INFORMATION TECHNOLOGIES

DOI: 10.15587/2706-5448.2026.356218

DEVELOPMENT OF AN APPROACH TO FORMING A FRAME-BASED DICTIONARY FOR THE PERSONALIZATION OF AN EDUCATIONAL CHATBOT

pages 6–14

Olha Kryazhych, *PhD, Senior Researcher, Associate Professor, Institute of Telecommunications and Global Information Space National Academy of Sciences of Ukraine, Kyiv, Ukraine, e-mail: economconsult@gmail.com, ORCID: https://orcid.org/0000-0003-1845-5014*

Vasyl Vasenko, *PhD, Associate Professor, Head of Department of Theory and Techniques of Technology Education and Computer Graphics, Hryhorii Skovoroda University in Pereiaslav, Pereiaslav, Ukraine, ORCID: https://orcid.org/0000-0002-2527-6359*

Oleksandr Vasenko, *PhD, Associate Professor, Head of Department of Digital Methods of Teaching, Hryhorii Skovoroda University in Pereiaslav, Pereiaslav, Ukraine, ORCID: https://orcid.org/0000-0002-8895-4284*

Anastasiia Pavlenko, *PhD, Associate Professor, Department of Digital Learning Technologies, Hryhorii Skovoroda University in Pereiaslav, Pereiaslav, Ukraine, ORCID: https://orcid.org/0000-0002-5863-0385*

Kateryna Iushchenko, *PhD, Junior Researcher, Institute of Telecommunications and Global Information Space of National Academy of Sciences of Ukraine, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0001-5183-816X*

The object of research is the process of functioning and using AI-based educational chatbots in the educational environment. The problem addressed in the research is the training of chatbots using dictionaries. The paper presents an approach to chatbot personalization through the use of a thematic dictionary and query adjustment with the help of prompts.

A frame-based model of a dictionary has been developed, which can be added to a chatbot as a PDF document. The frames represent the subject domain as a hierarchically organized system. User prompts and the processing of frame structures are integrated with the chatbot through thematic representations. This ensures flexible query formulation, scalability of dictionary resources, and the possibility of further expansion of the subject domain without violating the integrity of the language model.

Schemes for combining contextual projection of query interaction and dictionary search have been developed and substantiated. To implement prompts, an algorithm was designed based on the principle of a "marked bullet" selection of a term or expression. Chatbot personalization is achieved through the formation of a series of user-generated prompts.

Based on the results of experiments on adapting ChatGPT to users' educational needs, frame-based dictionaries were implemented and tested. For the sequential dictionary implementation scheme, at an accuracy level of 10^{-6}, the total computational complexity is approximately 4.67, while increasing the accuracy requirement to 10^{-8} reduces this value to 3.287. The hierarchical scheme, based on the frame organization of the dictionary and the use of TemaView, demonstrates comparable or lower complexity values ($10^{-6} = 6.69$ and $10^{-8} = 4.69$).

The practical application lies in supporting the educational process through the use of personalized educational chatbots within learning systems.

Keywords: prompt engineering, personalized learning, flexible query construction, table of thematic representations.

References

1. Fillmore, C. J. (1982). Frame semantics. *Linguistics in the Morning Calm.* Hanshin Publishing Company, 111–137. Available at: https://brenocon.com/Fillmore%201982_2up.pdf
2. Ruppenhofer, J., Ellsworth, M., Petruck, M. R. L., Johnson, C. R., Scheffczyk, J. (2010). *FrameNet II: Extended theory and practice.* International Computer Science Institute. Available at: https://my.eng.utah.edu/~cs6961/papers/FrameNet_book.pdf
3. Chundru, J. K., Poddar, R., Cao, J., Jiang, T. (2025). Do LLMs Encode Frame Semantics? Evidence from Frame Identification. *Proceedings of the 2025 Conference on Empirical Methods in Natural Language Processing.* Suzhou: Association for Computational Linguistics, 29476–29488. https://doi.org/10.18653/v1/2025.emnlp-main.1499
4. Kryazhych, O., Ivanov, I., Iushchenko, K., Kupri, O., Vasenko, O., Riznyk, V. et al. (2025). Devising an approach to preventing information chaos in chat bots using generative artificial intelligence. *Eastern-European Journal of Enterprise Technologies, 2 (2 (134))*, 84–95. https://doi.org/10.15587/1729-4061.2025.324957
5. Hase, P., Diab, M. T., Celikyilmaz, A., Li, X., Kozareva, Z., Stoyanov, V. et al. (2021). Do Language Models Have Beliefs? Methods for Detecting, Updating, and Visualizing Model Beliefs. *ArXiv.* Available at: https://www.semanticscholar.org/paper/Do-Language-Models-Have-Beliefs-Methods-for-and-Hase-Diab/4a247cbfca9dcf91e2da24e6d2d84601a9041a8f
6. Millière, R., Buckner, C. (2024). A philosophical introduction to language models – Part I: Continuity with classic debates. *arXiv.* https://doi.org/10.48550/arXiv.2401.03910
7. Li, Y., Qu, S., Shen, J., Min, S., Yu, Z. (2023). Curriculum-Driven Edubot: A Framework for Developing Language Learning Chatbots Through Synthesizing Conversational Data. *arXiv.* Available at: https://arxiv.org/abs/2309.16804
8. Bayraktar, R., Sarıtürk, B., Elmas Erdem, M. (2024). Assessing Fine-Tuning Efficacy in LLMs: A Case Study with Learning Guidance Chatbots. *International Journal of Innovative Science and Research Technology,* 2461–2471. https://doi.org/10.38124/ijisrt/ijisrt24may1600
9. Aldhafeeri, L., Aljumah, F., Thabyan, F., Alabbad, M., AlShahrani, S., Alanazi, F. et al. (2025). Generative AI Chatbots Across Domains: A Systematic Review. *Applied Sciences, 15 (20),* 11220. https://doi.org/10.3390/app152011220
10. McGrath, C., Farazouli, A., Cerratto-Pargman, T. (2024). Generative AI chatbots in higher education: a review of an emerging research area. *Higher Education, 89 (6),* 1533–1549. https://doi.org/10.1007/s10734-024-01288-w
11. Memarian, B., Doleck, T. (2024). Human-in-the-loop in artificial intelligence in education: A review and entity-relationship (ER) analysis. *Computers in Human Behavior: Artificial Humans, 2 (1),* 100053. https://doi.org/10.1016/j.chbah.2024.100053
12. Wölfel, M., Shirzad, M. B., Reich, A., Anderer, K. (2023). Knowledge-Based and Generative-AI-Driven Pedagogical Conversational Agents: A Comparative Study of Grice's Cooperative Principles and Trust. *Big Data and Cognitive Computing, 8 (1),* 2. https://doi.org/10.3390/bdcc8010002
13. Peng, B., Galley, M., He, P., Cheng, H., Xie, Y., Hu, Y. et al. (2023). Check Your Facts and Try Again: Improving Large Language Models with External Knowledge and Automated Feedback. *arXiv.* https://doi.org/10.48550/arXiv.2302.12813
14. Gao, Y., Xiong, Y., Gao, X., Jia, K., Pan, J., Bi, Y. et al. (2023). Retrieval-Augmented Generation for Large Language Models: A Survey. *arXiv.* https://doi.org/10.48550/arXiv.2312.10997
15. El mourabit, I., Jai Andaloussi, S., Ouchetto, O., Miyara, M. (2025). AI Chatbots in Higher Education: Opportunities and Challenges for Personalized and Mobile Learning. *International Journal of Interactive Mobile Technologies (IJIM), 19 (12),* 19–37. https://doi.org/10.3991/ijim.v19i12.54163
16. Chen, D.-L., Aaltonen, K., Lampela, H., Kujala, J. (2024). The Design and Implementation of an Educational Chatbot with Personalized Adaptive Learning Features for Project Management Training. *Technology, Knowledge and Learning, 30 (2),* 1047–1072. https://doi.org/10.1007/s10758-024-09807-5
17. Davar, N. F., Dewan, M. A. A., Zhang, X. (2025). AI Chatbots in Education: Challenges and Opportunities. *Information, 16 (3),* 235. https://doi.org/10.3390/info16030235
18. Labadze, L., Grigolia, M., Machaidze, L. (2023). Role of AI chatbots in education: systematic literature review. *International Journal of Educational Technology in Higher Education, 20 (1).* https://doi.org/10.1186/s41239-023-00426-1
19. Huang, Q., Liu, X., Ko, T., Wu, B., Wang, W., Zhang, Y. et al. (2024). Selective Prompting Tuning for Personalized Conversations with LLMs. *Findings of the Association for Computational Linguistics ACL 2024,* 16212–16226. https://doi.org/10.18653/v1/2024.findings-acl.959
20. Raj, K., Roy, K., Bonagiri, V., Govil, P., Thirunarayan, K., Goswami, R. et al. (2024). K-PERM: Personalized Response Generation Using Dynamic Knowl-

edge Retrieval and Persona-Adaptive Queries. *Proceedings of the AAAI Symposium Series, 3 (1),* 219–226. https://doi.org/10.1609/aaaiss.v3i1.31203

21. Krouska, A., Troussas, C., Voyiatzis, I., Mylonas, P., Sgouropoulou, C. (2024). ChatGPT-based Recommendations for Personalized Content Creation and Instructional Design with a Tailored Prompt Generator. *2024 2nd International Conference on Foundation and Large Language Models (FLLM).* Dubai: IEEE, 295–299. https://doi.org/10.1109/fllm63129.2024.10852487

DOI: 10.15587/2706-5448.2026.356851

PROOF-OF-INDICATORS: DEVELOPMENT AND VALIDATION OF AN ADAPTIVE CONSENSUS MECHANISM FOR INTERNET OF THINGS BLOCKCHAIN NETWORKS

pages 15–24

Leonid Chepel, *PhD Student, Department of Computer Engineering, Taras Shevchenko National University of Kyiv, Kyiv, Ukraine, ORCID: https://orcid.org/0009-0008-4209-8102, e-mail: leonid.chepel@knu.ua*

Yuriy Boyko, *PhD, Associate Professor, Department of Computer Engineering, Taras Shevchenko National University of Kyiv, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0003-1417-7424*

The object of this research is the consensus mechanism in blockchain networks for the Internet of Things (IoT). The expansion of IoT requires a decentralized approach, making blockchain a promising solution. The Proof of Authority (PoA) consensus protocol was identified as the most suitable base for heterogeneous IoT, however, it has limitations regarding fork occurrence, data duplication, and the signer selection process.

The obtained results include the creation of the Proof of Indicators (PoI) consensus protocol that optimizes IoT network by reducing block size and prioritizing capable nodes for consensus tasks for devices with different performance and network conditions. PoI is based on Go-Ethereum's PoA Clique implementation; and a comparative performance analysis was conducted between PoI and Clique in a simulated IoT network.

Testing shows that PoI reduces overall network traffic by 20.5% and decreases network forks by 80%. Under testing, PoI improves transaction throughput and decreases block propagation time, compared to Clique. These gains occur with a modest increase in resource consumption: an average rise of 6.5% in CPU usage and 5.4% in memory usage.

A distinctive feature of this work is combining dynamic node selection with light block propagation within the blockchain consensus layer to address previously found limitations.

The PoI system is a suitable solution for secure and purpose-specific blockchain application in IoT, where blockchain node can be hosted on low-powered devices, such as the Raspberry Pi, creating a fully decentralized cloud-independent infrastructure.

Keywords: proof-of-authority, decentralized networks, embedded systems, node selection, block size optimization.

