показань $SpO_2(2LED)_{out,\%}$ відомого і $SpO_2(HbCO)_{out,\%}$ запропонованого пульсоксиметрів, а також дійсного значення $SpO_2(Hb)_{in,\%}$ фракційної сатурації крові киснем від концентрації карбоксигемоглобіну в крові представлений в Додатку (*Рисунок 3*).

Залежності очікуваних показань $SpO_2(2LED)_{out,\%}$ відомого і $SpO_2(3LED)_{out,\%}$ запропонованого пульсоксиметрів, а також дійсного значення $SpO_{2,in\%}$ функціональної сатурації крові киснем від концентрації карбоксигемоглобіну в крові представлений в Додатку (*Рисунок 4*).

Обговорення

Абсолютна похибка відомого пульсоксиметра, яка спричинена наявністю в крові дисфункціональних фракцій гемоглобіну:

$$\Delta SpO_2(2LED)_{\%} = SpO_{2,in\%} - SpO_2(Hb)_{in,\%} = SpO_{2,in\%} \cdot (C_{HbCO} + \sum C_{Hb}), \quad (34)$$

а відносна дорівнює сумі відсоткових концентрацій дисфункціональних фракцій гемоглобіну:

$$\delta SpO_2(2LED)_{\%} = \frac{\Delta SpO_2(2LED)_{\%}}{SpO_{2,in\%}} \cdot 100\% = C_{HbCO,\%} + \sum C_{Hb,\%}. \quad (35)$$

Абсолютна похибка запропонованого пульсоксиметра, яка спричинена наявністю в крові дисфункціональних фракцій гемоглобіну:

$$\Delta SpO_2(HbCO)_{\%} = SpO_2(HbCO)_{in,\%} - SpO_2(Hb)_{in,\%} = SpO_2(HbCO)_{in,\%} \cdot \sum C_{Hb}. \quad (36)$$

а відносна похибка дорівнює сумі відсоткових концентрацій дисфункціональних фракцій гемоглобіну за виключенням карбоксигемоглобіну:

$$\delta SpO_2(HbCO)_{\%} = \frac{\Delta SpO_2(HbCO)_{\%}}{SpO_{2,in\%}} \cdot 100\% = \sum C_{Hb,\%}. \quad (37)$$

Таким чином, відносна похибка запропонованого пульсоксиметра з додатковим світлодіодом, на відміну від похибки відомого пульсоксиметра, не залежить від концентрації карбоксигемоглобіну в артеріальній крові пацієнта.

Застосування додаткового світлодіоду і врахування концентрації карбоксигемоглобіну дозволяє знизити абсолютну похибку вимірювання. Різниця

$$\Delta SpO_{2,\%} = SpO_{2,in,\%} - SpO_2(HbCO)_{in,\%} = \frac{C_{HbCO}}{1-\sum C_{Hb,\%}} \cdot SpO_{2,in,\%}. \quad (38)$$

Результати моделювання (*Рисунок 3*) показують, що при концентрації карбоксигемоглобіну в 10% і нормальному середньому значенні метгемоглобіну в 0,5% відомий пульсоксиметр відображує значення сатурації 96%. Тобто за результатом вимірювання можна зробити висновок, що проблеми з насиченням крові киснем відсутні в той час, як лише 87% від усього гемоглобіну крові сполучено з киснем.

Покази запропонованого пульсоксиметра з додатковим світлодіодом, який при вимірюванні враховує концентрацію карбоксигемоглобіну в крові, хоча й чутливі до величин концентрацій інших дисфункціональних фракцій гемоглобіну, проте наближені до дійсного значення фракційної сатурації. В ситуації, що розглядається, очікувані

показання такого пульсоксиметра становлять 86%, що одразу вказує на порушення перенесення кисню до тканин тіла.

За відомою (8) і запропонованою (25) залежностями розраховується одна і та сама величина – функціональна сатурація крові киснем, проте результати розрахунку різні (*Рисунок 4*). Це пояснюється тим, що при розрахунках за відомою формулою вважається, що в артеріальній крові присутні лише дві похідні гемоглобіну – окси- і дезоксигемоглобін, а світло в об'єкті поглинається лише цими двома речовинами. При розрахунках за запропонованою формулою враховується додаткове поглинання світла третьою похідною. І попри те, що при цьому частка оксигемоглобіну також визначається лише за функціональними фракціями, але результат розрахунку одержується з врахуванням концентрації карбоксигемоглобіну.

За відсутності ознак чи припущень щодо отруєння пацієнта чадним газом або щодо можливої підвищеної концентрації карбоксигемоглобіну в його крові доцільно вимірювати функціональну сатурацію крові киснем. І в цьому випадку застосування запропонованого пульсоксиметра з додатковим світлодіодом дозволяє компенсувати частину похибки, яка властива відомому пульсоксиметру і яка зумовлена присутністю карбоксигемоглобіну в крові.

Час вимірювання пульсоксиметрами дорівнює тривалості кардіоциклів, за якими визначаються сатурації і частота серцебиття. Тому процес вимірювання рівня оксигенації крові з врахуванням концентрації карбоксигемоглобіну не потребує збільшення витрат часу.

Висновки

Запропонований пульсоксиметр, на відміну від відомих, дозволяє виявити і оцінити зниження рівня оксигенації крові, яке викликане підвищенням концентрації карбоксигемоглобіну в крові пацієнта. Врахування в розробленому математичному забезпеченні того, що світло поглинається не тільки двома, а й третьою похідною гемоглобіну – карбоксигемоглобіном, підвищує точність запропонованого пульсоксиметра і при вимірюванні функціональної сатурації крові киснем.

Результати дослідження можуть застосовуватись при розробці технічного, математичного, алгоритмічного і програмного забезпечень пульсоксиметрів, в тому числі і пульсоксиметрів із додатковими світлодіодами, які вимірюють рівень оксигенації крові з врахуванням вмісту в ній дисфункціональних фракцій гемоглобіну.

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Додаток

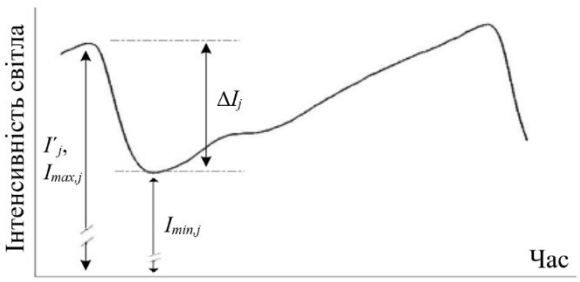

Рисунок 1. Зміна в часі інтенсивності світла, яке пройшло крізь об'єкт вимірювання, внаслідок пульсової зміни наповнення судин об'єкта артеріальної кров'ю (*Nitzan та ін., 2014*)

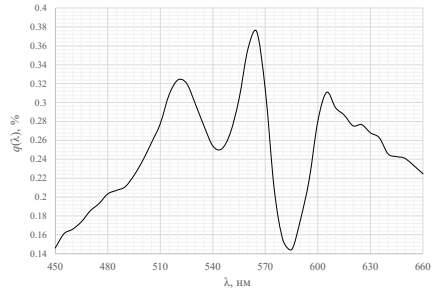

Рисунок 2. Залежність внеску карбоксигемоглобіну в оптичну густину об'єкта вимірювання від довжини хвилі світла

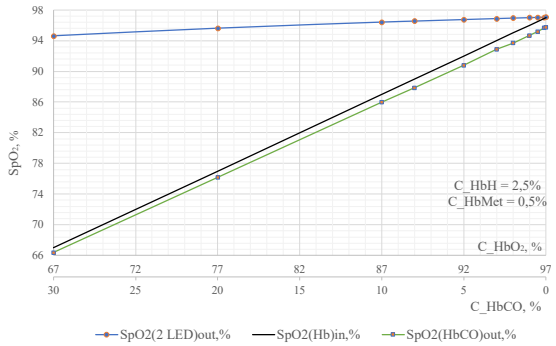

Рисунок 3. Залежності очікуваних показань відомого і запропонованого пульсоксиметрів, а також дійсного значення фракційної сатурації крові киснем від концентрації карбоксигемоглобіну в крові

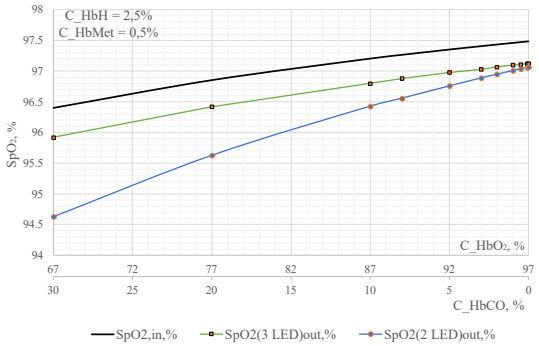

Рисунок 4. Залежності очікуваних показань відомого і запропонованого пульсоксиметрів, а також дійсного значення функціональної сатурації крові киснем від концентрації карбоксигемоглобіну в крові

Таблиця 1. Номінальні значення вхідних величин і параметрів моделі пульсоксиметра

Величина	Номінальне значення	Одиниці вимірювання
Вхідні величини:		
Концентрація оксигемоглобіну, C_{HbO2}:	96,5 144,75 $8{,}9834\cdot10^{-3}$	% г/л моль/л
Концентрація дезоксигемоглобіну, C_{HbH}:	2,5 3,75 $2{,}3273\cdot10^{-4}$	% г/л моль/л
Концентрація карбоксигемоглобіну, C_{HbCO}:	0,5 0,75 $4{,}6546\cdot10^{-5}$	% г/л моль/л
Збурення на процес вимірювання:		
Концентрація метгемоглобіну, C_{HbMet}:	0,5 0,75 $4{,}6546\cdot10^{-5}$	% г/л моль/л
Максимальний приріст товщини шару артеріальної крові в об'єкті вимірювання під час одного кардіоциклу, d_{max}	0,005	см
Інтенсивність зовнішнього світла, I_{zovn}	0,1	мВт/см^2
Параметри моделі:		
Коефіцієнти екстинкції світла з довжиною хвилі λ_1 =660 нм, $\varepsilon_{1,HbO2}$: $\varepsilon_{1,HbH}$: $\varepsilon_{1,HbCO}$: $\varepsilon_{1,HbMet}$:	 319,6 3227 104,41 3706,65	л/(моль·см)
Коефіцієнти екстинкції світла з довжиною хвилі λ_2 =940 нм, $\varepsilon_{2,HbO2}$: $\varepsilon_{2,HbH}$: $\varepsilon_{2,HbCO}$: $\varepsilon_{2,HbMet}$:	 1214 693,39 40 3480	л/(моль·см)
Коефіцієнти екстинкції світла з довжиною хвилі λ_3 = 610 нм,		л/(моль·см)

$\varepsilon_{3,HbO2}$: $\varepsilon_{3,HbH}$: $\varepsilon_{3,HbCO}$: $\varepsilon_{3,HbMet}$:	1506 9444 530,86 12766,17	
Загальна концентрація гемоглобіну, C_{Hb}:	150 $9{,}3093 \cdot 10^{-3}$	г/л моль/л
Коефіцієнти послаблення об'єктом вимірювання світла з довжинами хвиль λ_1, λ_2 і λ_3, $K_{a,1}$: $K_{a,2}$: $K_{a,3}$:	 10 10 10	
Номінальні струми світлодіодів з довжинами хвиль λ_1, λ_2 і λ_3, i_1: i_2: i_3:	 20 20 20	мА
Сила світла світлодіодів за номінальних струмів, I_{v1}: I_{v2}: I_{v3}:	 2,4 2,2 2,8	кд

Таблиця 2. Результати моделювання роботи пульсоксиметрів за різних значень концентрації карбоксигемоглобіну в крові