References

1. Minerva, R., Biru, A., Rotondi, D. (2015). *Towards a definition of the Internet of Things (IoT).* IEEE Internet Initiative.
2. Kuchuk, H., Malokhvii, E. (2024). Integration of IoT with cloud, fog, and edge computing: a review. *Advanced Information Systems, 8 (2),* 65–78. https://doi.org/10.20998/2522-9052.2024.2.08
3. Hossain, M., Kayas, G., Hasan, R., Skjellum, A., Noor, S., Islam, S. M. R. (2024). A Holistic Analysis of Internet of Things (IoT) Security: Principles, Practices, and New Perspectives. *Future Internet, 16 (2),* 40. https://doi.org/10.3390/fi16020040
4. Cao, K., Liu, Y., Meng, G., Sun, Q. (2020). An Overview on Edge Computing Research. *IEEE Access, 8,* 85714–85728. https://doi.org/10.1109/access.2020.2991734
5. Miller, R., Whelan, H., Chrubasik, M., Whittaker, D., Duncan, P., Gregório, J. (2024). A Framework for Current and New Data Quality Dimensions: An Overview. *Data, 9 (12),* 151. https://doi.org/10.3390/data9120151
6. Ullah, I., Havinga, P. J. M. (2023). Governance of a Blockchain-Enabled IoT Ecosystem: A Variable Geometry Approach. *Sensors, 23 (22),* 9031. https://doi.org/10.3390/s23229031
7. Susnjara, S., Smalley, I. What is blockchain? *IBM.* Available at: https://www.ibm.com/topics/blockchain
8. Upadhyay, V., Vaish, A., Kokila, J. (2024). The need for Lightweight Consensus algorithms in IoT environment: A review. *Proceedings of the 2024 Sixteenth International Conference on Contemporary Computing.* ACM, 366–376. https://doi.org/10.1145/3675888.3676072
9. Lin, S.-Y., Zhang, L., Li, J., Ji, L., Sun, Y. (2022). A survey of application research based on blockchain smart contract. *Wireless Networks, 28 (2),* 635–690. https://doi.org/10.1007/s11276-021-02874-x
10. Ahmad, A., Alabduljabbar, A., Saad, M., Nyang, D., Kim, J., Mohaisen, D. (2021). Empirically comparing the performance of blockchain's consensus algorithms. *IET Blockchain, 1 (1),* 56–64. https://doi.org/10.1049/blc2.12007
11. Islam, Md. M., Merlec, M. M., In, H. P. (2022). A Comparative Analysis of Proof-of-Authority Consensus Algorithms: Aura vs Clique. *2022 IEEE International Conference on Services Computing (SCC).* IEEE, 327–332. https://doi.org/10.1109/scc55611.2022.00054
12. Szilágyi, P. (2017). EIP-225: Clique proof-of-authority consensus protocol. *Ethereum Improvement Proposals.* Available at: https://eips.ethereum.org/EIPS/eip-225
13. Kopanitsa. Web3 Arduino: An Arduino (or ESP32) library to use web3 on Ethereum platform. *GitHub.* Available at: https://github.com/kopanitsa/web3-arduino
14. Almudayni, Z., Soh, B., Samra, H., Li, A. (2025). Energy Inefficiency in IoT Networks: Causes, Impact, and a Strategic Framework for Sustainable Optimisation. *Electronics, 14 (1),* 159. https://doi.org/10.3390/electronics14010159
15. Verma, L. P., Kumar, G., Khalaf, O. I., Wong, W.-K., Hamad, A. A., Rawat, S. S. (2024). Adaptive congestion control in IoT networks: Leveraging one-way delay for enhanced performance. *Heliyon, 10 (22),* e40266. https://doi.org/10.1016/j.heliyon.2024.e40266
16. Gordieiev, O., Rainer, A., Kharchenko, V., Pishchukhina, O., Gordieieva, D. (2024). A Unified Approach to the Development of Technology-Based Software Quality Models on the Example of Blockchain Systems. *IEEE Access, 12,* 118875–118889. https://doi.org/10.1109/access.2024.3448271
17. Hemminger, S. (2011). Tc-netem – Linux manual page. *Linux Foundation.* Available at: https://man7.org/linux/man-pages/man8/tc-netem.8.html
18. Albrecht, H. (2023). Introduction. *Edgeshark. Siemens.* Available at: https://edgeshark.siemens.io
19. Combs, G. *Wireshark: Network protocol analyzer.* Wireshark Foundation.
20. Alasmar, M., Clegg, R., Zakhleniuk, N., Parisis, G. (2021). Internet Traffic Volumes are Not Gaussian – They are Log-Normal: An 18-Year Longitudinal Study With Implications for Modelling and Prediction. *IEEE/ACM Transactions on Networking, 29 (3),* 1266–1279. https://doi.org/10.1109/tnet.2021.3059542

DOI: 10.15587/2706-5448.2026.358316

DEVELOPMENT OF A HYBRID METHOD VGG16-FrostNet FOR ADAPTIVE DESPECKLING OF SYNTHETIC APERTURE RADAR (SAR) IMAGES USING ATTENTION MECHANISM AND DIFFERENTIABLE FROST FILTER

pages 25–33

Raed Al-Senaikh, *PhD Student, Department of Information and Communication Technologies named after O. O. Zelensky, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, e-mail: r.z.alsenaikh@khai.edu, ORCID: https://orcid.org/0000-0002-8059-4237*

Oleksii Rubel, *PhD, Associate Professor, Department of Information and Communication Technologies named after O. O. Zelensky, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-6206-3988*

The object of research is the process of suppressing multiplicative speckle noise in synthetic aperture radar (SAR) images, which significantly complicates their analysis. The problem addressed is the lack of end-to-end hybrid methods capable of spatial adaptation by integrating a mathematical model of local statistics

ISSN-L 2664-9969; E-ISSN 2706-5448

(the Frost filter) directly into the neural network computation graph. This research is aimed at automating the process of adaptive SAR image filtering by developing the hybrid VGG16-FrostNet method. These research tasks were addressed by formulating a differentiable mathematical model of the classical Frost filter for integration into a neural network, developing an architecture based on a pretrained VGG16 (Visual Geometry Group) backbone (blocks 1–2), and integrating the Convolutional Block Attention Module (CBAM), which predicts a spatially varying damping coefficient map A_{map} within 0.5–10.0 for each pixel. The developed hybrid architecture includes a residual branch for detail recovery and was optimized end-to-end using a comprehensive loss function combining L1, Edge Loss (Sobel), SSIM, and attention regularization. The model was trained on synthetic data with gamma-distributed speckle (equivalent looks between 3.0 and 6.0) under typical SAR conditions. On the test set, experimental evaluation yielded a mean PSNR of 34.18 dB and SSIM of 0.97. The gain relative to the noisy image constituted 9.45 dB, and 3.36 dB in PSNR compared to the classical Frost filter with an optimal static coefficient. Edge indicators EPI = 0.8903 and FOM = 0.8340 substantiate reliable preservation of structural boundaries. It was established that the developed hybrid method provides spatially adaptive damping with interpretable attention maps, enabling its deployment in automated SAR data processing pipelines.

Keywords: SAR images, speckle noise, suppression, Frost filter, VGG16, CBAM, deep learning.

References

1. Oliver, C., Quegan, S. (2004). *Understanding synthetic aperture radar images*. SciTech Publishing, 479. Available at: https://books.google.com/books?id=0Ev3IoGbVSIC
2. Argenti, F., Lapini, A., Bianchi, T., Alparone, L. (2013). A Tutorial on Speckle Reduction in Synthetic Aperture Radar Images. *IEEE Geoscience and Remote Sensing Magazine, 1 (3),* 6–35. https://doi.org/10.1109/mgrs.2013.2277512
3. Touzi, R. (2002). A review of speckle filtering in the context of estimation theory. *IEEE Transactions on Geoscience and Remote Sensing, 40 (11),* 2392–2404. https://doi.org/10.1109/tgrs.2002.803727
4. Fracastoro, G., Magli, E., Poggi, G., Scarpa, G., Valsesia, D., Verdoliva, L. (2021). Deep Learning Methods For Synthetic Aperture Radar Image Despeckling: An Overview Of Trends And Perspectives. *IEEE Geoscience and Remote Sensing Magazine, 9 (2),* 29–51. https://doi.org/10.1109/mgrs.2021.3070956
5. Frost, V. S., Stiles, J. A., Shanmugan, K. S., Holtzman, J. C. (1982). A Model for Radar Images and Its Application to Adaptive Digital Filtering of Multiplicative Noise. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 4 (2),* 157–166. https://doi.org/10.1109/tpami.1982.4767223
6. Lee, J.-S. (1980). Digital Image Enhancement and Noise Filtering by Use of Local Statistics. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 2 (2),* 165–168. https://doi.org/10.1109/tpami.1980.4766994
7. Kuan, D. T., Sawchuk, A. A., Strand, T. C., Chavel, P. (1985). Adaptive Noise Smoothing Filter for Images with Signal-Dependent Noise. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 7 (2),* 165–177. https://doi.org/10.1109/tpami.1985.4767641
8. Lopes, A., Touzi, R., Nezry, E. (1990). Adaptive speckle filters and scene heterogeneity. *IEEE Transactions on Geoscience and Remote Sensing, 28 (6),* 992–1000. https://doi.org/10.1109/36.62623
9. Khudov, H., Makoveichuk, O., Tokarev, S., Andriushchenko, A., Pukhovyi, O., Rohulia, O. et al. (2026). Improving a method for filtering images acquired from a space-based radar observation system based on the Kuan algorithm. *Eastern-European Journal of Enterprise Technologies, 1 (9 (139)),* 40–46. https://doi.org/10.15587/1729-4061.2026.352347
10. Filipponi, F. (2019). Sentinel-1 GRD Preprocessing Workflow. *3rd International Electronic Conference on Remote Sensing,* 11. https://doi.org/10.3390/ecrs-3-06201
11. Abramov, S., Krivenko, S., Roenko, A., Lukin, V., Djurovic, I., Chobanu, M. (2013). Prediction of filtering efficiency for DCT-based image denoising. *2013 2nd Mediterranean Conference on Embedded Computing (MECO).* Budva: IEEE, 97–100. https://doi.org/10.1109/meco.2013.6601327
12. Lukin, V. V., Abramov, S. K., Rubel, A., Krivenko, S. S., Naumenko, A., Vozel, B. et al. (2014). An approach to prediction of signal-dependent noise removal efficiency by dct-based filter. *Telecommunications and Radio Engineering, 73 (18),* 1645–1659. https://doi.org/10.1615/telecomradeng.v73.i18.40
13. Rubel, O. S., Lukin, V. V., De Medeiros, F. S. (2015). Prediction of Despeckling Efficiency of DCT-Based Filters Applied to SAR Images. *2015 International Conference on Distributed Computing in Sensor Systems.* Fortaleza: IEEE, 159–168. https://doi.org/10.1109/dcoss.2015.16
14. Rubel, O., Lukin, V., Rubel, A., Egiazarian, K. (2019). NN-Based Prediction of Sentinel-1 SAR Image Filtering Efficiency. *Geosciences, 9 (7),* 290. https://doi.org/10.3390/geosciences9070290
15. Rubel, O., Lukin, V., Rubel, A., Egiazarian, K. (2021). Selection of Lee Filter Window Size Based on Despeckling Efficiency Prediction for Sentinel SAR Images. *Remote Sensing, 13 (10),* 1887. https://doi.org/10.3390/rs13101887
16. Rubel, O. S., Rubel, A. S., Lukin, V., Egiazarian, K. (2022). Optimal parameters selection of the Frost filter based on despeckling efficiency prediction for Sentinel SAR images. *Electronic Imaging, 34 (10),* 193-1-193–196. https://doi.org/10.2352/ei.2022.34.10.ipas-193
17. Chierchia, G., Cozzolino, D., Poggi, G., Verdoliva, L. (2017). SAR image despeckling through convolutional neural networks. *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS).* Fort Worth: IEEE, 5438–5441. https://doi.org/10.1109/igarss.2017.8128234
18. Zhang, K., Zuo, W., Chen, Y., Meng, D., Zhang, L. (2017). Beyond a Gaussian Denoiser: Residual Learning of Deep CNN for Image Denoising. *IEEE Transactions on Image Processing, 26 (7),* 3142–3155. https://doi.org/10.1109/tip.2017.2662206
19. Dalsasso, E., Denis, L., Tupin, F. (2021). SAR2SAR: A Semi-Supervised Despeckling Algorithm for SAR Images. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 14,* 4321–4329. https://doi.org/10.1109/jstars.2021.3071864
20. Dalsasso, E., Yang, X., Denis, L., Tupin, F., Yang, W. (2020). SAR Image Despeckling by Deep Neural Networks: from a Pre-Trained Model to an End-to-End Training Strategy. *Remote Sensing, 12 (16),* 2636. https://doi.org/10.3390/rs12162636
21. Russakovsky, O., Deng, J., Su, H., Krause, J., Satheesh, S., Ma, S. et al. (2015). ImageNet Large Scale Visual Recognition Challenge. *International Journal of Computer Vision, 115 (3),* 211–252. https://doi.org/10.1007/s11263-015-0816-y
22. Simonyan, K., Zisserman, A. (2015). Very deep convolutional networks for large-scale image recognition. *Proceedings of the International Conference on Learning Representations (ICLR).* arXiv. Available at: https://arxiv.org/abs/1409.1556
23. Vitale, S., Ferraioli, G., Pascazio, V. (2021). Multi-Objective CNN-Based Algorithm for SAR Despeckling. *IEEE Transactions on Geoscience and Remote Sensing, 59 (11),* 9336–9349. https://doi.org/10.1109/tgrs.2020.3034852
24. Moreira, A., Prats-Iraola, P., Younis, M., Krieger, G., Hajnsek, I., Papathanassiou, K. P. (2013). A tutorial on synthetic aperture radar. *IEEE Geoscience and Remote Sensing Magazine, 1 (1),* 6–43. https://doi.org/10.1109/mgrs.2013.2248301
25. Yosinski, J., Clune, J., Bengio, Y., Lipson, H. (2014). How transferable are features in deep neural networks? *Advances in Neural Information Processing Systems (NeurIPS),* 27. Available at: https://papers.nips.cc/paper/5347-how-transferable-are-features-in-deep-neural-networks
26. Pan, S. J., Yang, Q. (2010). A Survey on Transfer Learning. *IEEE Transactions on Knowledge and Data Engineering, 22 (10),* 1345–1359. https://doi.org/10.1109/tkde.2009.191
27. Woo, S., Park, J., Lee, J.-Y., Kweon, I. S. (2018). CBAM: Convolutional Block Attention Module. *Computer Vision – ECCV 2018,* 3–19. https://doi.org/10.1007/978-3-030-01234-2_1
28. Hu, J., Shen, L., Sun, G. (2018). Squeeze-and-Excitation Networks. *2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition.* Salt Lake City: IEEE, 7132–7141. https://doi.org/10.1109/cvpr.2018.00745
29. Wang, X., Girshick, R., Gupta, A., He, K. (2018). Non-local Neural Networks. *2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition.* Salt Lake City: IEEE, 7794–7803. https://doi.org/10.1109/cvpr.2018.00813
30. Al-Senaikh, R., Rubel, O. (2025). Predicting Filtered Image Quality Using Transfer Learning on Sentinel-1 Speckle Noise with DenseNet-121. *Ukrainian Journal of Remote Sensing, 12 (4),* 4–15. https://doi.org/10.36023/ujrs.2025.12.4.293
31. Wang, Z., Bovik, A. C., Sheikh, H. R., Simoncelli, E. P. (2004). Image quality assessment: from error visibility to structural similarity. *IEEE Transactions on Image Processing, 13 (4),* 600–612. https://doi.org/10.1109/tip.2003.819861
32. Wang, Z., Simoncelli, E. P., Bovik, A. C. (2003). Multiscale structural similarity for image quality assessment. *The Thrity-Seventh Asilomar Conference on Signals, Systems & Computers, 2003.* Pacific Grove: IEEE, 1398–1402. https://doi.org/10.1109/acssc.2003.1292216