$C_{HbO2,\%}$	$C_{HbH,\%}$	$C_{HbCO,\%}$	$C_{HbMet,\%}$	$SpO_{2,\ in,\%}$	SpO_2 $(2LED)_{out,\%}$	SpO_2 $(3LED)_{out,\%}$	SpO_2 $(HbCO)_{in,\%}$	SpO_2 $(HbCO)_{out,\%}$	SpO_2 $(Hb)_{in,\%}$
67	2,5	30	0,5	96,4	94,63	95,92	67,34	66,38	67
77	2,5	20	0,5	96,86	95,63	96,42	77,39	76,18	77
87	2,5	10	0,5	97,21	96,43	96,8	87,44	85,99	87
89	2,5	8	0,5	97,27	96,56	96,88	89,45	87,85	89
92	2,5	5	0,5	97,35	96,76	96,98	92,46	90,77	92
94	2,5	3	0,5	97,41	96,89	97,03	94,47	92,88	94
95	2,5	2	0,5	97,44	96,95	97,07	95,48	93,69	95
96	2,5	1	0,5	97,46	97,01	97,1	96,48	94,68	96
96,5	2,5	0,5	0,5	97,47	97,04	97,11	96,98	95,19	96,5
96,9	2,5	0,1	0,5	97,48	97,06	97,12	97,39	95,66	96,9
97	2,5	0	0,5	97,49	97,07	97,12	97,49	95,73	97

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Methodology of building a functionally sustainable in information system of an institution of higher education

Abstract. The study object is the methodology of building a functionally stable information system of a higher education institution. The study subject is the process of organizing the unified information space, in which all information resources are uniquely identified, for the further implementation of an information system that meets a high level of security, productivity, scalability, management, and access to the system is provided regardless of the user's location. The purpose is to improve the quality of management and education in institutions of higher education through the introduction of modern information technologies. To achieve the goal and solve the tasks, such methods as recognition methods of information system elements and their features, methods of reconstruction of missing features of elements in the information space, methods of graph theory and game theory are used. This paper presents the developed methodology for building a functionally stable information system for a higher education institution. It consists of performing two main procedures: (1) the procedure of organizing an information system based on a single information space of a higher education institution; and (2) procedures for ensuring the functional stability of the information system of the higher education institution. The methodology of the procedure for the organization of the information system based on the unified information space of the institution of higher education is based on the model of the unified information space of the institution of higher education, methods of recognition of information system elements, reconstruction of features of information system elements and synchronous recognition of elements, algorithms of relationships between elements and their sets of feature values allows to increase the effectiveness of the information system of the institution of higher education and management decision-making. The implementation of the information system aims to optimize processes and save resources (human, financial, informational, etc.), allowing tasks to be performed remotely while ensuring a high level of system security and productivity thanks to ensuring the functional stability of the entire information system of a higher education institution.

Keywords: information system of a higher education institution (IS), functional stability (FS), information protection, SD-WAN, unified information space.

Abbreviations:
FS – functionally stable;
IS – information system.

Introduction

The rapid development of information technologies and digitization of all processes requires higher education institutions to use new methods of obtaining and processing information for effective management decision-making and ensuring the reporting system of the entire higher education institution. The solution to this issue lies in the creation of the system, based on the concept of a single information space and provides access and processing of all accumulated information, optimization of information interaction, improvement of the

solution of complex management tasks in connection with the improvement of the organization of information support (*Bobrov et al., 2013*; *Shkitsa et al., 2019*; *Bannon & Bødker, 1997*).

Complex implementation and integration of all information systems of a higher education institution into the unified information space, based on which a functionally stable information system is built (*Mashkov et al., 2023*; *Sobchuk et al., 2022*), will provide, although not directly, a significant economic effect.

Informatization and digitalization are not a source of direct income but are an additional means of organizing the activities of the entire institution of higher education and an opportunity to effectively ensure management decisions, regulate financial flows, and organize the educational process (*Kopiyka & Korotchenko, 2018*; *Storchak et al., 2017*), cost minimization, preservation of personnel potential. The remote access provision for performing official duties is especially relevant in the conditions of the pandemic and martial law of Ukraine when higher education employees and students are scattered over large territories.

The main benefit of the implementation of higher education institution FS IS is to improve access to information resources of a higher education institution, both by employees and students of higher education, improve the reporting system and operational management, reduce the labour intensity of the implementation of the management process, i.e., reduce management costs, regulation of financial and economic indicators, reduction of labour costs for ensuring document circulation (*Smelyakov et al., 2018*).

Using the educational institution's information system based on the unified information space will make it possible to unambiguously recognize arbitrary information from various channels and systems and ensure its authenticity. At the same time, IS not only reduces information processing time, but also:

- implements automatic data processing in the "request-response" mode;
- integrates the information systems of various units into a single entity;
- reduces manipulation of information by IS users;
- avoids duplication of data when collecting primary information and when processing it;
- improves the general exchange of information;
- provides information users access to information resources of the institution;
- increases the efficiency of information management;
- allows to reduce the number of technical personnel in various structural units.

The main requirements for the IS are the low cost of restoring the functioning of the IS and ensuring the FS IS.

The study object is the methodology of building a functionally stable information system of a higher education institution.

The study subject is the process of organizing the unified information space, in which all information resources are uniquely identified, for the further implementation of an information system that meets a high level of security, productivity, scalability, management, and access to the system is provided regardless of the user's location.

The purpose is to improve the quality of management and education in institutions of higher education through introducing modern information technologies.

Based on the set goal, the following tasks are solved in the work:

- an analysis of modern approaches to the construction of information systems in higher education is performed;
- a procedure for organizing an information system based on the unified information space of a higher education institution is being developed;
- a procedure for ensuring the functional stability of the information system of a higher education institution is being developed using a combination of methods of functional reconfiguration of the top of the graph of the top level of the IS network hierarchy and functional reconfiguration of the hierarchical IS network in real time;
- a methodology is being developed that will allow to effectively build a safe, productive, scalable information system that corresponds to the specifics of the higher education institution and the educational process.

To achieve the purpose and solve the tasks, such methods as recognition methods of information system elements and their features, methods of reconstruction of missing features of elements in the information space, methods of graph theory and game theory are used.

In today's conditions, more and more diverse software, applications, technologies, and information services for the high-quality functioning of the information system of a higher education institution are appearing. However, on the other hand, restrictions on access to information are often imposed depending on the structural unit to which it belongs. That is, in the vast majority of information systems, even in one institution of higher education, they function in isolation, primarily in the interests of a separate structural unit (*Bobrov et al., 2013*). This causes the following:

- difficulties in accessing and exchanging information;
- the need for optimization during the collection and processing of information from the primary source;
- non-rational use of funds for operational costs.

The solution to these problems consists in the creation of the unified information space that provides access and processing of all accumulated information, optimization of information interaction, improvement of the solution of complex management tasks in connection with the improvement of the organization of information support (*Shkitsa et al., 2019*; *Storchak et al., 2017*). That is, the unified information space is a union of databases, information systems and information networks, technologies for their operation, which function and are organized according to unified rules, methods, approaches and provide information interaction between territorially distant centers and systems.

The unified information space consists of (*Bannon & Bødker, 1997*):

- information resources belonging to different databases and stored on different media;
- organizational structures that perform the collection, processing, storage, distribution, search and transfer of information for the expansion and stable functioning of the space;
- information technologies and means of their interaction, which provide access to information resources.

The unified information space concept provides (*Zavgorodnii et al., 2021*; *Zavgorodnii et al., 2019*) that information resources include information system data and applications implemented as part of information processing methods. At some levels, other information systems may be

available to them. At the same time, applications can act as clients and servers for each other and jointly solve some tasks. As a result, information resources are used much more efficiently since there is an optimal balance between software and hardware load, and the costs of management, maintenance and modification of the system as part of the unified information space are reduced since information and methods of their processing are localized within a specific IS.

Cloud networks are a convenient and reliable tool for organizing work in the unified information space (*Basu et al., 2020*; *Lemeshko et al., 2020*).

In addition, in the concept of the unified information space, one of the main criteria is a high level of security, fault tolerance and reliability that meets international standards (*Sobchuk et al., 2021*). Ensuring the functional stability of the information system against destabilizing factors and conflicts in the system that lead to failures in the functional processes of the information system consists in ensuring the ability of the system to preserve or restore certain functions over a long period of time (*Mashkov et al., 2023*; *Sobchuk et al., 2022*).

Methods for ensuring a high security and fault tolerance level were developed in (*Zamrii et al., 2024*), the essence of which consists of choosing the optimal strategy for continuing to perform tasks under the influence of destabilizing factors, a complete search of configurations in the hierarchical network of the information system of a higher education institution, and the redistribution of network resources based on game theory.

The research presented in this work is a logical continuation of scientific research conducted in (*Zamrii et al, 2022*; *Zamrii & Vyshnivskyi, 2022*; *Zamrii et al., 2024*) and consists of the development of a methodology for building a functionally stable information system of a higher education institution based on the processes of organizing the unified information space and ensuring the functional stability of the information system by means of reconfiguration of virtual networks in virtual cloud environments.

The results of the study

The methodology for building an FS IS consists of combining all organizational structures, information resources and external information influences for the IS organization based on a single information space of a higher education institution, systems, technologies and methods to ensure the functional stability of the IS. Using Prisma Access and Prisma SD-WAN software-defined WAN for this purpose (*Basu et al., 2020*; *Lemeshko et al., 2020*), the components of the Aruba SD-Branch solution are limited to a set of Aruba products that provide the ability to deploy and maintain the network, namely: Aruba Central; Aruba ClearPass; Aruba Headend Gateways of the Aruba 7200 series; Aruba Virtual Gateways; Aruba branch gateways (Aruba Branch Gateways – BGW) of the Aruba 9000, 7200 and 7000 series; Aruba Access Switches 2930F, 2930M, 3810M and 5400R; Aruba access points (Aruba Access Points) models Aruba AP-5xx (dual APs 802.11ax Wi-Fi 6), and models AP-3xx (dual APs 802.11ac Wave 2 Wi-Fi 5).

After performing the procedure of organizing the information system based on the unified information space of the institution of higher education, it is necessary to provide FS IS. In this way, the FS IS construction procedure will be divided into two parallel procedures:

(1) IS organization procedure based on the unified information space of a higher education institution.

(2) FS IS provisioning procedure.

We will describe each of the procedures in more detail.

IS organization procedure based on the unified information space of a higher education institution

The stage of input elements recognition.

It is intended for updating and adding new input elements to the unified information space using the input element recognition method, that is, performing a step-by-step analysis of the set of features of each input element and their connections. At the stage of input elements recognition, the following steps are performed:

Step 1. Reading by the utility of a set of values to establish the characteristics of the input element for a unified presentation in the unified information space.

Step 2. The element recognition by using the synchronous recognition method, i.e., simultaneous search and comparison in all information spaces of the set of values corresponding to the input element. This method is described in detail in (*Zamrii & Vyshnivskyi, 2022*).

Step 3. The recognition results analysis: if, as a result of the study, a similar set of attribute values is found in the unified information space, then the input element is considered recognized and already added to the unified data store. If an identical set of feature values is not found in the unified information space, then the input element is considered new.

Step 4. Updating the unified information space by adding a new element to the unified data store and establishing relationships with other elements of the unified information space.

The procedure for organizing an information system based on the unified information space of a higher education institution directly depends on the flow of information, both inside the information space and from the outside. This is because the effectiveness of IS functioning in conditions of uncertainty depends on the promptness and quality of the information received. Therefore, information resources are of fundamental importance for the IS organization and its further development.

IS is organized based on the unified information space, creates an environment for prompt use of reliable information regardless of the user's location and without time restrictions, and the information itself is of fundamental importance for the functioning and support of IS.

FS IS provisioning procedure

The stage of security functions analysis and use.

At this stage, input data is determined and the vertices of the IS network hierarchy graph, which are unable to function fully under the influence of destabilizing factors (malfunctions, failures, lack of resources, attacks, etc.), are identified. To eliminate problems, the Prisma Access infrastructure is used to bypass faulty connections in the IS network.

If the problem is eliminated and all tasks assigned to the IS network are completed, the procedure for ensuring functional stability ends. Otherwise, it is necessary to proceed to the next stage.

The stage of determining the characteristics.

Step 1. With the help of reading by the IS controller, the values for the execution periods of the server and user algorithms $\mathcal{T}_c$, $\mathcal{T}_k$, the execution time t_c and the multiplicity of execution k are determined to fulfill the condition:

$$\mathcal{T}_c = t_c + k\mathcal{T}_k.$$

The periods and execution time of the specified algorithms are shown in the appendix (*Figure 1*).

Step 2. For each function f, the following are defined:

$\mathcal{S}_0(a_{fj})$ is the best decision scenario;

$\delta(a_{fj})$ is a weighting factor that allows the controller to determine the priority of the performed functions in the system;

$Q_0(a_{fj})$ is a limitation in the case of a partial loss of productivity.