33. Zhang, L., Zhang, L., Mou, X., Zhang, D. (2011). FSIM: A Feature Similarity Index for Image Quality Assessment. *IEEE Transactions on Image Processing, 20 (8),* 2378–2386. https://doi.org/10.1109/tip.2011.2109730
34. Reisenhofer, R., Bosse, S., Kutyniok, G., Wiegand, T. (2018). A Haar wavelet-based perceptual similarity index for image quality assessment. *Signal Processing: Image Communication, 61,* 33–43. https://doi.org/10.1016/j.image.2017.11.001
35. Nafchi, H. Z., Shahkolaei, A., Hedjam, R., Cheriet, M. (2016). Mean Deviation Similarity Index: Efficient and Reliable Full-Reference Image Quality Evaluator. *IEEE Access, 4,* 5579–5590. https://doi.org/10.1109/access.2016.2604042
36. Sattar, F., Floreby, L., Salomonsson, G., Lovstrom, B. (1997). Image enhancement based on a nonlinear multiscale method. *IEEE Transactions on Image Processing, 6 (6),* 888–895. https://doi.org/10.1109/83.585239
37. Abdou, I. E., Pratt, W. K. (1979). Quantitative design and evaluation of enhancement/thresholding edge detectors. *Proceedings of the IEEE, 67 (5),* 753–763. https://doi.org/10.1109/proc.1979.11325
38. Mathieu, M., Couprie, C., LeCun, Y. (2016). Deep multi-scale video prediction beyond mean square error. *Proceedings of the International Conference on Learning Representations (ICLR).* arXiv. https://doi.org/10.48550/arXiv.1511.05440

DOI: 10.15587/2706-5448.2026.358187

DEVELOPING A TASK ALLOCATION MODEL FOR REMOTE HEALTH MONITORING IN SMART CITIES CONSIDERING LATENCY, ENERGY CONSUMPTION, AND PRIVACY ON FOG NODES

pages 34–47

Ivan Shevtsov, *PhD Student, Department of Electronic Computers, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0003-0597-1589, e-mail: ivan.shevtsov@nure.ua*

Tetiana Fesenko, *Doctor of Technical Sciences, Professor, Department of Electronic Computers, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-9636-9598*

The object of the research is the processes of dynamic distribution of computing tasks in multi-level infrastructures of a smart city. The possibilities of integrating edge, fog, and cloud computing resources for the development of remote patient monitoring systems (Remote Patient Monitoring, RPM) were investigated. The study addresses the challenge of balancing the rapid processing of critical medical signals with the limited energy resources of mobile devices. In addition, the need to ensure the confidentiality of personal data when transferring tasks to third-party fog nodes was addressed through encryption, remote attestation mechanisms, and isolated execution environments.

A comprehensive system model was developed to describe the processes of performing RPM tasks (ECG classification, audio analysis). An offloading strategy was developed, based on a weighted linear to minimize energy consumption and delay. An architectural framework is proposed to ensure the confidentiality of data processing on uncontrolled fog nodes, through the use of Trusted Execution Environment (TEE) technologies and the deployment of Trusted Applications (TA). To validate the solutions, a series of simulations was conducted in the YAFS (Yet Another Fog Simulator) environment to compare Mobile, Hybrid, and Fog scenarios.

It was experimentally established that transitioning to a Fog-oriented strategy results in a radical reduction in the average system latency (from 0.57 s to 0.027–0.030 s). The load on the smartphone is reduced by more than 10 times (from 222–225 mWh to 20.3–20.4 mWh), and the autonomy of wearable sensors increases almost fivefold. It is proven that the use of fog computing provides stable Quality of Service (QoS) on equipment with lower power (500 MIPS). The integration of attestation procedures according to RATS (Remote ATtestation procedureS) standard is intended to enable verification of the integrity of the computing stack before the transfer of confidential data.

Keywords: smart city, fog computing, remote health monitoring, energy efficiency, confidentiality, data distribution.

References

1. Farias, F. A. C., Dagostini, C. M., Bicca, Y. A., Falavigna, V. F., Falavigna, A. (2020). Remote Patient Monitoring: A Systematic Review. *Telemedicine and E-Health, 26 (5),* 576–583. https://doi.org/10.1089/tmj.2019.0066
2. Malasinghe, L. P., Ramzan, N., Dahal, K. (2017). Remote patient monitoring: a comprehensive study. *Journal of Ambient Intelligence and Humanized Computing, 10 (1),* 57–76. https://doi.org/10.1007/s12652-017-0598-x
3. Dadkhah, M., Mehraeen, M., Rahimnia, F., Kimiafar, K. (2021). Use of Internet of Things for Chronic Disease Management. *Journal of Medical Signals & Sensors, 11 (2),* 138–157. https://doi.org/10.4103/jmss.jmss_13_20
4. HealthTrack SG (2026). *Health Promotion Board.* Available at: https://www.hpb.gov.sg/healthy-living/healthtracksg
5. Nanehkaran, Y. A., Licai, Z., Chen, J., Zhongpan, Q., Xiaofeng, Y., Navaei, Y. D. et al. (2022). Diagnosis of Chronic Diseases Based on Patients' Health Records in IoT Healthcare Using the Recommender System. *Wireless Communications and Mobile Computing, 2022 (1).* https://doi.org/10.1155/2022/5663001
6. Rodrigues, V. F., da Rosa Righi, R., da Costa, C. A., Zeiser, F. A., Eskofier, B., Maier, A. et al. (2023). Digital health in smart cities: Rethinking the remote health monitoring architecture on combining edge, fog, and cloud. *Health and Technology, 13 (3),* 449–472. https://doi.org/10.1007/s12553-023-00753-3
7. *Pro zatverdzhennia normatyvnykh dokumentiv shchodo zastosuvannia telemedytsyny u sferi okhorony zdorovia* (2015). Nakaz MOZ Ukrainy No. 681. 19.10.2015. Available at: https://zakon.rada.gov.ua/go/z1400-15 Last accessed: 03.02.2026
8. Byshenko, H., Avtomieienko, Y. (2024). Analysis of the government policy of the reform of electronic health care and medicine of Ukraine. *State Formation, 1 (35),* 290–304. https://doi.org/10.26565/1992-2337-2024-1-22
9. *OpenFog Reference Architecture for Fog Computing* (2017). OpenFog Consortium, 162. Available at: https://www.iiconsortium.org/pdf/OpenFog_Reference_Architecture_2_09_17.pdf
10. Muneeb, M., Ko, K.-M., Park, Y.-H. (2021). A Fog Computing Architecture with Multi-Layer for Computing-Intensive IoT Applications. *Applied Sciences, 11 (24),* 11585. https://doi.org/10.3390/app112411585
11. Hossam, H. S., Abdel-Galil, H., Belal, M. (2024). An energy-aware module placement strategy in fog-based healthcare monitoring systems. *Cluster Computing, 27 (6),* 7351–7372. https://doi.org/10.1007/s10586-024-04308-7
12. Mahmoud, M. M. E., Rodrigues, J. J. P. C., Saleem, K. (2019). Cloud of Things for Healthcare: A Survey from Energy Efficiency Perspective. *2019 International Conference on Computer and Information Sciences (ICCIS).* Sakaka: IEEE, 1–7. https://doi.org/10.1109/iccisci.2019.8716388
13. Dong, S., Tang, J., Abbas, K., Hou, R., Kamruzzaman, J., Rutkowski, L. et al. (2024). Task offloading strategies for mobile edge computing: A survey. *Computer Networks, 254,* 110791. https://doi.org/10.1016/j.comnet.2024.110791
14. Matrouk, K., Alatoun, K. (2021). Scheduling Algorithms in Fog Computing: A Survey. *International Journal of Networked and Distributed Computing, 9 (1),* 59. https://doi.org/10.2991/ijndc.k.210111.001
15. Adhikari, M., Gianey, H. (2019). Energy efficient offloading strategy in fog-cloud environment for IoT applications. *Internet of Things, 6,* 100053. https://doi.org/10.1016/j.iot.2019.100053
16. Fan, J., Liu, J., Chen, J., Yang, J. (2018). LPDC: Mobility-and Deadline-Aware Task Scheduling in Tiered IoT. *2018 IEEE 4th International Conference on Computer and Communications (ICCC).* Chengdu: IEEE, 857–863. https://doi.org/10.1109/compcomm.2018.8780904
17. Gao, X., Huang, X., Bian, S., Shao, Z., Yang, Y. (2020). PORA: Predictive Offloading and Resource Allocation in Dynamic Fog Computing Systems. *IEEE Internet of Things Journal, 7 (1),* 72–87. https://doi.org/10.1109/jiot.2019.2945066
18. Li, C., Tang, J., Zhang, Y., Yan, X., Luo, Y. (2019). Energy efficient computation offloading for nonorthogonal multiple access assisted mobile edge computing with energy harvesting devices. *Computer Networks, 164,* 106890. https://doi.org/10.1016/j.comnet.2019.106890
19. Shevtsov, I. (2024). Actual problems of remote patient monitoring. *Computer-Integrated Technologies: Education, Science, Production, (56),* 5–11. https://doi.org/10.36910/6775-2524-0560-2024-56-01
20. Shevtsov, I. (2024). The comparative analysis of the effectiveness of edge computing and fog computing in medical monitoring systems. *Information Technology and Society, 3 (14),* 44–53. https://doi.org/10.32689/maup.it.2024.3.6