For the objective function of the top-level vertex of the IS network hierarchy, the maximization of the wins in each of the strategies and the minimization of the constraints will be:

$$\mathcal{F}(a_{fj}) = \sum a_{fj}\left(\left(\mathcal{S}_0(a_{fj}) - \mathcal{S}_m(a_{fj})\right) \times \delta(a_{fj}) + Q_0(a_{fj})\right) \to min.$$

Methods $\mathcal{B}_1$ are functional reconfiguration of the top of the graph of the top level of the IS network hierarchy and $\mathcal{B}_2$ are functional reconfiguration of the hierarchical IS network in real time are being configured. A detailed study of methods $\mathcal{B}_1$ and $\mathcal{B}_2$ are presented in the collective work of I. Zamrii, V. Vyshnivskyi and V. Sobchuk (*Zamrii et al., 2024*).

Step 3. $\mathcal{T}_c, \mathcal{T}_k, t_c, k$ are determined at the current time to adjust the order of application and execution time of the methods.

Step 4. Selection of the α value of partial IS productivity:

$$Q_0\left(a_{fj}\right) = Q_0^*\left(a_{fj}\right) + \alpha \times Q_1^*\left(a_{fj}\right).$$

Stage of implementation of methods.

To eliminate a malfunction in the system at the implementation stage, three options for the development of events are possible:

Option 1. Application of the $\mathcal{B}_1$ method of functional reconfiguration of the top of the graph of the top level of the IS network hierarchy.

Option 2. Application of the $\mathcal{B}_2$ method of functional reconfiguration of the IS hierarchical network in real time.

Option 3. Parallel application of both methods of functional reconfiguration of the hierarchical IS network in real time $\mathcal{B}_1$ and functional reconfiguration of the top of the graph of the top level of the IS network hierarchy $\mathcal{B}_2$.

After the deployment of events according to one of the scenarios, the level of functional stability of the IS is evaluated at the current moment in time using the SD-WAN cloud controller.

If, after assessing the level of functional stability of the information system with the help of the SD-WAN cloud controller, it was determined that the fault tolerance of the information system network of the higher education institution is ensured, then the procedure is completed.

In the opposite case, there is a return to the stage of determining the characteristics to adjust the values of $\mathcal{T}_c$, $\mathcal{T}_k$, t_c, k and α.

The methodology of building a functionally stable information system of a higher education institution can be presented as shown in the appendix (*Figure 2*).

Therefore, the methodology of building a functionally stable information system of a higher education institution is based on the use of the unified information space and consists of the joint implementation of methods and techniques for ensuring the functional stability of the information system network to spread the property of functional stability to the entire system.

Thus, due to the implementation of two main procedures, the functional stability of the entire information system of the higher education institution is ensured.

Discussion

War constantly creates new dangers and generates new challenges that require quick adaptation and flexible approaches to solving problems. The implementation of the information system will make it possible to relieve people, optimize processes, and save resources, allowing tasks to be remotely performed while ensuring an increased level of security and productivity of the system thanks to ensuring the functional stability of the entire information system of the institution of higher education. Such an approach, subject to compliance with the developed methodology, can be applied to the functioning of other critical structures.

Conclusions

The effect of a functionally stable information system of a higher education institution is to increase labour productivity, i.e., to reduce work time. According to estimates, if the use of the system is extended to all tasks, it can be predicted that half of the employees' working time will be freed from unproductive time-consuming tasks.

A characteristic feature of increasing informatization in the institution due to the use of IS is that the more time and money is spent on the system, the higher the economic benefit from its use. If all processes are defined, identified and adjusted at the design and implementation stage of FS IS due to the selection of a software-defined network, increased information protection and management, then the time and costs of future operations can be significantly reduced, especially at the level of divisions, services and employees.

Thus, FS IS implementation reduces the costs of organizing effective interaction between all units, simplifies information exchange, and document flow, and reduces the time required to complete tasks. At the same time, a high level of system security and productivity is ensured due to ensuring the functional stability of the entire information system and the possibility of remote work for deploying branches in different countries and even continents.

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Appendix

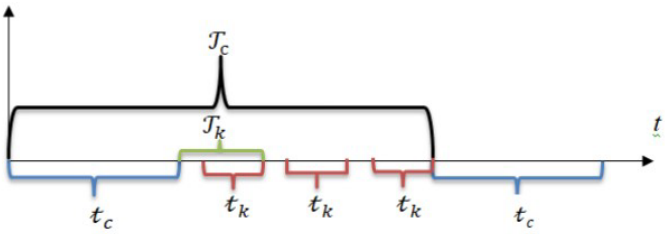

Figure 1. Periods and execution time of algorithms

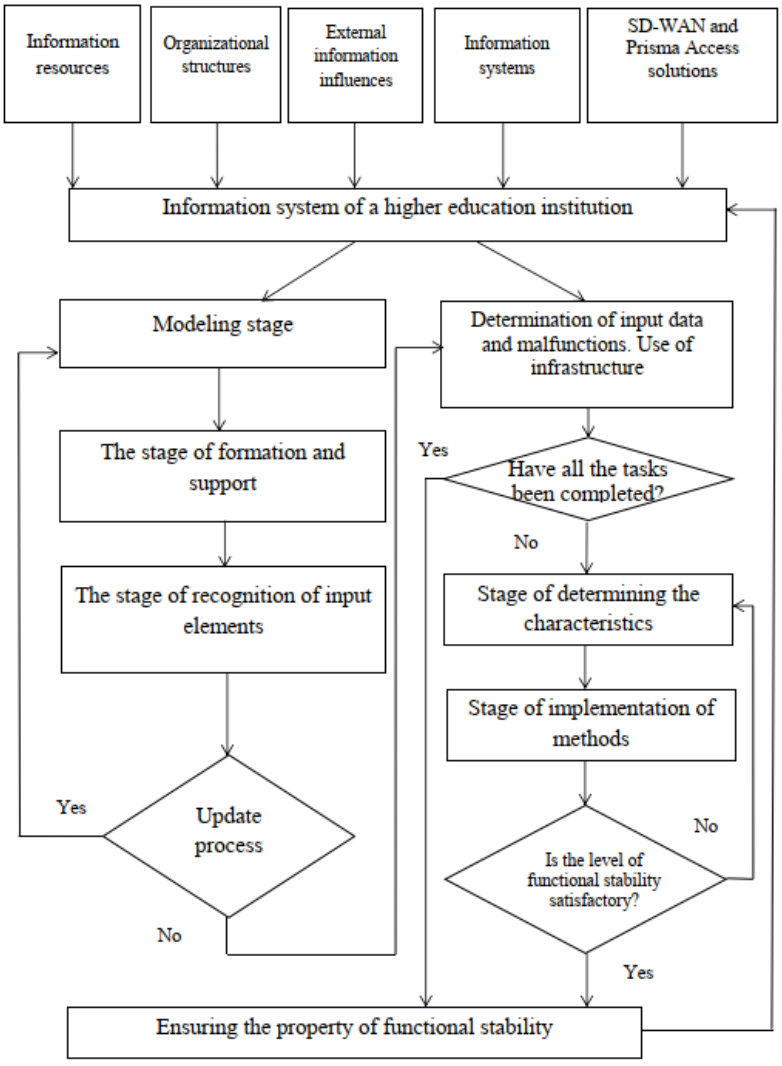

Figure 2. Methodology for building a functionally stable information system of a higher education institution

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The influence of the working cell geometric parameters on electrochemical 3D printing accuracy

Abstract: The main technological parameters of electrochemical 3D printing are the rate of metal deposition and resolution. Electrochemical 3D printing resolution can be characterized by the ratio between the estimated metal deposition area width and the working electrode-anode diameter. In this work, the influences of the diameter of the working electrode-anode and the inter-electrode distance on electrochemical 3D printing accuracy have been investigated. The purpose of the study was to establish the influence of electrochemical cell geometric parameters' ratio on electrochemical 3D printing resolution. The author used the sources of Ukrainian scientists such as R. Babchuk, V. Vorobyova, O. Linyucheva, M. Kotyk, G. Vasyliev and foreign researchers such as K. Bouzek, K. Borve, O. Lorentsen, K. Osmundsen, I. Rousar, J. Thonstad, M. Rafiee, R. Farahani, D. Therriault and others. It was shown that the smaller the diameter of the anode (dielectric capillary) and the greater the distance from the anode dielectric housing edge to the surface of the cathode (interelectrode distance), the wider the metal deposition area. It was found that the larger the working electrode diameter, the larger the inter-electrode distance can be used to ensure the required electrochemical 3D printing resolution.

Keywords: electrochemical 3D printing, resolution, anode diameter, interelectrode distance.

Вплив геометричних параметрів робочої комірки на точність електрохімічного 3Д друку

Анотація: Основними технологічними параметрами електрохімічного 3Д друку є швидкість нашарування металу та роздільна здатність. Роздільна здатність електрохімічного 3Д-друку може бути охарактеризована співвідношенням між шириною оціночної області осадження металу та діаметром робочого електрода анода. У даній роботі досліджено вплив діаметром робочого електрода анода та міжелектродної відстані на точність електрохімічного 3Д друку. Метою дослідження було встановити вплив співвідношення геометричних параметрів електрохімічної комірки на роздільну здатність електрохімічного 3D друку. Автор використав джерела українських вчених, таких як Р. Бабчук, В. Воробйова, О. Лінючева, М. Котик, Г. Васильєв, та зарубіжних дослідників, таких як К. Бузек, К. Борве, О. Лоренцен, К. Осмундсен, І. Русар, Дж. Тонстад, М. Рафіє, Р. Фарахані, Д. Терріо та ін. Показано, що чим меншим є діаметр анода (діелектричного корпусу) і більшою відстань від краю діелектричного корпуса анода до поверхні катода (міжелектродна відстань), тим ширшою є область осадження металу. Встановлено, що чим більшим є діаметр робочого електрода, тим більшою може бути використана величина міжелектродної відстані з метою забезпечення необхідної роздільної здатності електрохімічного 3Д друку.

Ключові слова: електрохімічний 3Д друк, роздільна здатність, діаметр анода, міжелектродна відстань.

Introduction

The electrochemical type of the latest additive 3D printing technology is characterized by energy efficiency and environmental safety and makes it possible to obtain metal products with unique properties (*Rafiee et al., 2020*; *Chen et al., 2017*). The main technological parameters of this process are metal deposition rate and the accuracy or resolution. Electrochemical 3D printing resolution is determined by the characteristic size of the metal deposition zone directly under the working electrode-anode. The resolution (*Babchuk et al., 2024*) is determined by the properties of the electrochemical system regarding the redistribution of the current on the surface of the cathode on which electrodeposition is performed. In particular, when the electrolyte is supplied under pressure (*3D printing apparatus…, 2024*), it causes an expansion of electric current distribution area on the cathode surface contributing to the expansion of metal electrochemical deposition area and a decrease in the resolution of 3D printing. A decrease in the throwing power of the electrolyte, on the contrary, contributes to an increase in the localization of metal deposition and, as a result, to an increase in resolution (*Vasyliev et al., 2021a*). To limit current spreading area during electrochemical 3D printing, the working electrode-anode arrangement is often used in the dielectric capillary.

Most often, the current distribution in the electrolyte is secondary and depends both on the cell geometric parameters and the electrode reaction characteristics, namely, first of all, the cathode polarizability – the value corresponding to the cathodic polarization curve slope (*Bouzek et al., 1995*; *Electrode growth…, 2015*). During copper electrodeposition, the current efficiency approaches 100%, so the metal distribution is consistent with the current distribution on the cathode surface. This, accordingly, makes it possible to conduct model studies with greater accuracy (*Vasyliev et al., 2021a*). If the same electrolyte with fixed known physicochemical parameters is used in research, electrochemical 3D printing resolution will be affected by such system geometric parameters as the working electrode-anode diameter and the distance between the edge of the anode dielectric capillary and the cathode surface (interelectrode distance). Establishing these parameters' correlation influence on electrochemical 3D printing resolution is a significant scientific and technical task.

Thus, the purpose of this work, based on model studies, is to establish the influence of electrochemical cell geometric parameters' ratio on electrochemical 3D printing resolution.

Based on the purpose, the following tasks were identified:

- conduct modeling of the metal electrodeposition process during electrochemical 3D printing;
- investigate the electrochemical cell geometric parameters influence on electrochemical 3D printing accuracy.

The considered literary sources are devoted to the basic technological principles of the implementation of metal products electrochemical 3D printing method. In particular, the influence of the electrochemical cell geometric parameters and the electrochemical system properties on the metal distribution uniformity during electrodeposition have been considered. An analysis of factors influencing the resolution of electrochemical 3D printing was performed. The author used the sources of Ukrainian scientists such as R. Babchuk, V. Vorobyova, O. Linyucheva, M. Kotyk, G. Vasyliev and foreign researchers such as K. Bouzek, K. Borve, O. Lorentsen, K. Osmundsen, I. Rousar, J. Thonstad, M. Rafiee, R. Farahani, D. Therriault and others.

Research methodology

The COMSOL Multyphysics 4.3 software was used to model the influence of the 3D printer electrochemical cell geometric parameters on the locally electrodeposited fragment profile and, accordingly, electrochemical 3D printing resolution. Long-term copper deposit growth model was used (*Electrode growth…, 2015*). Based on the model's geometric parameters modification, electrochemical 3D printer working cell model (*Vasyliev, et al., 2022*; *Vasyliev, et al., 2023*; *Ushchapovskyi et al., 2022*; *Vasyliev et al., 2021b*) was developed in the appropriate software, presented in Appendix (*Figure 1*).

According to the corresponding model, calculations and the profile of the copper deposit long-term growth on the working cathode surface were performed *(Figure 1*, position 1). Calculations were performed to achieve a maximum height of the deposit growth profile of 100 μm. The simulation was performed for the following values of the relevant parameters. The distance between the cathode surface and the anode dielectric capillary edge (l), mm: 0,1; 0,5; 1. Anode diameter (D), mm: 1; 4; 6. The parameters of the selected electrochemical system were as follows. A copper sulfate electrolyte was chosen for modeling, for which the slope of the cathodic and anodic polarization curves corresponded to 1000 $mA \cdot cm^{-2} \cdot V^{-1}$; the electrical conductivity of the electrolyte was 0,08 S/cm.

Research results

To achieve the idealized maximum electrochemical 3D printing accuracy, locally electrodeposited object model profile should be rectangular (*Ushchapovskyi et al., 2022*). However, due to the peculiarities of the current distribution in the electrochemical cell, as was shown earlier (*Vasyliev et al., 2021a*; *Vasyliev, et al., 2022*; *Vasyliev, et al., 2023*), it approaches the parabolic one. The results of model studies on the influence of the working electrode-anode dielectric capillary width and the distance from the corresponding capillary edge to the cathode surface on the metal local electrodeposition area width are shown in the Appendix (*Figure 2*). As can be seen from this figure, the smaller the diameter of the anode (dielectric capillary) and the greater the distance from the anode dielectric capillary edge to the cathode surface, the wider is metal deposition area and the larger is the metal deposit growth profile deviation from the idealized (rectangular) shape. For the purpose of quantitative assessment and establishment of relevant regularities, the following was adopted in this work. The metal deposition area estimated width (W) was determined under the condition that the deposit growth profile height corresponds to 10% of the maximum height of the profile of the locally electrodeposited fragment of the metal deposit and in this case is 10 μm. For convenience, the ratio between the metal deposition evaluation region width and the anode diameter – W/D – was adopted in this work as a criterion that allows for a quantitative assessment of geometric parameters influence on electrochemical 3D printing resolution. The W/D dependences on the distance between the working electrode-anode dielectric capillary edge and the cathode surface l for different values of working electrode-anode diameters D are presented in the Appendix (*Figure 3*).

Thus, the following can be summarized from the studies presented in *(Figure 2*; *Figure 3*). To focus the electric field and narrow metal deposition region, the distance l between the anode

dielectric capillary edge and the cathode surface during local electrochemical deposition must remain constant and acquire the minimum possible value. Based on the data shown in the Appendix (*Figure 3*), the dependence of the minimum possible values of W/D depending on the working electrode-anode diameter D was obtained under the condition that $l \to 0$ (*Figure 4*). If it is assumed that the value $W/D = 1.25$ corresponds to the maximum value of the relative error permissible for engineering calculations of 25%, the dependence of the optimal distance between the dielectric capillary edge and the cathode surface l on the working electrode-anode diameter D corresponds to the following in the Appendix (*Figure 4*). Thus, it can be concluded that the larger the value of D, the larger the value of l can be applied to provide the necessary electrochemical 3D printing resolution.

Discussion

Electrochemical 3D printing resolution determines the characteristic size of the created object, just like its quality and compliance with geometric parameters. With electrochemical 3D printing in an electrolyte solution, the resolution will be increased by focusing the electric field in the interelectrode space. For this, the electrolyte composition selection, just like the variation of the working electrode geometric parameters, can be used. Further research in this direction may be aimed at investigating the influence of the current mode, and in particular, the pulse mode, on metal product electrochemical 3D printing accuracy and quality.

Conclusion

The effect of the main electrochemical cell geometric parameters on electrochemical 3D printing resolution has been investigated. A regularity describing the correlation between the working electrode diameter and the interelectrode distance was established. It has been shown that the larger the working electrode-anode diameter and the smaller the inter-electrode distance, the smaller the metal deposition area relative expansion and the higher electrochemical 3D printing resolution.

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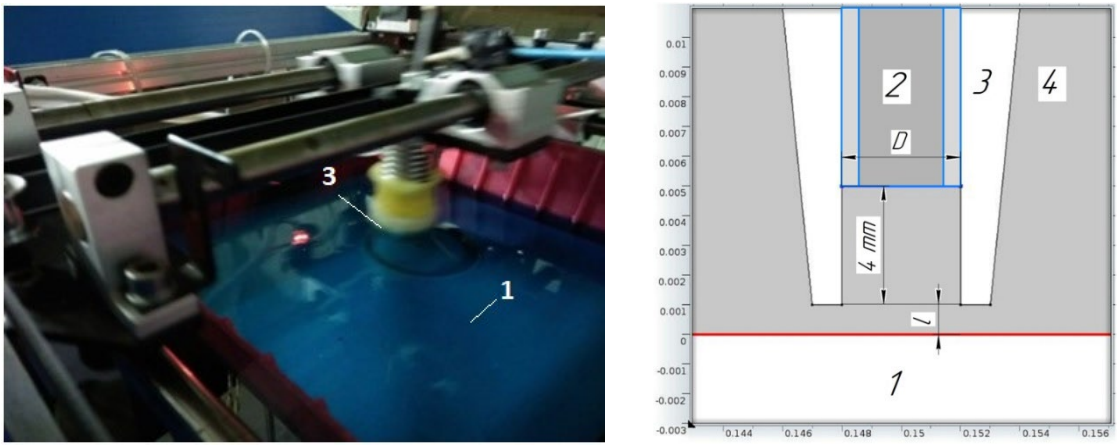
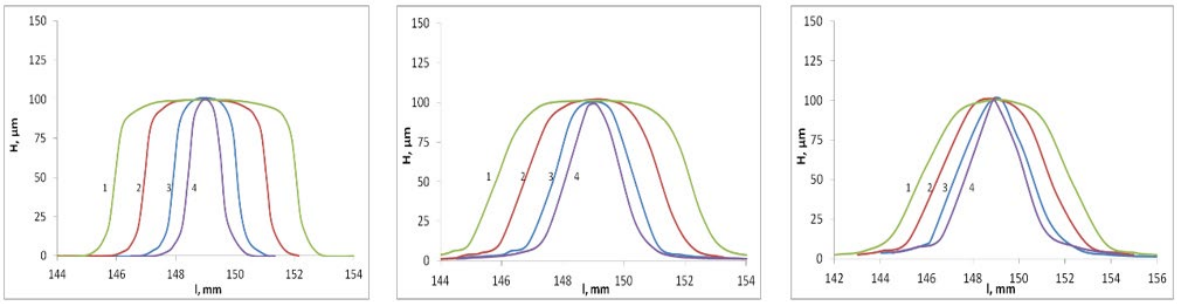
Appendix



(a) (b)

Figure 1. Image (a) and schema of model of electrochemical cell of 3D printer (b): 1 – cathode; 2 – anode; 3 – dielectric capillary; 4 – electrolyte



(a) (b) (c)

Figure 2. Influence of the distance l between the edge of the dielectric capillary of the working electrode-anode and the cathode surface on the model profile of the copper deposit. Value l, mm: a – 0.1; b – 0.5; c – 1. Diameter of the working electrode of the anode D, mm: 1–1; 2–2; 3–4; 4–6.

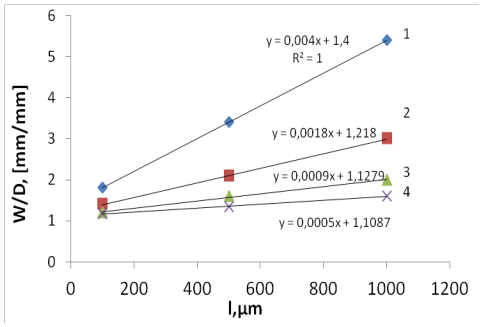


Figure 3. Dependencies of the relative expansion of the metal deposition area W/D on the distance l between the edge of the dielectric capillary of the working electrode-anode and the surface of the cathode, for the corresponding values of D, mm: 1–1; 2–2; 3–4; 4–6.

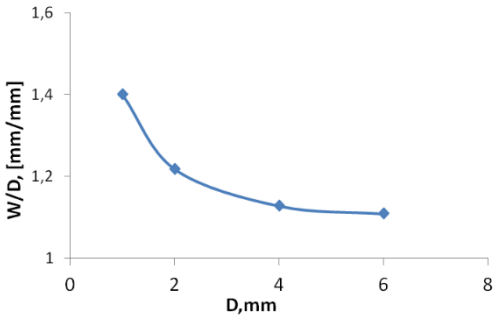


Figure 4. Dependencies of the value of the relative expansion of the metal deposition area W/D on D, provided that $l \rightarrow 0$

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Socio-psychological characteristics of sociopaths in relationships

Abstract: The relevance of the problem under study lies in the controversial issue that modern psychologists and psychotherapists are trying to solve: antisocial personality disorder is caused by heredity or is it the result of negligent upbringing? A sociopath has difficulty adapting to society, ignores the norms and rules of society, and has a low development of emotional intelligence. Given deviant behaviours, people with such a mental disorder are prone to breaking the law and committing serious crimes, so such people can be dangerous to others. Thus, the purpose of this study is to examine the manifestation of the personal characteristics of a sociopath in relations with the environment. The main method that was used to examine this problem was a psychological experiment, through which it was possible to comprehensively consider the characteristic features of sociopaths and analyse the main types of attachments. The main result of the study is proving that a certain parenting style in infancy activates the inherited gene of this mental illness. The study also presents the criteria by which it will be possible to quickly establish the diagnosis of antisocial psychopathy. The main prerequisites for the development of sociopathy are covered and the features of their manifestation in adult life are identified. The use of techniques as the most successful diagnostic tools for investigating the psychological phenomenon stated in the subject of the study is justified. In practical terms, the materials of the study allow expanding the context of sociopathic diseases. In clinical practice, specialists will be able to improve the treatment protocol: from the very beginning of therapy, it is necessary to consider negative childhood experiences, difficulties in socialisation and emotional regulation. Given the specific features of building relationships of a sociopath with other people, this study highlights the importance of forming a collaborative, well-defined therapeutic relationship that is key to the recovery of a patient. The study also notes the need for preventive measures by the social service among parents, during which the significance of a harmonious family environment and parent-child relationships are highlighted.

Keywords: personal mental disorder; psychopathy; psychotraumatic factor; personality of the patient; antisocial behaviour.

Introduction

According to the International classification of diseases ICD-10, sociopathy is a type of psychopathology characterised by impulsivity, irresponsibility, and often criminal behaviour (*International classification…, 2021*). In the middle of the 19th century, the antisocial disorder was considered moral insanity, later it was attributed to psychopathy (*Bozhik, 2020*). There are few thorough studies on personality psychology and sociopath behaviour patterns, and most often, these observations provide a collective portrait of personality disorder. It can be difficult to involve an ardent sociopath in the study, so documented cases of successful treatment or correction of sociopathy are not enough to formulate a treatment protocol from them. In addition, the final diagnosis can be made only after 18 years. Today, sociopathy is an object of research by psychotherapists, psychologists, and criminologists. The latter are interested in sociopaths because such people are good manipulators, indifferent to the environment and their feelings, they perceive the world as a means to achieve their own goals, which makes them potential criminals (*Purse, 2022*).