ISSN-L 2664-9969; E-ISSN 2706-5448

21. Shevtsov, I. O. (2024). Hybrid computing models (fog and edge) for optimizing remote monitoring of chronic diseases. *Scientific Notes of Taurida National V. I. Vernadsky University. Series: Technical Sciences, 1 (5),* 343–353. https://doi.org/10.32782/2663-5941/2024.5.1/48
22. *TEE Internal Core API Specification*. GlobalPlatform. Available at: https://globalplatform.org/wp-content/uploads/2021/03/GPD_TEE_Internal_Core_API_Specification_v1.3.1_PublicRelease_CC.pdf
23. *RFC 9334: Remote ATtestation procedureS (RATS) Architecture*. IETF Datatracker. Available at: https://datatracker.ietf.org/doc/rfc9334/
24. Ménétrey, J., Göttel, C., Khurshid, A., Pasin, M., Felber, P., Schiavoni, V. et al. (2022). Attestation Mechanisms for Trusted Execution Environments Demystified. *Distributed Applications and Interoperable Systems.* Cham: Springer, 95–113. https://doi.org/10.1007/978-3-031-16092-9_7
25. Albahri, O. S., Albahri, A. S., Mohammed, K. I., Zaidan, A. A., Zaidan, B. B., Hashim, M. et al. (2018). Systematic Review of Real-time Remote Health Monitoring System in Triage and Priority-Based Sensor Technology: Taxonomy, Open Challenges, Motivation and Recommendations. *Journal of Medical Systems, 42 (5).* https://doi.org/10.1007/s10916-018-0943-4
26. Kraemer, F. A., Braten, A. E., Tamkittikhun, N., Palma, D. (2017). Fog Computing in Healthcare – A Review and Discussion. *IEEE Access, 5,* 9206–9222. https://doi.org/10.1109/access.2017.2704100
27. Skorin-Kapov, L., Matijasevic, M. (2010). Analysis of QoS Requirements for e-Health Services and Mapping to Evolved Packet System QoS Classes. International *Journal of Telemedicine and Applications, 2010,* 1–18. https://doi.org/10.1155/2010/628086
28. Gallego, J. R., Hernandez-Solana, A., Canales, M., Lafuente, J., Valdovinos, A., Fernandez-Navajas, J. (2005). Performance analysis of multiplexed medical data transmission for mobile emergency care over the UMTS channel. *IEEE Transactions on Information Technology in Biomedicine, 9 (1),* 13–22. https://doi.org/10.1109/titb.2004.838362
29. Ding, N., Wagner, D., Chen, X., Pathak, A., Hu, Y. C., Rice, A. (2013). Characterizing and modeling the impact of wireless signal strength on smartphone battery drain. *Proceedings of the ACM SIGMETRICS/International Conference on Measurement and Modeling of Computer Systems,* 29–40. https://doi.org/10.1145/2465529.2466586
30. Arm Firmware Framework for Arm A-profile (2025). *Arm Ltd.* Available at: https://developer.arm.com/-/cdn-downloads/permalink/Architectures/Armv9/DEN0077A_Firmware_Framework_Arm_A-profile_1.3_ALP1_ALP2_Diff.pdf
31. Pei, M., Tschofenig, H., Thaler, D. (2023). Trusted Execution Environment Provisioning (TEEP) Architecture. *Internet Engineering Task Force.* Available at: https://datatracker.ietf.org/doc/html/rfc9397
32. Remote Integrity Verification of Network Devices Containing Trusted Platform Modules (2024). *IETF.* Available at: https://datatracker.ietf.org/doc/rfc9683/ Last accessed: 27.03.2026
33. *Security-Enhanced Linux in Android.* Available at: https://source.android.com/docs/security/features/selinux/ Last accessed: 27.03.2026
34. Lera, I., Guerrero, C., Juiz, C. (2019). YAFS: A Simulator for IoT Scenarios in Fog Computing. *IEEE Access, 7,* 91745–91758. https://doi.org/10.1109/access.2019.2927895
35. Chen, X., Ding, N., Jindal, A., Hu, Y. C., Gupta, M., Vannithamby, R. (2015). Smartphone Energy Drain in the Wild. *ACM SIGMETRICS Performance Evaluation Review, 43 (1),* 151–164. https://doi.org/10.1145/2796314.2745875
36. Liu, X., Chen, T., Qian, F., Guo, Z., Lin, F. X., Wang, X. et al. (2017). Characterizing Smartwatch Usage in the Wild. *Proceedings of the 15th Annual International Conference on Mobile Systems, Applications, and Services,* 385–398. https://doi.org/10.1145/3081333.3081351
37. Abdelmoneem, R. M., Benslimane, A., Shaaban, E. (2020). Mobility-aware task scheduling in cloud-Fog IoT-based healthcare architectures. *Computer Networks, 179,* 107348. https://doi.org/10.1016/j.comnet.2020.107348
38. Dubey, H., Yang, J., Constant, N., Amiri, A. M., Yang, Q., Makodiya, K. (2015). Fog Data: Enhancing Telehealth Big Data Through Fog Computing. *Proceedings of the ASE BigData & SocialInformatics 2015,* 1–6. https://doi.org/10.1145/2818869.2818889
39. Dubey, H., Monteiro, A., Mahler, L., Yang, Q., Mankodiya, K. (2016). FIT: A Fog Computing Device for Speech TeleTreatments. *2016 IEEE International Conference on Smart Computing (SMARTCOMP).* https://doi.org/10.13140/RG.2.1.1023.8328
40. Rahmani, A. M., Gia, T. N., Negash, B., Anzanpour, A., Azimi, I., Jiang, M. et al. (2018). Exploiting smart e-Health gateways at the edge of healthcare Internet-of-Things: A fog computing approach. *Future Generation Computer Systems, 78,* 641–658. https://doi.org/10.1016/j.future.2017.02.014
41. Gia, T. N., Jiang, M., Rahmani, A.-M., Westerlund, T., Liljeberg, P., Tenhunen, H. (2015). Fog Computing in Healthcare Internet of Things: A Case Study on ECG Feature Extraction. *2015 IEEE International Conference on Computer and Information Technology; Ubiquitous Computing and Communications; Dependable, Autonomic and Secure Computing; Pervasive Intelligence and Computing.* Liverpool: IEEE, 356–363. https://doi.org/10.1109/cit/iucc/dasc/picom.2015.51
42. AMD Geode LX Processors Data Book (2009). *AMD.* Available at: https://www.amd.com/content/dam/amd/en/documents/archived-tech-docs/datasheets/33234H_LX_databook.pdf
43. Gomez, K., Rasheed, T., Riggio, R., Miorandi, D., Sengul, C., Bayer, N. (2013). Achilles and the tortoise: Power consumption in IEEE 802.11n and IEEE 802.11g networks. *2013 IEEE Online Conference on Green Communications (OnlineGreenComm). Piscataway: IEEE,* 20–26. https://doi.org/10.1109/onlinegreencom.2013.6731023
44. Bulić, P., Kojek, G., Biasizzo, A. (2019). Data Transmission Efficiency in Bluetooth Low Energy Versions. *Sensors, 19 (17),* 3746. https://doi.org/10.3390/s19173746

SYSTEMS AND CONTROL PROCESSES

DOI: 10.15587/2706-5448.2026.351953

DEVELOPMENT OF A HYBRID FUZZY DECISION SUPPORT SYSTEM FOR ASSESSING THE EFFECTIVENESS OF ARTILLERY FIRE IN CONDITIONS OF UNCERTAIN DISTURBANCES

pages 48–57

Maksym Maksymov, *Doctor of Technical Sciences, Professor, Department of Computer Technologies of Automation, Odesa Polytechnic National University, Odesa, Ukraine, ORCID: https://orcid.org/0000-0002-7536-2570*

Oleksiy Kozlov, *Doctor of Technical Sciences, Professor, Department of Intelligent Information Systems, Petro Mohyla Black Sea National University, Mykolaiv, Ukraine, e-mail: kozlov_ov@ukr.net, ORCID: https://orcid.org/0000-0003-2069-5578*

Oleksiy Maksymov, *PhD, Associate Professor, Department of Radio Engineering Armament, Communications and Robotics, Institute of Naval Forces of the National University "Odesa Maritime Academy", Odesa, Ukraine, ORCID: https://orcid.org/0000-0003-2504-0853*

Ruslan Riaboshapka, *Department of Computer Technologies of Automation, Odesa Polytechnic National University, Odesa, Ukraine, ORCID: https://orcid.org/0009-0004-2068-0290*

The object of research is the processes of determining the effectiveness of artillery fire under conditions of uncertain disturbances, which include wear of the gun barrel, deterioration of the quality of charges and shells of a certain batch. This work addresses the problem of ensuring the adequacy of assessing the effectiveness of artillery fire in cases where the parameters of the gun barrel, the quality of powder charges or shells deviate from the nominal values and are determined inaccurately.

The research used fuzzy logic methods to formalize decision-making processes under conditions of uncertainty, as well as methods of mathematical modeling and statistical analysis to simulate firing sequences and determine effectiveness estimates.

A hybrid fuzzy-logical decision support system (DSS) has been developed and tested, which allows for a comprehensive and highly accurate assessment of the effectiveness of artillery fire. When forming estimates, the DSS takes into account three key parameters that characterize the most significant sources of

uncertainty: barrel wear, deterioration of the quality of charges, deterioration of the quality of shells.

The results of computational experiments for various realistic artillery fire scenarios were obtained. In turn, artillery installations with initial barrel wear values of 0.1 and 0.25 were studied when using charges and shells of different quality. During the experiments, it was established that the proposed system provides an adequate, practically useful assessment of the fire efficiency of artillery installations under realistic conditions of uncertainty. In particular, the calculated efficiency values during the entire firing process changed by no more than 12% in the first three experiments and no more than 21% in the next three.

The developed DSS can be used in modern artillery complexes to increase the efficiency of making control decisions, reduce the proportion of misses, save scarce ammunition and reduce the risk of damage to equipment and personnel.

Keywords: artillery fire, efficiency assessment, barrel wear, decision support system, fuzzy logic.