The study of the causes of this disease was conducted by E. Zaredinova (*Zaredinova, 2020*), D.J. Lieberman (*Lieberman, 2022*), L. Hachak-Velychko and O. Rolyuk (*Hachak-Velychko & Rolyuk, 2020*). The most common opinion of researchers is that a child inherits an antisocial personality disorder, especially when both parents had a mental illness in the family. Another factor contributing to the development of antisocial psychopathology is psychological trauma in childhood and physiological brain damage (*Horkovska, 2022*). In the studies of M. Zimmerman, 4% of people are diagnosed with sociopathy, and most of them are men (*Zimmerman, 2022*). They have a special style of communication – unpredictable, there is risk in their actions, disregard for external circumstances, feelings and emotions of others.

K.A. Fisher and M. Hany state that one in three out of a hundred people suffers from antisocial personality disorder (*Fisher & Hany, 2022*). According to researchers, one of the main reasons for the development of sociopathy is the stress that a child experiences in early childhood while in an incomplete dysfunctional family. Children from such families can become victims of physical or sexual violence, and the parenting style with an unstable psyche leads to a sense of danger and distrust of the world. However, the authors have positive results in treating sociopaths and believe that the disease can be eliminated through competent psychotherapy or independently. About a third of the subjects lost their antisocial behaviour by having a long-term, harmonious relationship with a mentor.

The diagnosis of sociopathy is outdated in scientific circles, so in the modern theory of psychology, the term antisocial personality disorder is used. A psychiatrist can make such a diagnosis if during the diagnosis it was possible to identify the following signs: high self-esteem, high level of aggression, demonstrativeness, exalted accentuation of character, lack of empathy, a tendency to delinquent behaviour, a low level of ability to form an attachment to people. While the first four signs can occur in any type of psychopathy, the last three are substantial signs of sociopathy. Victims of sociopaths describe them as charismatic, attractive, idealising their behaviour until the first cases of humiliation, insults, and accusations. A characteristic feature of sociopaths is manipulation; they use other people to meet their own needs. I. Fragkaki et al. analysed the ability of sociopaths to establish close relationships (*Fragkaki et al., 2019*). Given how easy and simple it is for sociopaths to make acquaintances, they don't have a truly long-term and close relationship with anyone, not even their family. Researchers consider their pathological lies, disregard for their own safety and the safety of others, cases of repeated violations of the law, and the commission of serious crimes to be the main obstacle to establishing close relationships.

According to the above information, the purpose of this study is to develop measures for the timely identification of signs of a sociopath, followed by the provision of qualified psychotherapeutic assistance.

Materials and Methods

In the course of the study, the following theoretical research methods were used: analysis, synthesis, concretisation, and generalisation of scientific-methodological literature on psychology, psychotherapy, criminology. Among the diagnostic methods used were questionnaires, psychological observation, interviews, and psychodiagnostic. In the course of the empirical part of the experiment, the following psychodiagnostic methods were used: a

multifactorial personality study by R. Cattell, the method "The past. The present. The future", the method of portrait choices by L. Szondi, diagnostics of interpersonal relations by T. Leary (modification of L.N. Sobchyk), and the "Experiences in Close Relationships" technique. Using the methods of mathematical statistics and graphical representation of the results, data processing was conducted, and theoretical and practical conclusions were summarised.

A clinical and anamnestic analysis of the medical history was conducted from the control cards of dispensary care for a patient with a mental disorder to achieve the goal set in the study and implement the tasks. In total, the experiment involved 80 people aged 18 to 21 years (30 – female and 50 – male), who had a general diagnosis of "personality disorder". Group 1 included 46 people from the sample who were brought to criminal responsibility and underwent a forensic psychiatric examination. Group 2 included 34 people who have no history of committing criminal acts, but the clinical picture of these patients shows aggressive tendencies. All patients were analysed for the absence of somatic diseases and signs of physiological brain damage.

During the empirical study, all the components of a clinical and psychiatric examination were applied: questioning, external examination, observation of behaviour, and analysis of objective signs of a disorder or features of a mental state. After collecting all the necessary information, a psychodiagnostic block was started. The survey was conducted over three months. Method of multifactorial research of the personality by R. Cattell was used to assess the individual psychological characteristics of the patient. The raw scores that were obtained from the responses were converted to the scales, and then the combination of a pair of primary factors and their value level (high, medium, low) were determined by the highest indicators. The methodology "The past. The present. The future." was used to examine the temporal and spatial organisation of consciousness. Each respondent was asked to draw the past, the present, and the future on three sheets of paper, after which it was necessary to explain the meaning of the drawing. Responses were recorded by the values of personal content, meaning, and subject content. The method of portrait choices of L. Szondi was used to test the ability to adequately understand and differentiate the emotional state of other people. Using this method, respondents were offered photos of a group of people with different moods. The subjects had to correlate them by emotion. All elections of respondents were recorded in the protocol. Methodology for diagnosing interpersonal relationships by Leary (modification of L.N. Sobchyk) was used to examine the ideas of the subjects about themselves and the ideal "Self", and to examine relationships in small groups. Depending on the obtained indicators, the types of attitudes toward others in both groups were distinguished. The "Experiences in Close Relationships" method is aimed at investigating specific attachment relationships inherent in childhood: avoiding intimacy, fear of abandonment, and striving for closeness.

The Results of the Study

Modern research in psychopathology is aimed at investigating mental disorders that were formed in childhood. In this issue, the researchers were divided into two groups: those who consider biological factors to be the driving factor in the development of the disease, and those who consider the influence of social factors the cause of the development of the disease. Proponents of biological factors indicate that the basis for the development of sociopathy is

genetic, constitutional, anatomical, or physiological factors, namely: low reactivity and excitability of the nervous system, the predominance of the "run" reaction to danger, delayed development of brain structures due to damage or dysfunction of the brain, violation of biological processes in the perinatal period of fetal development.

Representatives of the behavioural approach prove that the social environment has a substantial impact on the development of a personality of a sociopath. Especially the style and quality of the parent-child relationships: hostility, cruelty, and the presence of alcohol and drug addiction in parents. First of all, it is believed that the lack of object relations is a substantial factor in the fact that a person becomes a sociopath. While the infant is extremely dependent on the mother and father, object relationships act as an appropriate template through which the child's feelings, beliefs, and expectations are determined. Consequently, the internal object world of the child substantially affects their interaction with people and reality in general. That is, children with somatic diseases do not necessarily have to become sociopaths, but children with unreliable attachment in infancy are at risk of developing sociopathy. That is why patients of the psychiatric department with somatic diseases did not take part in this study. Results of diagnostics using the method of multifactorial personality study by R. Cattell are shown in the figure (*Figure 1*).

From Figure 1, it can be concluded that 74% of people from group 1 who were subject to criminal proceedings are characterised by irresponsibility, flexibility in relation to social norms, disregard for moral values, regulation of behaviour under the influence of circumstances, and a tendency to antisocial manifestations (G- scale). 73% have a sufficient level of intelligence on the B- scale (concreteness, rigidity, and reduced efficiency of thinking, difficulties in solving abstract problems, insufficient level of general verbal culture), half of the subjects of the first group are prone to patronage, have a changeable mood (I+ scale). Practicality, everyday aspirations, and limited imagination (M- scale) is inherent in 73% of people in group 1. On the F+ scale, 51% of respondents from group 1 have a high level of expressiveness, however, such a high level of importance of emotional relationships with people is manifested due to the tendency of patients with sociopathy to attract attention to themselves. Paranoid tendencies, a high degree of suspicion, uncertainty, and tension (L+ scale) are inherent in 74% of respondents from group 1. On the O+ and Q4 + scales, 74% of patients have high levels of anxiety and tension, respectively. Patients with personality disorder from group 2 have some traits of individuals from the first group on the I+ and L+ and O+ scales (emotional softness, paranoiality, high level of anxiety). However, on the F- scale, such patients are characterised by prudence in choosing a communication partner, pessimism, and restraint in expressing emotions. Conformism on the Q2- scale is a characteristic feature of a group of respondents who committed criminal acts.

Aggressiveness, hostility, and malice can often be symptoms of pathopsychological changes. Such symptoms were detected in respondents from group 1 during anamnestic analysis and psychodiagnostic examination of individual psychological characteristics of the individual. Due to the lack of timely examination and lack of competent therapy, the development of these symptoms leads to a mood disorder, which is manifested by tension with an angry-mournful affect, irritability, which develops into outbursts of anger with aggression. Confirmation of this

opinion is reflected in the results of psychodiagnostics using the method of interpersonal relations. Leary (modification of L.N. Sobchyk) (*Table 1*).

Consequently, it is these types of interpersonal relationships that predominate among patients with sociopathic personality disorder, as shown in Table 1. Namely, aggressive (100%) and egoistical (100%). It is worth noting that the responsible-generous (altruistic) type of interpersonal relationship is a sign of a pathological tendency to lie, a kind of "mask" that the patient uses to hide their manipulative way of communicating. In group 2, aggressive (98%) and egoistical (95%) types of interpersonal relationships also predominate among those who were not prosecuted. However, they are also characterised by authoritarian (98%), suspicious (96%), and the latter was the most pronounced type of interpersonal relationships for which the highest number of points was chosen (13-16), that is, respondents of the second group perceive the world as hostile and try to stay away, subject everything to doubts. These results indicate that patients in group 2 do not have a tendency to sociopathy, but they are characterised by other types of personality disorder. Results of psychodiagnostic examination according to the method "The past. The present. The future." are presented in the table (*Table 2*).

The results of the experiment shown in Table 2 indicate that patients with sociopathy (group 1) have a limited emotional field, which causes certain difficulties in the subjective perception of reality (only 6% of respondents were able to explain the content of the figure "The Past" and "The present"). None of the respondents could explain the personal content of the drawings. The overwhelming majority of respondents stated the presence of the depicted objects in the drawing (subject content). For example, to the question "What is shown in this drawing?" they gave the following answers: "a tree, a house, a person, an animal. The question: "What do they mean to you?" could not be answered by none of the study participants who were once brought to criminal responsibility. This is explained by the fact that in the process of forming images in the minds of sociopaths, they lose the individual-semantic component of the object, their emotions go beyond awareness and the patient cannot give indirect subjective meanings to the object. In simple words, the cognitive field falls from the emotional field into dependence, which leads to affective reactions.

In the intellectual actions of a sociopath, there is no basis for the meaning of a mental image, especially when it comes to the future, that is, they are not able to integrate accumulated experience, adhere to social norms, predict, and plan. Consequently, the inability to regulate one's behaviour in accordance with the requirements of society leads to a violation of critical thinking and mediation. In this connection, the existence of content-forming motives becomes impossible, the behaviour of sociopaths is controlled by stimuli. Any hierarchy of motives in this case is impossible, such people are aware of the world through specific things and circumstances.

Thus, difficulties in recognising one's own emotions and observing social norms lead to inadequate differentiation of other people's emotional states, which makes sociopathy the most dangerous type of pathology. For comparison, the diagnostic results of group 2 in Table 2 are presented. A small number of patients with various types of personality disorders are still able to integrate their own experience, have the ability to empathise, and tend to adhere to social norms. Confirmation of the above is demonstrated by the results of diagnostics of the method of portrait choices by L. Szondi (*Table 3*).

At the end of the diagnosis, the results of which are presented in Table 3, quantitative analysis of the data showed that sadism-masochism manifests itself in 98% with a tendency to s+, that is, in patients from group 1, such painful signs of the factor as sadism and antisocial behaviour with violent manifestations predominate. The paranoid factor was manifested in 98% of respondents with the p- pole, that is, these patients are characterised by expansive schizoid accentuation, megalomania, alcoholism, drug addiction, illegal actions: fraud, hooliganism. Similar signs are inherent in 100% of respondents who have a depressive state with the d+ pole, and 96% with a manic state at the m- pole. It is worth noting that it was difficult for respondents from the first group to form groups of photos according to any mood, on average they managed to form 3 groups each, difficulties were caused by the instruction "choose a photo of a person that you like/dislike". While the subjects from group 2 were able to complete the task – forming 5-6 groups on average, they still have behavioural deviations.

According to Table 3, according to the factor of sexual undifferentiation – 56% of respondents have sexual behaviour disorders, 12% have the sadism-masochism factor manifested with s- pole with a tendency to harm their own lives. Epileptoid tendencies were manifested in 97% of the second group with the e+ pole, such patients are characterised by psychosomatic diseases, have a pathological tendency to follow the rules and control others in this. 98% have hysterical tendencies with the hy + pole, 100% – catatonic manifestations with the c+ pole: anxiety-suspicious, obsessive states, depressive-hypochondriac disorders, complete passivity, and isolation. 47% have paranoid tendencies in personality disorder (p- pole). A depressive state with d- pole in 35% is characteristic of respondents from the second group. 10% are dominated by a manic state with the m+ pole, which is dominated by hysterical and psychosomatic disorders, fixed fears, and hypomania.

That is, the subjects from group 1 do not distinguish between subtle tones of emotional experiences. They understand that emotions exist, but their differentiation and definition do not reach the necessary level of awareness, and for some patients, it is impossible. Consequently, such people do not respond adequately to the behaviour of the environment due to ongoing violations of social adaptation. The assumption is that environmental factors, including sexual or physical violence in childhood, stress, and an unfavourable psychological atmosphere in the family where the child grew up, are the main cause of antisocial personality disorder (*Table 4*).

In any area of psychology, there are experiments in which it is proved that the cause of personality disorders was traumatisation in childhood. Similarly, the study of the experience of close relationships in people aged 18-21 years, the results of which are presented in Table 4, proves that the type of attachment in which children were at an early age formed an unhealthy model of building relationships in them. Among all the subjects, the highest percentage based on "avoidance of intimacy" in group 1 (60%) are those people who are afraid of intimacy, have a pathological distrust of the world, have learned to emotionally distance themselves from relationships, have a negative attitude to any manifestations of interest in their personality in advance, and refuse sexual relations forever. Fear of abandonment also prevails among the participants of the first group (97%). Patients with this type of attachment do not accept their personality, appearance, and have dysmorphophobia. Because of this, they do not consider themselves worthy to have a relationship, but it is excruciatingly painful for them to admit their inferiority, so they blame other people for their inability to build relationships with them. The

"desire for closeness" characteristic also prevails among respondents from group 1 (98%). The distortion of this type of attachment lies in the fact that from the outside such people demonstrate a desire to be in the company of people, creating warm, emotionally substantial relationships, but their behaviour creates situations that make it impossible to get closer at the level of communication, love, friendship. From the outside, the relationships of such people seem perfect, but in fact, it is the most pathological type of co-dependent relationship.

Discussion

Summarising the results of the study, the following criteria that can be used to determine the personal characteristics of sociopaths in relationships can be distinguished (*Table 5*).

The sociopath has a history of sadistic-masochistic, paranoid, manic, and depressive states. All the signs listed in Table 5 form aggressive and egoistical styles of interpersonal relationships. The reasons why a person can develop sociopathy are inconsistencies between the intellectual and emotional fields of the child due to careless upbringing on the part of parents and the lack of close object relationships. The result of such parenting can be three types of relationship strategies: avoiding intimacy, fear of abandonment, and the desire for closeness. None of these strategies involves a close emotional connection to the environment. On the contrary, due to constant stress in childhood, some brain structures remain underdeveloped, such as the limbic system. Therefore, it is very difficult for a sociopath to manage their emotions and understand the emotions of other people. This is also the reason for non-compliance with the rules in society. Cognitive processes remain influenced by affective responses that the cerebral cortex is not able to grasp. Language is used as a tool for manipulating and controlling people.

M. De Lisi et al. insist that there should be a balance between the physical and emotional development of a child, that is, from birth, a child should feel safe and emotionally comfortable (*De Lisi et al., 2019*). Developing in a state of constant anxiety, in unstable, constantly traumatic circumstances, the child is not able to form a sense of deep attachment. In such conditions, they can only form an idea of themselves – "I am bad" and a desire to take revenge on the whole world. According to the results of the researchers, 70-80% of the subjects who have antisocial personality disorder experienced physical or sexual violence in the families in which they were raised. The presence of a weak, depressed, indifferent mother with masochistic tendencies causes the child to become frustrated with primary needs. The baby will try their best to get the attention of the parents, however, T. Crow and K. Levy note that the father in such a family either cannot protect the child from the traumatic actions of the mother or has an explosive, inconsistent character and a tendency to sadism (*Crow & Levy, 2019*). The authors state in their study that such a child in adulthood tries to find a safe place for themselves by entering only those relationships in which other people can be manipulated and controlled. That is, their behaviour model lacks the ability to create close, harmonious relationships.

In addition, the presence of a dismissive mother leads to a lack of understanding of the process of managing their own emotions by a child. E. Rufenacht et al. prove the need for the process of containerising the emotions of a child (anxiety, fear, resentment, joy) and returning them in a socially accepted form (*Rufenacht et al., 2021*). If this process occurs in harmony, the child learns to manage their emotions through the cognitive field. Otherwise, when the mother left the child alone with their experiences, the latter learned to separate from them. The problem

occurs when a sociopath finds themselves in a situation that triggers an instant response from the emotional area, which researchers call the affective state. In those moments when an event leads to an emotional reaction, there are no regulatory processes in the critical thinking of a patient with antisocial behaviour, due to which they could control the situation. In such situations, sociopaths sometimes blame the victim for the committed crime. M.Z. Sagha et al. call this projective identification, a defence mechanism of sociopaths against guilt (*Sagha et al., 2019*).

The ability to contain emotions additionally affects the ability to form symbols. One of the symbolic acts by which parents contain the emotions of their child is speech. Through speech, parents form images of feelings that the child experiences. The verbalisation of emotions leads to the development of an image in the child with which the emotion will be associated in the future. However, as the results of a study using the method "The past. The present. The future" show, sociopaths lack the ability to form images. Instead of verbalising their experiences, they respond with immediate action. Thus, the randomness of relationships with important adults is a psychotraumatic factor that leads to getting stuck in the phase of attachment development. Getting people to pay attention to them and earn the love and affection of others are the reasons why sociopaths are on the verge. However, all attempts to get the favour of other people lead to the fact that sociopaths betray them. K. Steele et al., investigating the problem of building long-term mutual relations of sociopaths, concluded about the pathology of object constancy development (*Steele et al., 2019*). The tendency to use other people as a tool to achieve their own desires and goals is one of the criteria for the personality of a sociopathic patient. The constancy of an object, according to researchers, is formed in a child when an adult constantly maintains contact with them at the time of meeting needs. The mother, satisfying the child's need for love and security, forms the child's support, trust in the world. In moments of anger and frustration, this support provides a solid foundation for building object relationships in adult life.

J. Florange and S. Herpertz give another example of the parent–child relationships that can lead to a personal mental disorder of an antisocial nature (*Florange & Herpertz, 2019*). Parents who form the understanding "I am the best in the whole world", distort the sense of reality of the child. Such children in adulthood have to face the reality that meeting their needs is not the primary task of the environment. However, some people disagree with this state of affairs and resort to manipulation, lies, and antisocial behaviour to attract attention. That is, excessive guardianship can also lead to the development of signs of sociopathy in the child, which will be fixed in them in adulthood. Before the age of 18, that is, until the personality is formed, it is difficult to determine the signs of sociopathy in children. However, some features of behaviour that are considered deviations should become the object of observation. Among such features, the nature of the child's relationship with the world around them is distinguished: rudeness, aggressiveness, and hostility are a reason for parents and social services to be wary. Especially if this aggressiveness is shown to animals. Perhaps this behaviour is a sign of an age-related crisis, but it should be understood that a systematic violation of generally accepted norms can lead to an exacerbation of sociopathic disorder.

Even in the last century, sociopathy was considered an incurable mental illness. Fortunately, modern methods of psychotherapy can improve the social behaviour of the patient, even if basic characteristics such as empathy are absent. On average, according to statistics, 10% of

patients are able to overcome their illness if the lifestyle of the patient is not burdened with alcoholism, drug or gambling addictions, and sexual behaviour disorders. In short-term therapy, there are adaptive approaches that effectively help to master crisis states and solve problems. In the course of long-term therapy, there are chances to change stable coping strategies only if the patient is fully prepared, there is a certain stability in life, and the therapist is highly qualified. Drug treatment helps to cope with aggression, depression, and helps the patient to control behaviour due to the stabilisation of serotonin in the brain. The studies by P. Tyer et al. show the EEG results, according to which the brain of sociopaths responds with slow excitation of the autonomic nervous system to the warning and expectation of stress (*Tyer et al., 2019*). Thus, the researchers note that it can be difficult for sociopaths to recognise situations that threaten emotional stability. Thus, antisocial behaviour can attract sociopaths precisely because of the physiological arousal that leads to risk and a thirst for adventure.

Conclusions

A person is a subject of socio-cultural life that develops in the context of social relations. The nature of the relationships that a person enters into can be diverse: economic, social, working, family. The presence of relationships is determined by the individual decision of a person to exchange their emotions, views, attitudes, habits with other people who are subject to certain norms and rules of society. However, this is one of the main features of a sociopath – destructive behaviour in relation to generally accepted social norms, traditions that have historically developed and are justified by the practice of everyday life.

The second feature that manifests itself in sociopaths in relationships is the lack of empathy. Personal relationships involve a deep level of trust that is achieved through the ability to express feelings in communication. However, as proved in the study of this paper, 100% of respondents do not have the ability to identify feelings using language. Healthy people use language as their primary means of turning images into words. For sociopaths, it serves as a means of manipulating and controlling others. This fact is confirmed by the results of the study of interpersonal relationships in this paper – 100% of respondents from group 1 have aggressive and egoistical interpersonal relationships. The last feature that was used to determine the main features of sociopaths in relationships in this study is the type of attachment. The analysis of scientific psychological literature has shown that the style of family education has a direct impact on the development of sociopathic traits in a person. As proof, 60% of respondents have a tendency to avoid intimacy, 97% – fear of abandonment, 98% – desire for closeness. That is, the vast majority of participants in the experiment did not have a harmonious close relationship with their parents.

Given the antisocial nature of the life path of a sociopath, it is necessary to keep people with deviant behaviour under constant control among psychologists, criminologists, and psychiatrists starting from childhood. Therefore, the prospect of further research should be the creation of a social, psychological, and legal regulatory framework for investigating, helping, and protecting patients with sociopathy.

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Appendix

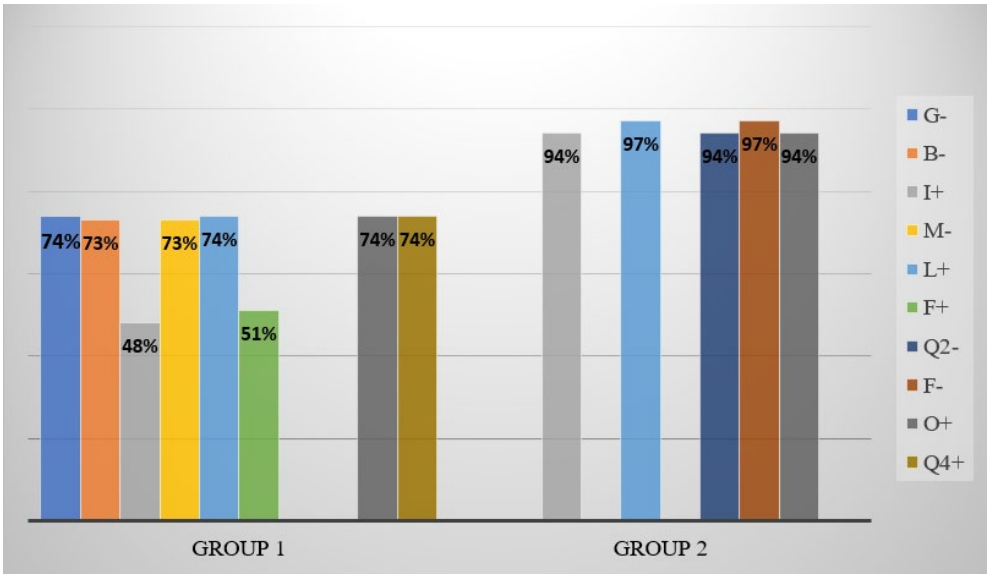

Figure 1. Results of a multifactorial psychodiagnostic examination of the individual according to the method of R. Cattell (*Khomenko, 2021*)

Table 1. Results of diagnostics using the method of interpersonal relations by T. Leary (modification of L.N. Sobchyk)

Type of interpersonal relationships	Group 1	Group 2
Authoritarian	3%	98%
egoistical	100%	95%
Aggressive	100%	98%
Suspicious	56%	96%
Subordinate	3%	67%
Dependent	3%	71%
Friendly	98%	22%
Altruistic	97%	12%

Source: (*Ivanchenko, 2021*)

Table 2. Results of psychological diagnostics using the "The past. The present. The future"

Criteria	The Past		The Present		The future	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
Personal content	-	78%	-	82%	-	65%
Value	6%	89%	6%	71%	-	90%
Subject content	97%	98%	97%	88%	100%	95%

Table 3. Results of diagnostics using the method of portrait choices by L. Szondi

Factor	Group 1	Group 2
u – sexual undifferentiation	-	56%
s – sadism-masochism	98%	12%
e – epileptoid tendencies	-	97%
hy – hysterical tendencies	-	98%
c – catatonic manifestations	-	100%
p – paranoiality	98%	47%
d – depressive state	100%	35%
m – manic state	96%	10%

Source: (*Nikolaevska, 2020*)

Table 4. Results of psychodiagnostic examination using the "Experiences in Close Relationships" method

	Avoiding intimacy	Fear of abandonment	Striving for closeness
Group 1	60%	97%	98%
Group 2	54%	78%	45%

Table 5. The main criteria for the manifestation of personal characteristics of a sociopath in relationships

Criteria	Features of the manifestation
Intelligence	Concreteness, rigidity, reduced efficiency of thinking, difficulties in solving abstract problems, insufficient level of general verbal culture.
Anxiety	High level. Suspicion, tension.
Normativity of behaviour	Impermanence. Do not make efforts to fulfil group requirements, as they indulge their own desires and random circumstances.
Expressiveness	Emotional affectivity in communicating with people, passion for the importance of social contacts.
Sensitivity	Vulnerability, a penchant for artistry and an artistic vision of the world.
Imagination	Lack of ability to form images.
Type of interpersonal relationships	Aggressive, egoistical.
Attachment type	Avoiding intimacy, fear of abandonment, desire for closeness.