References

1. Bartulović, V., Trzun, Z., Hoić, M. (2023). Use of Unmanned Aerial Vehicles in Support of Artillery Operations. *Strategos, 7 (1)*, 71–92. Available at: https://hrcak.srce.hr/305562
2. Chávez, K., Swed, O. (2023). Emulating underdogs: Tactical drones in the Russia-Ukraine war. *Contemporary Security Policy, 44 (4),* 592–605. https://doi.org/10.1080/13523260.2023.2257964
3. Oprean, L.-G. (2023). Artillery and Drone Action Issues in the War in Ukraine. *Scientific Bulletin, 28 (1),* 73–78. https://doi.org/10.2478/bsaft-2023-0008
4. Świętochowski, N. (2023). Field Artillery in the defensive war of Ukraine 2022–2023. Part I. Combat potential, tasks and tactics. *Scientific Journal of the Military University of Land Forces, 210 (4),* 341–358. https://doi.org/10.5604/01.3001.0054.1631
5. Świętochowski, N. (2024). Field Artillery in the defensive war of Ukraine 2022-2023. Part II. Methods of task implementation. *Scientific Journal of the Military University of Land Forces, 211 (1),* 57–76. https://doi.org/10.5604/01.3001.0054.4136
6. Brzozowski, M., Pakowski, M., Nowakowski, M., Myszka, M., Michalczewski, M. (2019). Radars with the function of detecting and tracking artillery shells – selected methods of field testing. *2019 IEEE 5th International Workshop on Metrology for AeroSpace (MetroAeroSpace).* Turin, 429–434. https://doi.org/10.1109/metroaerospace.2019.8869656
7. Kislitsyn, A., Dorofeev, N. (2021). Directions for the development of domestic self-propelled artillery systems based on the analysis of samples of artillery weapons from the leading countries of the world. *Social Development and Security, 11 (6),* 98–107. https://doi.org/10.33445/sds.2021.11.6.7
8. Ganjiyev, S. J., Usmonov, S. R., Karimov, A. Kh. (2023). Use of artillery in modern war: a brief analysis of the Ukrainian conflict. *Galaxy International Interdisciplinary Research Journal, 11 (3),* 118–121. Available at: https://internationaljournals.co.in/index.php/giirj/article/view/3646
9. Oprean, L.-G. (2020). Artillery from the Perspective of Firing Effects and Ensured Capabilities. *Scientific Bulletin, 25 (2),* 107–113. https://doi.org/10.2478/bsaft-2020-0015
10. Petlyuk, I., Shchavinsky, Y. (2021). Use of simulation modeling systems for determination of appropriate characteristics of prospective artillery weapons. *Collection of Scientific Works of Odesa Military Academy, 1 (14),* 11–22. https://doi.org/10.37129/2313-7509.2020.14.1.11-22
11. *STANAG 4355 The Lieske modified point mass and five degrees of freedom trajectory models – AOP-4355 EDITION A* (2022). Washington: United States Department of Defense. Available at: https://quicksearch.dla.mil/qsDocDetails.aspx?ident_number=107513
12. Zhuravlev, A., Orlov, S., Shuliakov, S. (2020). Mathematical model of the flight path of a projectile of a long-range artillery system. *Systems of Arms and Military Equipment, 3 (63),* 62–68. https://doi.org/10.30748/soivt.2020.63.09
13. Khalil, M. (2022). Study on modeling and production inaccuracies for artillery firing. *Archive of Mechanical Engineering, 69 (1),* 165–183. https://doi.org/10.24425/ame.2021.139802
14. Khudov, H., Yuzova, I., Lisohorskyi, B., Solomonenko, Y., Mykus, S., Irkha, A. et al. (2021). Development of methods for determining the coordinates of firing positions of roving mortars by a network of counter-battery radars. *EUREKA: Physics and Engineering, 3,* 140–150. https://doi.org/10.21303/2461-4262.2021.001821
15. Shim, Y., Atkinson, M. P. (2018). Analysis of artillery shoot-and-scoot tactics. *Naval Research Logistics, 65 (3),* 242–274. https://doi.org/10.1002/nav.21803
16. Grishyn, M., Maksymova, O., Kirkopulo, K., Klymchuk, O. (2025). Development of methods of artillery control for suppression of an enemy amphibious operation in video game simulations. *Technology Audit and Production Reserves, 1 (2 (81)),* 26–33. https://doi.org/10.15587/2706-5448.2025.321797
17. Wang, X., Li, X., Sun, Q., Xia, C., Chen, Y.-H. (2025). Improved Manta Ray Foraging Optimization for PID Control Parameter Tuning in Artillery Stabilization Systems. *Biomimetics, 10 (5),* 266. https://doi.org/10.3390/biomimetics10050266
18. Xiao, H., Yang, G., Ge, J. (2017). Surrogate-based multi-objective optimization of firing accuracy and firing stability for a towed artillery. *Journal of Vibroengineering, 19 (1),* 290–301. https://doi.org/10.21595/jve.2016.17108
19. Mady, M., Khalil, M., Yehia, M. (2020). Modelling and Production of artillery firing-tables: case-study. *Journal of Physics: Conference Series, 1507 (8),* 082043. https://doi.org/10.1088/1742-6596/1507/8/082043
20. Manev, N., Achkoski, J., Petreski, D., Gocic, M., Rancic, D. (2017). Smart field artillery information system: Model development with an emphasis on collisions in single sign-on authentication. *Vojnotehnicki Glasnik, 65 (2),* 442–463. https://doi.org/10.5937/vojtehg65-12703
21. Sun, Y., Zhang, S., Lu, G., Zhao, J., Tian, J., Xue, J. (2022). Research on a Simulation Algorithm for Artillery Firepower Assignment According to Region. *2022 3rd International Conference on Computer Science and Management Technology (ICCSMT). Shanghai,* 353–356. https://doi.org/10.1109/iccsmt58129.2022.00082
22. Wang, L., Chen, Z., Yang, G. (2021). An Uncertainty Analysis Method for Artillery Dynamics with Hybrid Stochastic and Interval Parameters. *Computer Modeling in Engineering & Sciences, 126 (2),* 479–503. https://doi.org/10.32604/cmes.2021.011954
23. Litsman, A., Nesterov, D. (2020) Definitions degree of influence of individual factors on mechanical equipment failure rate during artillery operation. *Collection of scientific works of the National Academy of the State Border Guard Service of Ukraine. Series: Military and Technical Sciences, 80,* 283–99. https://doi.org/10.32453/3.v80i2.204
24. Kumar, D., Kalra, S., Jha, M. S. (2022). A concise review on degradation of gun barrels and its health monitoring techniques. *Engineering Failure Analysis, 142,* 106791. https://doi.org/10.1016/j.engfailanal.2022.106791
25. Shen, C., Zhou, K., Lu, Y., Li, J. (2019). Modeling and simulation of bullet-barrel interaction process for the damaged gun barrel. *Defence Technology, 15 (6),* 972–986. https://doi.org/10.1016/j.dt.2019.07.009
26. Dobrynin, Y., Maksymov, M., Boltenkov, V. (2020). Development of a method for determining the wear of artillery barrels by acoustic fields of shots. *Eastern-European Journal of Enterprise Technologies, 3 (5 (105)),* 6–18. https://doi.org/10.15587/1729-4061.2020.206114
27. Boltenkov, V., Brunetkin, O., Dobrynin, Y., Maksymova, O., Kuzmenko, V., Gultsov, P. et al. (2021). Devising a method for improving the efficiency of artillery shooting based on the Markov model. *Eastern-European Journal of Enterprise Technologies, 6 (3 (114)),* 6–17. https://doi.org/10.15587/1729-4061.2021.245854
28. Toshev, O., Kirkopulo, K., Klymchuk, O., Maksymov, M. (2025). Optimization of ammunition preparation strategies for modern artillery operations in computer simulation. *Technology Audit and Production Reserves, 2 (2 (82)),* 50–57. https://doi.org/10.15587/2706-5448.2025.326225
29. Mendel, J. M. (2024). *Explainable Uncertain Rule-Based Fuzzy Systems.* Cham: Springer, 580. https://doi.org/10.1007/978-3-031-35378-9
30. Kondratenko, Y., Kozlov, O., Zheng, Y., Wang, J., Kuzmenko, V., Aleksieieva, A. B. (2024). Bio-inspired optimization of fuzzy control system for inspection robotic platform: comparative analysis of hybrid swarm methods. *CEUR Workshop Proceedings, 3711,* 109–123. Available at: https://ceur-ws.org/Vol-3711/paper7.pdf
31. Skakodub, O., Kozlov, O., Kondratenko, Y. (2021). Optimization of Linguistic Terms' Shapes and Parameters: Fuzzy Control System of a Quadrotor Drone. *2021 11th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS),* 566–571. https://doi.org/10.1109/idaacs53288.2021.9660926
32. Kozlov, O. (2021). Information Technology for Designing Rule bases of Fuzzy Systems using Ant Colony Optimization. *International Journal of Computing, 20 (4),* 471–486. https://doi.org/10.47839/ijc.20.4.2434
33. Congxiang, L., Kozlov, O., Kondratenko, G., Aleksieieva, A. (2024). Decision Support System for Maintenance Planning of Vortex Electrostatic Precipitators Based on IoT and AI Techniques. *Research Tendencies and Prospect Domains*

ISSN-L 2664-9969; E-ISSN 2706-5448

for AI Development and Implementation. New York: River Publishers, 87–105. https://doi.org/10.1201/9788770046947-5

34. Solesvik, M., Kondratenko, Y., Kondratenko, G., Sidenko, I., Kharchenko, V., Boyarchuk, A. (2017). Fuzzy decision support systems in marine practice. *2017 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE),* 1–6. https://doi.org/10.1109/fuzz-ieee.2017.8015471
35. Maksymov, M., Kozlov, O., Dobrynin, Y., Sidelnykov, O., Kapalin, V., Vodichev, V. (2025). Verification of artillery systems' shots: selection of the most appropriate sensors based on the fuzzy evaluation model. *EUREKA: Physics and Engineering, 2,* 199–210. https://doi.org/10.21303/2461-4262.2025.003662
36. Pedrycz, W., Li, K., Reformat, M. (2015). Evolutionary Reduction of Fuzzy Rule-Based Models. *Fifty Years of Fuzzy Logic and Its Applications.* Cham: Springer, 459–481. https://doi.org/10.1007/978-3-319-19683-1_23
37. Volna, E. (2017). Fuzzy-based decision strategy in real-time strategic games. *AIP Conference Proceedings, 1906,* 080002. https://doi.org/10.1063/1.5012346
38. Werners, B., Kondratenko, Y. (2017). Alternative Fuzzy Approaches for Efficiently Solving the Capacitated Vehicle Routing Problem in Conditions of Uncertain Demands. *Complex Systems: Solutions and Challenges in Economics, Management and Engineering.* Cham: Springer, 521–543. https://doi.org/10.1007/978-3-319-69989-9_31
39. Raskin, L., Sira, O. (2020). Development of methods for extension of the conceptual and analytical framework of the fuzzy set theory. *Eastern-European Journal of Enterprise Technologies, 6 (4 (108)),* 14–21. https://doi.org/10.15587/1729-4061.2020.217630
40. Kozlov, O. V. (2021). Optimal Selection of Membership Functions Types for Fuzzy Control and Decision Making Systems. *CEUR Workshop Proceedings, 2853,* 238–247. Available at: https://ceur-ws.org/Vol-2853/paper22.pdf
41. Kozlov, O., Kondratenko, G., Aleksieieva, A., Maksymov, M. (2025). Complex Structural-Parametric Optimization of Fuzzy Control Systems Based on Bioinspired Algorithms. *CEUR Workshop Proceedings, 4048,* 1–15. Available at: https://ceur-ws.org/Vol-4048/paper01.pdf
42. Kozlov, O., Kondratenko, G., Aleksieieva, A., Maksymov, M., Tarakhtij, O. (2024). Swarm optimization of the drone's intelligent control system: comparative analysis of hybrid techniques. *CEUR Workshop Proceedings, 3790,* 1–12. https://ceur-ws.org/Vol-3790/paper01.pdf
43. Maksymov, M., Kozlov, O., Shynder, A., Maksymova, O., Aleksieieva, A. (2025). Development of mathematical models for temperature control objects in thermal destruction systems based on transient process identification. *EUREKA: Physics and Engineering, 3,* 207–220. https://doi.org/10.21303/2461-4262.2025.003802