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The main aspects of forming the social work digitalisation strategy

Abstract: Today's need to improve the process of providing social services to needy segments of the population finding themselves in difficult life circumstances has intensified interest in forming a strategy for digitalising social work. The study object is strategies for digitalising social work. The subject of this study is the factors and conditions that influence the formation of strategies for digitalising social work. The purpose is to study the factors and conditions to choose digital technologies by social work specialists, in particular those that ensure the provision of social services. During the study, the author used methods of analysis, synthesis, generalisation, and comparison. The website content of the Ministry of Digital Transformation of Ukraine was analysed; Decree of the Cabinet of Ministers of Ukraine "On approval of the Strategy of Digital Transformation of the Social Sphere" and Resolution of the Cabinet of Ministers of Ukraine "On Approval of the Regulation on the Unified Information System in the Social Sphere". The scientific works of A. Hrytsenko, T. Burlai, H. Davydenko, T. Yehorova-Lutsenko, V. Malinovskyi, L. Khromushyna, in which modern approaches to various social work digitalisation strategies in Ukraine are studied; V. Togobytska and M. Khaustova, examining benefits, risks and problems for the social sphere during digital transformation; V. Prysiazhnyuk, investigating the digital transformation of the social sphere in the conditions of war. The author concludes that this process should be general, in which the key role is played by the state, involving various stakeholders, including Social Work specialists, clients and heads of Social Services, Information Technology Developers, academic institutions and non-profit organisations engaged in social work and perform socially useful functions. It confirms the need for further scientific research in social work digitalisation, contributing to improving the practice of Social Work and requires state support.

Keywords: social work, digitalisation strategy of social work, digital technologies in the process of social support, difficult life circumstances, approach to strategy evaluation.

Основні аспекти формування стратегії цифровізації соціальної роботи

Анотація: Сьогоденні потреби в удосконаленні процесу надання соціальних послуг потребуючим верствам населення, які опинилися в складних життєвих обставинах, активізували інтерес до формування стратегії цифровізації соціальної роботи. Об'єкт дослідження є стратегії цифровізації соціальної роботи. Предметом цього дослідження є чинники та умови, які впливають на формування стратегій цифровізації соціальної роботи. Метою статті є вивчення чинників та умов вибору фахівцями соціальної роботи цифрових технологій, зокрема тих, які забезпечують надання соціальних послуг. Під час дослідження використано методи аналізу, синтезу, узагальнення та порівняння. Проаналізовано зміст сайту Міністерства цифрової трансформації України та Міністерства соціальної політики України; офіційний сайт Пенсійного фонду України; Розпорядження Кабінету Міністрів України «Про схвалення Стратегії цифрової трансформації соціальної сфери» та Постанову Кабінету Міністрів України «Про затвердження Положення про Єдину інформаційну систему в соціальній сфері»; Електронний кейс-менеджмент та ЄІССС. Опрацьовано наукові роботи А. Гриценко, Т. Бурлай, Г. Давиденко, Т. Єгорової-Луценко, Л. Хромушиної, в яких досліджуються сучасні підходи до різних стратегій цифровізації соціальної роботи в Україні; В. Тогобицької та М. Хаустової, де розглядаються вигоди, ризики та проблеми для соціальної сфери під час цифрової трансформації. Автор робить висновок, що цей процес має носити спільний характер, в якому головну роль відіграє держава,

залучаючи до нього різні зацікавлені сторони, включаючи фахівців з соціальної роботи, клієнтів та керівників соціальних служб, розробників інформаційних технологій, академічні установи та некомерційні організації, які займаються соціальною роботою і виконують суспільно корисні функції. Це засвідчує необхідність подальших наукових досліджень у сфері цифровізації соціальної роботи, що сприяє вдосконаленню практики соціальної роботи та потребує державної підтримки.

Ключові слова: соціальна робота, стратегія цифровізації соціальної роботи, цифрові технології в процесі надання соціальних послуг, складні життєві обставини, підхід до оцінювання стратегії.

Introduction

Modern challenges and needs facing social work specialists require optimisation of the process of providing social services. Helping vulnerable groups, including people with disabilities, migrants, the homeless, the elderly, and those who have lost their jobs, requires reducing bureaucracy, responding quickly to public needs, and improving the availability of services. Therefore, the digitalisation of social work is relevant, which contributes to increasing public confidence, improves professional standards and practices of social work, and promotes the development of innovative approaches in social work, thereby ensuring more efficient use of limited financial and human resources. In the general global movement context towards the digitalisation of various life spheres, developing digital technologies in social work becomes necessary to respond to modern challenges and needs.

The study object is Strategies for Digitalization of Social Work.

The study subject is the factors and conditions influencing the formation of Strategies for Digitalization of Social Work.

The purpose is to study the factors and conditions of choice of digital technologies by social work specialists, in particular, those that ensure the provision of social services to the needy segments of the population who find themselves in difficult life circumstances.

Based on the set purpose, the following tasks were solved:

- investigate the main approaches to evaluating the Strategy of Digitalisation of Social Work in Ukraine;
- analyse various digital technologies content in the activities of social services and organisations;
- justify the impact of social services on the choice of digital technologies by specialists in social work;
- consider digital technologies in social work in the conditions of war in Ukraine.

In the study course, the author used the methods of analysis, synthesis, generalisation and comparison.

The content of the official website of the Ministry of Digital Transformation of Ukraine (*Ministry of Digital Transformation…, 2023*), the official website of the Ministry of Social Policy of Ukraine (*Ministry of Social Policy…, 2023*), the official website of the Pension Fund of Ukraine (*The Pension Fund…, 2023*), the Order of the Cabinet of Ministers of Ukraine (*On the Approval of the Strategy…, 2020*), the resolution of the Cabinet of Ministers of Ukraine on approval of the

regulation on the unified information system in the social sphere (*On the Approval of the Regulation…, 2023*), Electronic case management and USIS (*Electronic Case Management…, 2023*). Scientific works of such researchers as A. Hrytsenko and T. Burlai (*Hrytsenko & Burlai, 2020*), G. Davydenko (*Davydenko, 2023*), T. Yehorova-Lutsenko (*Yehorova-Lutsenko, 2020*), which examines modern approaches to various strategies for digitalization of social work in Ukraine. V. Togobytska (*Togobytska, 2017*) and M. Khaustova (*Khaustova, 2023*) examine the benefits, risks and challenges for the social sphere during digital transformation. L. Khromushyna (*Khromushyna, 2023*) focused on the strategic aspects of transforming management activities in the digital economy and society of Ukraine. The author addresses the study results to managers who manage social processes and social work specialists who provide social services and assistance to needy segments of the population who find themselves in difficult life circumstances.

The results of the study

1. Main approaches to evaluating the strategy of digitalisation of social work in Ukraine

The current socio-political and military situation in Ukraine puts forward new requirements for providing social services to the population in difficult life circumstances (hereinafter – DLC). The ability of social specialists to ensure the resilience of Ukrainian citizens and their adaptation to the crisis conditions of today depends on the effectiveness of this process. Transformational processes related to legal, medical, educational, economic, psychological and rehabilitation problems require, first of all, the empowerment of the population in the context of self-provision of basic life needs.

The general trend in forming effective social work digitalisation is to focus on developing and implementing a strategy to improve the process of providing social services to the population finding themselves in DLC. For successful and effective actions in this direction, it is necessary to identify and develop a general long-term conceptual scenario, i.e., a holistically comprehensive action plan defining the course of forming social work digitalisation, which is its strategy (*Yehorova-Lutsenko, 2020*).

The role of strategy in shaping population resilience is so significant that it is worth approaching as a broadly specialised concept. After all, the growing number of people in need of social services due to ageing, the spread of chronic diseases, unemployment, and poverty requires more effective and affordable methods of providing social services.

The social work digitalising strategy is aimed at automating tasks, including the introduction of documentation, scheduling meetings, processing requests, consulting, and the like. It plays a significant role in risk assessment, forecasting customer needs and personalising services, using mobile applications to track customer progress, reminding about medication and communicating with electronic services. The advantage of digital technologies in the practice of social work is to ensure the availability of 24/7 services to internally displaced persons, people with disabilities and people who live in remote areas or in the occupied territories of the country.

There are five approaches to assessing the strategy for forming social work digitalisation in the context of providing social services to needy segments of the population finding themselves in a society.

The analytical and resource approach is aimed at identifying the needs and problems faced by these population segments, and studying how digital technologies can help solve these problems. To assess a digitalisation strategy formation in social work, a customer record-keeping system is needed, which should store information about their needs and the services provided to them. An online survey based on which the relevant indicators can be calculated. The advantage of using the analytical resource approach is the availability of information, as a rule, the ability to analyse social networks and mobile applications, determine geospatial data to determine needs and resources in certain geographical regions, collect data from websites (web scraping) (*Yehorova-Lutsenko, 2020*).

A target-based or problem-based approach aims to identify clear and measurable goals of digitalising strategy that must be aligned with the overall goals of Social Work and customer needs. The digitalisation strategy level in the context of providing social services is evaluated based on their effectiveness and effectiveness, namely, improving access, reducing costs and increasing customer satisfaction. For efficient strategy study and evaluation, only one generalising indicator (e.g., the provision of Social Services) is not enough since the strategy concerns various types of social services, including home care, social adaptation, social integration and reintegration, emergency (crisis) intervention, counselling, representation of interests, etc. In addition, you can highly evaluate the developed strategy, but its implementation will not give the expected results. Therefore, it is advisable to evaluate the strategy based on the principles of success and effectiveness of its implementation. A comprehensive assessment of forming a strategy to digitalise social work (hereinafter – the strategy) in the context of providing social services is performed on the basis of an assessment of improving the quality of life of representatives of Target groups, saving time and resources, increasing the level of independence, developing skills to overcome difficulties, and raising awareness of their own rights (*Togobytskaya, 2017*).

Quality of life assessment consists of studying indicators related to health (chronic diseases, physical activity, mental disorders, stress and anxiety), social relationships (love and respect in family relationships, mutual understanding and absence of conflicts with friends and society), economic situation (income level, access to housing, food, education and health care).

To save time and resources, it is advisable to analyse the time spent by customers waiting in queues, travelling to and from social service offices, filling out forms and collecting information. Social work specialists process paperwork, make phone calls and correspondence, and meet clients. Identify the coefficient of expenses for transportation of representatives of Target groups and specialists, office supplies, and remuneration of Social Service Employees.

Assessing the clients' independence level, provided with social services, involves studying the ability to make decisions about their lives, take responsibility for these decisions, defend their rights and interests, and take part in social life (study, work, engage in volunteering and charity).

Coping skills formation involves studying resilience level, self-control and self-support: the ability to recover from crises and failures, manage your emotions, stay calm in difficult situations, concentrate on tasks, motivate yourself, believe in yourself and care for yourself.

Perhaps the most important thing is to study the clients' awareness level, provided with social services, in their rights. It involves analysing their knowledge not only about their rights

but also about how they are worth protecting knowledge presence about basic human rights; what rights are guaranteed by law; how to find information about their rights; what to do and where to apply in case of violation of rights; the ability to protect their rights independently or with the help of others (*Davidenko, 2023*).

The structural and functional approach aims to develop an action plan describing how the strategy's goals will be achieved. In addition, the action plan should include the time frame, budget, and responsibility of individuals. The advantages of this approach are to optimise the use of resources, ensure consistency of actions of different stakeholders, and avoid duplication and fragmentation of efforts. This approach allows us to explore how adaptation takes place to changes in technology and people's needs, which makes the digitalisation process more transparent. The structural and functional approach application allows us to consider social work as a system consisting of interrelated elements (services, processes, people, infrastructure). It is significant to note that the success of its implementation depends on several factors: political will, availability of resources and competence of participants (*Hrytsenko & Burlai, 2020*).

The practice-oriented approach involves the involvement of all stakeholders in the strategy development and implementation, including the needy segments of the population, social work professionals, government agencies, non-governmental organizations and the private sector. The benefits of this approach are to provide a better understanding of customer needs and concerns, as well as the resources and capabilities of various stakeholders. It is more likely that all stakeholders will use the strategy, and they will be more sustainable and flexible, which allow it to adapt to changing needs in the context of providing social services to the target audience. The advantage of using this approach is the creation of a coordination council to ensure the participation of all interested parties in communication, consultations to collect opinions and suggestions, the creation of joint working groups to develop and implement specific aspects of the strategy, and the use of online tools to facilitate communication and cooperation. At the same time, it is worth noting that the involvement of all stakeholders can be a difficult task, which requires identifying all relevant partners, taking into account their needs and interests, and effectively leading a process that should be fair (*Ministry of Digital Transformation…, 2023*).

The evaluation and monitoring approach, which aims to develop an evaluation and monitoring system to track progress and make necessary changes to the strategy, includes interviewing stakeholders using digital social services to get an opinion on their quality and availability, analysing the results obtained to track progress in social work, conducting focus groups and interviews to get feedback and suggestions on improving social services and digitalising social work. The advantage of this approach is that it allows you to compare the results of digital social services with the results of traditional social services and track the progress of customers using digital social services to improve communication and attract more people in need to use them (*On the Approval of the Strategy…, 2020*).

Thus, the formation of a strategy for digitalization of social work in the context of providing social services to the needy segments of the population who find themselves in the DLC with great uncertainty leads to the non-use of opportunities, the risk of lagging behind other countries and organizations that are already actively implementing digital technologies in social work. The absence of such a strategy can lead to chaotic and inefficient practices of social work, underestimation of risks, difficulty in cooperation and exchange of information between various

social services and organizations, problems with accountability and evaluation, and generally neglect of people's needs.

It should consider the conditions for choosing strategies that provide for a set of actions that do not go beyond the legal framework and the implementation of which contributes to the formation of digitalization of social work in the context of providing social services.

2. Digital technologies in the activities of social services

The new philosophy of Ukraine's social policy is designed to help everyone overcome the crisis and difficult life circumstances and form the ability to move forward. For this purpose, the unified social information system (hereinafter – USIS) has been introduced into the practice of social work on the Diya portal, through which most traditional social services are transferred online. It simplifies the work of social services and increases the speed of providing such services for personal requests from citizens (*On the Approval of the Strategy…, 2020*).

USIS allows Ukrainians to use social services from the comfort of their homes:

- application for a subsidy;
- compensation for employment for internally displaced persons;
- advice on the adoption of a child;
- obtaining and canceling the status of unemployed;
- custody, custody of a child;
- verification of medical reports, etc.

It saves time and effort by making services more accessible to people with reduced mobility or those who live in remote localities. The advantage of USIS is that it has a voice-over function for the visually impaired, reduces administrative costs, and uses advanced data protection technologies to ensure the security of user information. Constant updating and adding new features and services make it a convenient tool for the population that found itself in the DLC and also a powerful system for developing e-democracy in Ukraine.

To simplify work and improve services for personal appeals of persons with disabilities, specialists use digitalised cooperation forms with public associations, enterprises and organisations, including the "Electronic Cabinet of Persons with Disabilities" and the "eHelp" platform (*Ministry of Social Policy…, 2023*).

The digital technology "electronic cabinet of a person with a disability" is aimed at centralised accumulation, storage and automated information processing. It provides convenience and prompt provision of a package of documents to add auxiliary rehabilitation tools. Confirmation that this digital form is more and more effective is provided by the data of territorial branches of the Social Protection Fund in several regions of Ukraine, which indicate that at the beginning of 2024, 4,583 people with disabilities used this service.

The Ministry of Social Policy of Ukraine with the support of the Ministry of Digital Transformation of Ukraine and the United Nations Development Programme in Ukraine with financial support from Sweden created the eHelp platform. It helps to meet the urgent needs of citizens affected by Russian aggression, in particular, on the platform, you can learn how to get money from the state, leave a request for assistance or offer to support others by providing food, clothing, medicines, etc. The advantage of the eHelp platform is that it is available online

around the clock from any device connected to Internet resources, designed to meet the needs of people with various types of disabilities, and has subtitles and accessible sign language. A person with a disability can use the step-by-step instructions to submit a request for assistance here, track the status of their applications, receive consultations, and communicate with social work specialists online.

Significantly, people with disabilities have the opportunity to receive services using the eHelp platform and also any vulnerable segments of the population with social statuses - a pensioner, a single father or mother, a large family, and a recipient of assistance to low-income families. The transparency and accountability of the assistance process that the platform provides allows users to see the services available to them, the steps needed to be taken to receive them, and how the information they provide will be used. By using this digital service form in social work, specialists reduce the time required to process applications and improve results for people who need help. This is especially true for internally displaced persons, who can receive assistance from the state and charitable foundations, volunteers and international humanitarian organisations.

The project "Pension Fund of Ukraine in a Smartphone" (*The Pension Fund…, 2023*) provides for the functioning of several online services, including "Pension Calculator" and "SMS-free information". Their implementation allows the user to apply for the appointment of a pension in "one touch" and get certificates on the amount of pension, on the payment of wages. The advantage of the services is that they provide an opportunity to create an electronic employment record and check data on a person's work activity, calculate a future Old-Age Pension; get information related to the appointment or recalculation of a pension, the person's insurance experience, and the employer's payment of insurance premiums. However, to register for these services, a person must have an electronic signature key or be registered on the foundation's web portal using a username and password. Therefore, the use of these services causes several problems among the population (especially the elderly), associated with the need to use specific technical means and the lack of desire, need and skills on the part of users to work with them and inability to generate an electronic signature and apply this key. This requires social work specialists to develop a system of knowledge and skills for using services to optimise the process of providing social services (*Yehorova-Lutsenko, 2020*).

It is significant to note that digital technologies in Social Work allow people who are in DLC to participate in online forums (Facebook, Telegram and other social networks), support groups and chatbots to communicate with those who have experienced similar experiences and understand their problems. Digital technologies influence the processes of human decision-making regarding the receipt of social services. The online surveys and focus groups use allows social work professionals to receive digital feedback from the population about what services they need and how they can be improved (*Khaustova, 2023*).

Thus, digital technologies are changing the traditional practice of social work even though they, together with technological problems, give rise to several ethical issues regarding the relationship between specialists and clients, providing confidential information, adding them to traditional methods of work, form fundamentally new social services to create conditions for the population to leave DLC. In turn, it sets new challenges for higher education institutions in the context of training future specialists in social work.

3. Digital technologies in social work in the context of the war in Ukraine

The need for digitalising services in social work has become more relevant in modern conditions of military conflict because millions of people have found themselves in the category of Internally Displaced Persons (hereinafter – IDPs) who need social support and assistance from the state. It is achieved thanks to the introduction of the first stage of the unified information system of the social sphere (*On the Approval of the Regulation…, 2023*).

To date, the project "automation of IDP payments in USIS" has been implemented in this system, which won the European Social Service Award in the Digital Transformation category. The IDP living allowance implementation (under this project) begins with submitting an application through the "Diya" application for timely receipt of payments to victims of military aggression. It is advisable to focus on the fact that since 2023, the portal "Diya" has implemented the possibility of registration of four types of social assistance, namely: for adoption, for children with serious illnesses, persons with disabilities from childhood and for children to single mothers. Their advantages are speed, transparency, reduced bureaucracy and stress, accessibility, and targeted use of funds (*Ministry of Digital Transformation…, 2023*).

Yes, you can apply for adoption online at any time and from any place, saving you time and effort. Parents of children with serious illnesses do not need to spend energy visiting the authorities, which significantly reduces stress levels. After all, thanks to the online system, aid funds are guaranteed to be transferred to the account of specific children. In addition, single mothers have the option to receive information support regarding current assistance programs and other useful resources.

It is significant to note that during the military conflict, the monetisation project "eRehabilitation" was introduced for children who need special attention and support with health and recreation services. It allows the state to subsidise the cost of services and set some standards for their quality, rather than ensuring that children receive the necessary assistance in appropriate conditions (*"eRehabilitation" Programme…, 2023*).

Since 2023, the social education platform has been launched on the Web page of the Ministry of Social Policy, which was created with the support of the Government of Canada project "Support for Government Reforms in Ukraine (SURGe)", implemented by Alinea International Ltd. The platform allows you to ensure the formation of professional competencies not only among social service providers working in the social sphere but also among representatives of local self-government bodies (*Social Education Platform, 2022*).

The latest is that the Ministry of Social Policy of Ukraine plans to introduce "electronic case management – a systematic approach to case management, i.e., structured provision of services and support to meet individual needs" (*Khromushina, 2023*). Its specific feature is that all information about clients, their needs, plans and results is stored in a single electronic secure format. The project includes the creation of electronic cabinets for clients, social service providers and case managers. The main advantage of electronic case management is its effectiveness and the ability to focus on providing direct support to clients since most administrative and organisational tasks can be automated (*Electronic case management…, 2023*).

Thus, in the context of military operations, social work focuses on the formation of digital technologies, which allows specialists to modernise the process of providing social services,

optimise its components and create conditions for preventing the occurrence of difficult life circumstances.

Discussion

Each of the above topics can be interpreted differently in the practice of social work, which depends on:

(1) further development of the socio-economic and martial law of the country;
(2) the specifics of providing social services to segments of the population in need who find themselves in difficult life circumstances;
(3) social work practices and their configuration directly in the social sphere.

The interdependence of these points requires additional analysis and modeling of their practical implementation, taking into account a complex of various factors and conditions.

Conclusion

Targeted actions of the state towards improving the strategy of social work digitalisation will gradually increase the ability to provide efficient social services to the population in need. In turn, it will help save time optimise the use of resources by social work specialists, and ensure consistency in the work of social services with various stakeholders. At the same time, it will increase the likelihood of better understanding the needs and concerns of individuals caught up in the DLC, using online tools to facilitate collaboration with them, assessing risks promptly and sharing information with various social institutions, and preventing problems with accountability and evaluating social work practices.

Under the conditions of digital technology introduction into social work practice, the population will have access to the necessary social services, such as payment of assistance, paperwork, counselling, etc. Their application will allow the implementation of targeted projects aimed at solving specific needs of the population, conducting research to identify the levels of their impact on the process of providing social services to the population included in the DLC. Under such conditions, social work specialists will be interested in forming and developing digital technologies that can improve the social work practice and make it transparent, accessible and understandable.

In the conditions of war, digitalisation of services in social work through the introduction of the first stage of the unified information system of the social sphere is developing, which allows internally displaced persons in Ukraine, persons with disabilities from childhood, children of single mothers, children with serious illnesses not only to survive and adapt to the crisis but also to become stronger and show resilience.

Studies of the main aspects of the formation of a strategy for the digitalisation of social work give grounds to argue that this process should be of a general nature, in which the core role is played by the state, involving various stakeholders, including Social Work specialists, clients and heads of Social Services, Information Technology Developers, academic institutions and non-profit organisations, engaged in social work and perform socially useful functions. It

confirms the need for further scientific research in digitalising social work, which contributes to improving the practice of Social Work and requires state support.

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