DOI: 10.15587/2706-5448.2026.355420

IDENTIFICATION OF THE CHARACTERISTICS OF CONTROL SIGNAL GENERATION FOR IMPLEMENTING THE TRACTION MODE OF A PHYSICAL MODEL OF MAGNETIC LEVITATION TRANSPORT

pages 58–65

Yehor Chupryna, *PhD Student, Department of Electrical Engineering and Electromechanics, Ukrainian State University of Science and Technologies, Dnipro, Ukraine, e-mail: nesty.lords@gmail.com, ORCID: https://orcid.org/0000-0002-0986-1283*

Andrii Mukha, *Doctor of Technical Sciences, Professor, Leading Researcher, Department of Control Systems in Vehicles, Institute of Transport Systems and Technologies of the National Academy of Sciences of Ukraine, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0002-5629-4058*

Serhii Plaksin, *Doctor of Physical and Mathematical Sciences, Senior Researcher, Department of Control Systems in Vehicles, Institute of Transport Systems and Technologies of the National Academy of Sciences of Ukraine, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0001-8302-0186*

Dmytro Ustymenko, *PhD, Associate Professor, Senior Researcher, Department of Control Systems in Vehicles, Institute of Transport Systems and Technologies of the National Academy of Sciences of Ukraine, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0003-2984-4381*

Oleh Bondar, *PhD, Associate Professor, Department of Electrical Engineering and Electromechanics, Ukrainian State University of Science and Technologies, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0003-3884-5589*

Oksana Marenych, *PhD, Associate Professor, Department of Electrical Engineering and Electromechanics, Ukrainian State University of Science and Technologies, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0003-3602-5851*

Oleksandr Holota, *PhD Student, First-class Engineer, Department of Control Systems in Vehicles, Institute of Transport Systems and Technologies of the National Academy of Sciences of Ukraine, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0002-0282-2767*

Andrii Antoniuk, *PhD Student, Department of Electrical Engineering and Electromechanics, Ukrainian State University of Science and Technologies, Dnipro, Ukraine, ORCID: https://orcid.org/0009-0004-9101-1537*

The object of this research is the process of generating control signals for implementing the traction mode of a physical model of a magnetic levitation transport system.

The problem that was solved was the formation of control signals for implementing the traction mode of the physical model and the method of switching track coils.

In the experimental physical model, the traction mode is implemented by control signals formed on the basis of the angular values of the encoder corresponding to the position of the crew. Based on these signals, the traction modules of the stand are commutated to ensure the necessary polarity of the magnetic field, which creates traction force and ensures the movement of the crew past the section.

The implementation of the traction mode requires accurate determination of the position of the crew relative to the track structure. For this purpose, an encoder signal is used, the information from which is processed in the control unit of the track structure section. A schematic solution and an algorithm for the operation of this unit for a physical model are proposed.

The search for an element base for control boards requires performance verification. From several variations of boards, the one that implements the proposed algorithm with satisfactory process quality was selected.

The main research method is an experiment conducted on a physical model stand. A switching control unit for the traction section of the physical model stand has been developed and implemented, which includes: control boards, a motherboard and software on the Arduino platform. A board option with three DC-DC converters was selected, which ensured stable operation of the traction section.

The main characteristics of electrodynamic processes were obtained, namely: moments of polarity switching of modules, changes in voltage, current and power during the passage of the crew past the section. The switching range of the traction section is approximately five seconds.

The results obtained create the prerequisites for the development of experimental stands and models of maglev transport for further research into traction modes.

Keywords: magnetic levitation transport, traction module, physical model, control boards, electrodynamic processes, traction mode.

References

1. Holota, O., Ustymenko, D., Mukha, A., Plaksin, S., Chupryna, Y. (2025). Determination of the inductiveness of a physical model of track coils for high-speed transport. *Technology Audit and Production Reserves, 3 (1 (83)),* 52–57. https://doi.org/10.15587/2706-5448.2025.331995
2. Holota, O. O., Mukha, A. M., Ustymenko, D. V., Plaksin, S. V. (2024). Investigation of Processes in the Traction Capacitor Circuit of the Model of High-Speed Magnetolevitation Transport. *Science and Transport Progress, 1 (105),* 30–41. https://doi.org/10.15802/stp2024/301521
3. Holota, O. (2025). Research of control modes of the track structure of a physical model of maglev transport. *Transport Systems and Transportation Technologies, 30,* 29–36. https://doi.org/10.15802/tstt2025/340121

4. Lee, H.-W., Kim, K.-C., Lee, J. (2006). Review of maglev train technologies. *IEEE Transactions on Magnetics, 42 (7),* 1917–1925. https://doi.org/10.1109/tmag.2006.875842
5. He, X. (2025). Magnetic Levitation: Electrodynamic Suspension and Electromagnetic Suspension Technologies. *Applied and Computational Engineering, 192 (1),* 45–51. https://doi.org/10.54254/2755-2721/2026.ka27983
6. Gao, H., Shi, T., Gao, X., Lei, Y., Yan, D., Guo, L., Yan, Y. (2024). Electromagnetic characteristic analysis and design of a linear motor used for ultra-high-speed EMS maglev train. *Science China Technological Sciences, 67 (6),* 1957–1973. https://doi.org/10.1007/s11431-023-2558-9
7. Zhu, Q., Wang, S.-M., Ni, Y.-Q. (2024). A Review of Levitation Control Methods for Low- and Medium-Speed Maglev Systems. *Buildings, 14 (3),* 837. https://doi.org/10.3390/buildings14030837
8. Kuptsov, V., Fajri, P., Rasheduzzaman, Md., Magdaleno-Adame, S., Hadziristic, K. (2022). Combined Propulsion and Levitation Control for Maglev/Hyperloop Systems Utilizing Asymmetric Double-Sided Linear Induction Motors. *Machines, 10 (2),* 131. https://doi.org/10.3390/machines10020131
9. Deng, Z., Shi, H., Chen, Y., Ke, Z., Liang, L., Liu, X., Li, K., Zhang, W. (2025). A cost-effective linear propulsion system featuring PMEDW for HTS maglev vehicle: design, implementation, and dynamic test. *Measurement, 240,* 115618. https://doi.org/10.1016/j.measurement.2024.115618
10. Liu, D., Wu, D., Xu, J., Li, Y., Gul, M. Z., Ni, F. (2025). Machine Learning in Maglev Transportation Systems: Review and Prospects. *Actuators, 14 (12),* 576. https://doi.org/10.3390/act14120576
11. Plaksin, S., Mukha, A., Ustymenko, D., Shkil, Y., Holota, O., Chupryna, Y. (2022). 2-mode traction-levitation module of a promising magnetic-levitation transport system. *Electromechanical and Energy Saving Systems, 58 (2),* 56–65. https://doi.org/10.30929/2072-2052.2022.2.58.49-53
12. Hovorov, P., Khvorost, M., Kindinova, A. (2023). Increasing the Efficiency of Solar Power Plants Based on the Use of Voltage Booster Transformers. *2023 IEEE 5th International Conference on Modern Electrical and Energy System (MEES),* 1–5. https://doi.org/10.1109/mees61502.2023.10402408
13. Fu, C., Sun, P., Wang, Q., Feng, X. (2025). Modeling and energy-saving operation optimization of high-speed maglev trains. *Journal of Cleaner Production, 519,* 146031. https://doi.org/10.1016/j.jclepro.2025.146031
14. Lai, Q., Liu, J., Haghani, A., Meng, L., Wang, Y. (2020). Energy-efficient speed profile optimization for medium-speed maglev trains. *Transportation Research Part E: Logistics and Transportation Review, 141,* 102007. https://doi.org/10.1016/j.tre.2020.102007

DOI: 10.15587/2706-5448.2026.355663

DEVELOPMENT OF A PARAMETER-EFFICIENT METHOD FOR BIOMEDICAL IMAGE SYNTHESIS BY SUBSTITUTING TEXT CONDITIONING WITH PATHOLOGY FOUNDATION MODEL EMBEDDINGS IN LATENT DIFFUSION

pages 66–75

Sergii Kuzmin, *PhD Student, Department of Automated Control Systems, Lviv Polytechnic National University, Lviv, Ukraine, e-mail: kuzminos22@gmail.com, ORCID: https://orcid.org/0009-0001-7182-2883*

Oleh Berezsky, *Doctor of Technical Sciences, Professor, Department of Computer Engineering, West Ukrainian National University, Ternopil, Ukraine, ORCID: https:/orcid.org/0000-0001-9931-4154*

The object of research is the process of synthesizing patches of histopathological images conditioned by embeddings of the pathology foundation model. One of the key problems is that existing approaches to diffusion synthesis either rely on text conditioning via CLIP encoders, which lack morphological understanding, or require full retraining of the generative base model, which requires significant computational resources.

The research used a parameter-efficient adaptation of the previously trained latent diffusion model using low-rank adaptation (LoRA) of the U-Net attention layers in combination with a training MLP projector that reflects the embeddings of the pathology foundation model UNI2-h in the conditioning space of the cross-attention mechanism. Ablation studies of 12 configurations were conducted varying the adapter rank, the number of conditioning tokens, and the projector architecture.

It is confirmed that embeddings of the pathology foundation model can effectively replace text conditioning for the synthesis of histopathology images in a parameter-efficient mode. The optimal configuration achieved FID 77.59 on the validation set and FID 84.17 on the test set when training only 5.53 million parameters, which is 0.64% of the parameters of the base model. This is due to the fact that the proposed method has a number of characteristic features, in particular: embeddings of the pathology foundation model provide morphologically richer conditioning than CLIP-based text representations, and low rank adaptation limits the trainable space to the conditioning pathway.

This provides the possibility of generating histopathology images without text annotations and without full retraining of the model using approximately 12 GB of video memory. Compared to the previous text-conditioned approach on the same dataset, which demonstrated class-wise FID values in the range of 113 to 138, the embedding conditioning method provides significantly higher generation quality while maintaining parameter efficiency.

Keywords: latent diffusion models, pathology foundation models, histopathology image synthesis, medical image generation.

References

1. Litjens, G., Bandi, P., Ehteshami Bejnordi, B., Geessink, O., Balkenhol, M., Bult, P. et al. (2018). 1399 H&E-stained sentinel lymph node sections of breast cancer patients: the CAMELYON dataset. *GigaScience, 7 (6).* https://doi.org/10.1093/gigascience/giy065
2. Walsh, E., Orsi, N. M. (2024). The current troubled state of the global pathology workforce: a concise review. *Diagnostic Pathology, 19 (1).* https://doi.org/10.1186/s13000-024-01590-2
3. Guan, H., Yap, P.-T., Bozoki, A., Liu, M. (2024). Federated learning for medical image analysis: A survey. *Pattern Recognition, 151,* 110424. https://doi.org/10.1016/j.patcog.2024.110424
4. Zhang, Y., Kang, B., Hooi, B., Yan, S., Feng, J. (2023). Deep Long-Tailed Learning: A Survey. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 45 (9),* 10795–10816. https://doi.org/10.1109/tpami.2023.3268118
5. Campanella, G., Hanna, M. G., Geneslaw, L., Miraflor, A., Werneck Krauss Silva, V., Busam, K. J. et al. (2019). Clinical-grade computational pathology using weakly supervised deep learning on whole slide images. *Nature Medicine, 25 (8),* 1301–1309. https://doi.org/10.1038/s41591-019-0508-1
6. Jose, L., Liu, S., Russo, C., Nadort, A., Di Ieva, A. (2021). Generative Adversarial Networks in Digital Pathology and Histopathological Image Processing: A Review. *Journal of Pathology Informatics, 12 (1),* 43. https://doi.org/10.4103/jpi.jpi_103_20
7. Saad, M. M., O'Reilly, R., Rehmani, M. H. (2024). A survey on training challenges in generative adversarial networks for biomedical image analysis. *Artificial Intelligence Review, 57 (2).* https://doi.org/10.1007/s10462-023-10624-y
8. Dhariwal, P., Nichol, A. (2021). Diffusion models beat GANs on image synthesis. *arXiv:2105.05233.* https://doi.org/10.48550/arXiv.2105.05233
9. Rombach, R., Blattmann, A., Lorenz, D., Esser, P., Ommer, B. (2022). High-Resolution Image Synthesis with Latent Diffusion Models. *2022 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR),* 10674–10685. https://doi.org/10.1109/cvpr52688.2022.01042
10. Radford, A., Kim, J. W., Hallacy, C., Ramesh, A., Goh, G., Agarwal, S. et al. (2021). Learning transferable visual models from natural language supervision. *arXiv:2103.00020.* https://doi.org/10.48550/arXiv.2103.00020
11. Chen, R. J., Ding, T., Lu, M. Y., Williamson, D. F. K., Jaume, G., Song, A. H. et al. (2024). Towards a general-purpose foundation model for computational pathology. *Nature Medicine, 30,* 850–862. https://doi.org/10.1038/s41591-024-02857-3
12. Yellapragada, S., Graikos, A., Prasanna, P., Kurc, T., Saltz, J., Samaras, D. (2024). PathLDM: Text conditioned Latent Diffusion Model for Histopathology. *2024 IEEE/CVF Winter Conference on Applications of Computer Vision (WACV),* 5170–5179. https://doi.org/10.1109/wacv57701.2024.00510
13. Graikos, A., Yellapragada, S., Le, M.-Q., Kapse, S., Prasanna, P., Saltz, J., Samaras, D. (2024). Learned Representation-Guided Diffusion Models for Large-Image Generation. *2024 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR),* 8532–8542. https://doi.org/10.1109/cvpr52733.2024.00815
14. Boada, J. C., Umer, R. M., Marr, C. (2025). CytoDiff: AI-Driven Cytomorphology Image Synthesis for Medical Diagnostics. *2025 IEEE/CVF International Confer-*

ISSN-L 2664-9969; E-ISSN 2706-5448

ence on Computer Vision Workshops (ICCVW), 1136–1144. https://doi.org/10.1109/iccvw69036.2025.00122
15. Hu, E. J., Shen, Y., Wallis, P., Allen-Zhu, Z., Li, Y., Wang, S. et al. (2022). LoRA: low-rank adaptation of large language models. *arXiv:2106.09685.* https://doi.org/10.48550/arXiv.2106.09685
16. Ho, J., Jain, A., Abbeel, P. (2020). Denoising diffusion probabilistic models. *Proceedings of the 34th International Conference on Neural Information Processing Systems, 34,* 6840–6851. https://doi.org/10.48550/arXiv.2006.11239
17. Yellapragada, S., Graikos, A., Triaridis, K., Prasanna, P., Gupta, R., Saltz, J., Samaras, D. (2025). ZoomLDM: Latent Diffusion Model for multi-scale image generation. *2025 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR),* 23453–23463. https://doi.org/10.1109/cvpr52734.2025.02184
18. Mao, Y., Li, H., Pang, W., Papanastasiou, G., Yang, G., Wang, C. (2024). SeLoRA: self-expanding low-rank adaptation of latent diffusion model for medical image synthesis. *arXiv:2408.07196.* https://doi.org/10.48550/arXiv.2408.07196
19. Berezsky, O., Melnyk, G., Liashchynskyi, P., Pitsun, O.; Babichev, S., Lytvynenko, V. (Eds.) (2025). Biomedical Image Datasets. *Lecture Notes on Data Engineering and Communications Technologies, vol 244.* Cham: Springer, 61–82. https://doi.org/10.1007/978-3-031-88483-2_3
20. Berezsky, O., Liashchynskyi, P., Melnyk, G., Dombrovskyi, M., Berezkyi, M. (2024). Synthesis of biomedical images based on generative intelligence tools. *Proceedings of the 7th International Conference on Informatics & Data-Driven Medicine (IDDM 2024). Birmingham. CEUR Workshop Proceedings, 3892,* 349–362. Available at: https://ceur-ws.org/Vol-3892/paper23.pdf
21. Berezsky, O., Liashchynskyi, P., Pitsun, O., Izonin, I. (2024). Synthesis of Convolutional Neural Network architectures for biomedical image classification. *Biomedical Signal Processing and Control, 95,* 106325. https://doi.org/10.1016/j.bspc.2024.106325
22. Berezsky, O., Liashchynskyi, P., Pitsun, O., Melnyk, G. (2024). Method and Software Tool for Generating Artificial Databases of Biomedical Images Based on Deep Neural Networks. *6th International Conference on Informatics & Data-Driven Medicine Bratislava.* https://doi.org/10.48550/arXiv.2405.16119
23. Kuzmin, S., Berezsky, O. (2025). Analysis of diffusion models and biomedical image generation tools. *Computer Systems and Information Technologies, 2,* 8–19. https://doi.org/10.31891/csit-2025-2-1
24. Zhu, C., Chen, W., Peng, T., Wang, Y., Jin, M. (2022). Hard Sample Aware Noise Robust Learning for Histopathology Image Classification. *IEEE Transactions on Medical Imaging, 41 (4),* 881–894. https://doi.org/10.1109/tmi.2021.3125459
25. Ho, J., Salimans, T. (2022). *Classifier-free diffusion guidance.* arXiv:2207.12598. https://doi.org/10.48550/arXiv.2207.12598
26. Heusel, M., Ramsauer, H., Unterthiner, T., Nessler, B., Hochreiter, S. (2017). GANs trained by a two time-scale update rule converge to a local Nash equilibrium. *31st Conference on Neural Information Processing Systems (NIPS 2017).* Long Beac. https://doi.org/10.48550/arXiv.1706.08500
27. Bińkowski, M., Sutherland, D. J., Arbel, M., Gretton, A. (2018). Demystifying MMD GANs. *International Conference on Learning Representations (ICLR).* https://doi.org/10.48550/arXiv.1801.01401

DOI: 10.15587/2706-5448.2026.356296

IDENTIFICATION OF INFLUENTIAL RAILWAY STATIONS USING LOCAL SYNCHRONIZATION IN COMPLEX NETWORKS OF TRAIN FORMATION PLANS

pages 76–83

Andrii Kyman, *PhD, Associate Professor, Department of Freight and Commercial Operations, Ukrainian State University of Railway Transport, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-4000-3287*

Andrii Prokhorchenko, *Doctor of Technical Sciences, Professor, Department of Operations Management, Ukrainian State University of Railway Transport, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0003-3123-5024*

Mykhailo Kravchenko, *Doctor of Philosophy (PhD), Department of Operations Management, Ukrainian State University of Railway Transport, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-7445-8952*

Mykhailo Muzykin, *PhD, Associate Professor, Department of Transport Technologies and International Logistics, University of Customs and Finance, Dnipro, Ukraine, e-mail: mihailmuzykin@gmail.com, ORCID: https://orcid.org/0000-0003-2938-7061*

The object of research is the dynamic processes of coordination of interactions among railway stations within the train formation plan (TFP) network. The problem addressed lies in the insufficiency of traditional topological approaches for identifying influential stations in railway networks. An analysis based solely on degree centrality indicators does not allow the detection of hidden sources of dynamic vulnerability.

An approach is proposed for identifying critical stations and links that reduce the coherence of the TFP network, based on the investigation of local synchronization characteristics. A procedure for analyzing station influence is developed through the integration of centrality measures with a local order parameter calculated using the Kuramoto model. The application of the proposed procedure to real TFP networks representing different structural states revealed changes in local synchronization characteristics. The average value of the local order parameter within the largest strongly connected component decreased from 0.6664 to 0.4976. It was established that topologically significant marshalling stations may exhibit low values of the local order parameter, that is, they may remain locally desynchronized from their immediate neighborhood. It is substantiated that the key factor reducing local synchronization of stations is the phase heterogeneity of their nearest neighborhood, in particular the presence of adjacent stations belonging to other phase clusters.

The practical application of the results is possible provided that the TFP is formalized as a network model and data on the structure of train assignments are available. The proposed approach can be used to support managerial decision-making regarding adjustments to the TFP, improvement of station coordination, and enhancement of the resilience of the railway system under structural changes.

Keywords: railway, wagon flow, railway stations, train formation plan, Kuramoto model, local synchronization.

References

1. Butko, T., Prokhorchenko, A., Kyman, A. (2015). Formalization of the technology of arranging tactical group trains. *Eastern-European Journal of Enterprise Technologies, 4 (3 (76)),* 38–43. https://doi.org/10.15587/1729-4061.2015.47886
2. Cargo transportation. *JSC Ukrzaliznytsia.* Available at: https://www.uz.gov.ua/cargo_transportation
3. Zahorianskyi, V., Zahorianska, O., Moroz, M., Moroz, O. (2022). Development of a Model for Minimizing the Energy Costs of the Transport and Technological Complex. *2022 IEEE 4th International Conference on Modern Electrical and Energy System (MEES),* 1–5. https://doi.org/10.1109/mees58014.2022.10005635
4. Zhao, Y., Li, D., Yin, Y., Zhao, X. (2023). Integrated optimization of demand-driven timetable, train formation plan and rolling stock circulation with variable running times and dwell times. *Transportation Research Part E: Logistics and Transportation Review, 171,* 103035. https://doi.org/10.1016/j.tre.2023.103035
5. Prokhorchenko, A., Kyman, A., Kravchenko, M., Medvediev, I. (2026). Structural evolution of Ukraine's freight rail transportation system under partial network loss. *Journal of Transport Geography, 131,* 104554. https://doi.org/10.1016/j.jtrangeo.2026.104554
6. Wang, W., Du, W., Liu, K., Tong, L. (2022). The Evolution of China's Railway Network (CRN) 1999–2019: Urbanization Impact and Regional Connectivity. *Urban Rail Transit, 8 (2),* 134–145. https://doi.org/10.1007/s40864-022-00168-9
7. Panchenko, A., Prokhorchenko, A., Panchenko, S., Dekarchuk, O., Gurin, D., Medvediev, I. (2020). Predicting the estimated time of cargo dispatch from a marshaling yard. *Eastern-European Journal of Enterprise Technologies, 4 (3 (106)),* 6–15. https://doi.org/10.15587/1729-4061.2020.209912
8. Yanovska, V., Król, M., Pittman, R. (2025). The logistics of grain exports from wartime Ukraine: What are the highest priority areas to Address? *Transportation Research Interdisciplinary Perspectives, 30,* 101363. https://doi.org/10.1016/j.trip.2025.101363
9. Arenas, A., Díaz-Guilera, A., Kurths, J., Moreno, Y., Zhou, C. (2008). Synchronization in complex networks. *Physics Reports, 469 (3),* 93–153. https://doi.org/10.1016/j.physrep.2008.09.002

10. Kuramoto, Y.; Araki, H. (Ed.) (1975). Self-entrainment of a population of coupled non-linear oscillators. *International Symposium on Mathematical Problems in Theoretical Physics*. Springer, 420–422. https://doi.org/10.1007/bfb0013365
11. Acebrón, J. A., Bonilla, L. L., Pérez Vicente, C. J., Ritort, F., Spigler, R. (2005). The Kuramoto model: A simple paradigm for synchronization phenomena. *Reviews of Modern Physics, 77 (1),* 137–185. https://doi.org/10.1103/revmodphys.77.137
12. Tang, Y., Qian, F., Gao, H., Kurths, J. (2014). Synchronization in complex networks and its application – A survey of recent advances and challenges. *Annual Reviews in Control, 38 (2),* 184–198. https://doi.org/10.1016/j.arcontrol.2014.09.003
13. Motter, A. E., Myers, S. A., Anghel, M., Nishikawa, T. (2013). Spontaneous synchrony in power-grid networks. *Nature Physics, 9 (3),* 191–197. https://doi.org/10.1038/nphys2535
14. Shahal, S., Wurzberg, A., Sibony, I., Duadi, H., Shniderman, E., Weymouth, D. et al. (2020). Synchronization of complex human networks. *Nature Communications, 11 (1).* https://doi.org/10.1038/s41467-020-17540-7
15. Rodriguez, M., Fathy, H. K. (2022). Distributed Kuramoto Self-Synchronization of Vehicle Speed Trajectories in Traffic Networks. *IEEE Transactions on Intelligent Transportation Systems, 23 (7),* 6786–6796. https://doi.org/10.1109/tits.2021.3062178
16. Kyman, A., Prokhorchenko, A., Panchenko, A., Zolotarov, S., Kravchenko, M., Prokhorchenko, H., Orda, O. (2025). Devising of a method for analysing the propagation speed of car flows in a train formation plan based on synchronisation theory in complex networks. *Eastern-European Journal of Enterprise Technologies, 5 (3 (137)),* 56–67. https://doi.org/10.15587/1729-4061.2025.341559
17. Zabaleta-Ortega, Á., Masoller, C., Guzmán-Vargas, L. (2025). Unveiling synchronization transitions in networks of coupled oscillators through persistent homology of local structures. *Scientific Reports, 15 (1).* https://doi.org/10.1038/s41598-025-27083-w
18. Chen, J., Cao, J., Huang, W. (2023). Traffic-driven explosive synchronization with adaptive local routing in complex networks. *Chaos, Solitons & Fractals, 168,* 113142. https://doi.org/10.1016/j.chaos.2023.113142
19. Li, X., Ye, J., Ji, P. (2026). The impact of topological heterogeneity on local synchronization in complex networks. *Chaos, Solitons & Fractals, 204,* 117745. https://doi.org/10.1016/j.chaos.2025.117745
20. Rodrigues, F. A., Peron, T. K. DM., Ji, P., Kurths, J. (2016). The Kuramoto model in complex networks. *Physics Reports, 610,* 1–98. https://doi.org/10.1016/j.physrep.2015.10.008
21. Newman, J., Rowland Adams, J., Clemson, P. T., Stefanovska, A. (2025). An order parameter for synchronisation of angular velocities. *The European Physical Journal Special Topics.* https://doi.org/10.1140/epjs/s11734-025-01984-3
22. Lind, P. G., Gallas, J. A. C., Herrmann, H. J.; Ausloos, M., Dirickx, M. (Eds.) (2006). Coherence in Complex Networks of Oscillators. *The Logistic Map and the Route to Chaos.* Springer, 77–97. https://doi.org/10.1007/3-540-32023-7_5
23. Zhou, M., Li, X., Xiong, W., Wu, X., Liao, H. (2019). Cooperation of local and collective synchronization in complex networks. *Physica A: Statistical Mechanics and Its Applications, 526,* 120963. https://doi.org/10.1016/j.physa.2019.04.199
24. Strogatz, S. H. (2000). From Kuramoto to Crawford: exploring the onset of synchronization in populations of coupled oscillators. *Physica D: Nonlinear Phenomena, 143 (1–4),* 1–20. https://doi.org/10.1016/s0167-2789(00)00094-4

DOI: 10.15587/2706-5448.2026.356834

DEVELOPMENT OF A METHOD FOR ADAPTATION OF RADIOACOUSTIC SOUNDING SYSTEMS OF THE ATMOSPHERE TO THE METEOROLOGICAL CONDITIONS

pages 84–91

Volodymyr Kartashov, *Doctor of Technical Sciences, Professor, Head of Department of Media Engineering and Information Radioelectronic Systems, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-8335-5373, e-mail: volodymyr.kartashov@nure.ua*

Igor Kondrashov, *PhD Student, Department of Media Engineering and Information Radioelectronic Systems, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, ORCID: https://orcid.org/0009-0008-0359-4605*

Oleksandr Kartashov, *PhD Student, Department of Media Engineering and Information Radioelectronic Systems, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, ORCID: https://orcid.org/0009-0002-7569-0264*

Roman Bobniev, *PhD Student, Department of Media Engineering and Information Radioelectronic Systems, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-9322-9722*

Anton Shamrai, *PhD Student, Department of Media Engineering and Information Radioelectronic Systems, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, ORCID: https://orcid.org/0009-0006-4858-7033*

The object of research is the process of ensuring the Bragg condition between the lengths of acoustic and electromagnetic waves when measuring the altitude profiles of the atmosphere using the radioacoustic sounding (RAS) method.

The problem solved in the work is the lack of a generalized theoretical basis for developing methods for adapting RAS systems to maintain the Bragg condition during the movement of the acoustic wave packet (AWP) in the atmosphere.

In the work, using the theory of stochastic optimal control, a method for frequency adaptation of RAS systems was developed to ensure the Bragg condition along the sounding path. The method includes the operations of estimating the speed of sound, stochastic linear filtering of the AWP state parameter vector and controlling the frequency of the radio signal based on the obtained data. A method for estimating the information parameters of the signal was proposed, and an algorithm for sequential filtering of AWP parameters was developed.

The developed frequency adaptation method will significantly improve the quality indicators of RAS systems – the accuracy of measuring atmospheric temperature profiles and the efficiency of sounding. The use of the method in practice will also allow to increase the range of sounding systems by more effectively adjusting to the Bragg conditions at small values of the signal-to-noise ratio, characteristic of long ranges.

The improvement of the main characteristics of the systems is achieved by more accurately ensuring the Bragg condition in the process of measuring the sound speed values, as a result of which the measurement results do not have systematic errors, and the random component of errors is significantly reduced. Therefore, the averaging time of individual measurement results to achieve the required integral accuracy of estimating the atmospheric temperature profile is significantly reduced, from tens to units of minutes.

The proposed method can be implemented in practice by improving the existing RAS atmospheric systems manufactured by industry.

Keywords: radioacoustic sounding of the atmosphere, Bragg condition, frequency adaptation, stochastic control, sounding signal.

References

1. Emeis, S. (2021). Sodar and RASS. *Springer Handbook of Atmospheric Measurements.* Cham: Springer, 661–681. https://doi.org/10.1007/978-3-030-52171-4_23
2. Bradley, S. (2007). *Atmosphere Acoustic Remote Sensing.* Principes and Application. CRC Press, 267. Available at: https://www.taylorfrancis.com/books/mono/10.1201/9781420005288/atmospheric-acoustic-remote-sensing-stuart-bradley
3. Kartashov, V., Babkin, S., Kartashov, A., Pershyn, Y. (2023). Development of the Atmosphere Radio-Acoustic Sounding Method in Ukraine and in the World in the Period of 1961-2000. *2023 IEEE International Conference on Information and Telecommunication Technologies and Radio Electronics (UkrMiCo).* Kyiv, 372–376. https://doi.org/10.1109/ukrmico61577.2023.10380339
4. Emeis, S. (2011). *Surface-Based Remote Sensing of the Atmospheric Boundary Layer.* Berlin, Heidelberg: Springer, 175. https://doi.org/10.1007/978-90-481-9340-0
5. Garcia-Benadi, A., Bech, J., Udina, M., Campistron, B., Paci, A. (2022). Multiple Characteristics of Precipitation Inferred from Wind Profiler Radar Doppler Spectra. *Remote Sensing, 14 (19),* 5023. https://doi.org/10.3390/rs14195023

ISSN-L 2664-9969; E-ISSN 2706-5448

6. Thampy, B. P., Judy, M. V., Kottayil, A. (2023). Wind profiler Doppler power spectrum segmentation using U-Net. *2023 International Conference on Advances in Intelligent Computing and Applications (AICAPS),* 1–6. https://doi.org/10.1109/aicaps57044.2023.10074415
7. Lataitis, R. J. (1993). *Theory and Application of a radio-acoustic sounding system (RASS): NOAA Technical Memorandum ERL WPL-230.* Nat. Oceanic and Atmos. Admin. Environ, Res. Labs. Boulder, CO, 207. Available at: https://repository.library.noaa.gov/view/noaa/32558
8. Lehmann, V., Brown, W.; Foken, T. (Ed.) (2021). *Radar Wind Profiler.* Springer Handbook of Atmospheric Measurements. Cham: Springer, 901–933. https://doi.org/10.1007/978-3-030-52171-4_31
9. Kartashov, V. M., Babkin, S. I., Tolstykh, Y. G., Lepeha, N. G. (2016). Systematic errors in measurement of meteorological variables in correlation processing of signal of radio acoustic sounding systems. *Telecommunications and Radio Engineering, 75 (9),* 835–843. https://doi.org/10.1615/telecomradeng.v75.i9.80
10. Temperature Profiler RASS. *Metek*. Available at: https://metek.de/product-group/rass/ Last accessed: 18.11.2025
11. *Overview.* RASS (Radio Acoustic Sounding System) addition to the SODAR PCS2000. Available at: https://www.biral.com/product/rass-sodar-pcs2000/#product-overview Last accessed: 18.11.2025
12. *Remtech Radio Acoustic Sounding System (RASS) for remote sensing of temperature.* RASS. Available at: https://remtechinc.com/wp-content/uploads/RASS3.pdf Last accessed: 18.03.2025
13. *Remtech PA-0 SODAR acoustic wind profiler.* PA-0. Available at: https://remtechinc.com/wp-content/uploads/PA-0.pdf Last accessed: 18.11.2025
14. *RASS for Radar Wind Profilers.* Available at: https://www.scintec.com/catalogs/rass-for-radar-wind-profilers/ Last accessed: 18.11.2025
15. *RASS for Sodar Wind Profilers.* Available at: https://www.scintec.com/catalogs/rass-for-sodar-wind-profilers/ Last accessed: 18.11.2025
16. Lindenberg column. *DWD.* Available at: https://www.dwd.de/EN/research/observing_atmosphere/lindenberg_column/lindenberg_column_node.html;jsessionid=8458988E48142AB0B4F55375227909C7.live11054 Last accessed: 18.11.2025
17. Skolnik, I. M. (2008). *Radar Handbook*. New York: McGraw-Hill Education, 1328. Available at: https://ftp.idu.ac.id/wp-content/uploads/ebook/tdg/ADNVANCED%20MILITARY%20PLATFORM%20DESIGN/Radar%20Handbook.pdf
18. Terrell, W. J. (1999). Some Fundamental Control Theory II: Feedback Linearization of Single Input Nonlinear Systems. *The American Mathematical Monthly, 106 (9),* 812–828. https://doi.org/10.1080/00029890.1999.12005126
19. Kychak, V. M., Volovyk, A. Yu., Shutylo, M. A., Chervak, O. P. (2018). *Radiotekhnichni systemy (Osnovy proektuvannia. Chastyna 1).* Vinnytsia: VNTU, 122. Available at: http://pdf.lib.vntu.edu.ua/books/IRVC/Kichak_P1_2018_122.pdf
20. Kartashov, V. M., Babkin, S. I., Kushnir, M. K., Oleinikova, E. I. (2015). Formation of empirical and methodical foundations of science in the field of atmosphere radioacoustic sounding systems. *Telecommunications and Radio Engineering, 74 (15),* 1391–1407. https://doi.org/10.1615/telecomradeng.v74.i15.70
21. Dorf, R. C., Bishop, R. H. (2022). *Modern Control Systems.* Pearson, 512. Available at: https://studylib.net/doc/27877119/modern-control-systems-book
22. Kartashov, V. M. (2003). Signal Scattering Functions of Atmospheric Sounding Systems. *Telecommunications and Radio Engineering, 59 (7-9).* https://doi.org/10.1615/telecomradeng.v59.i7-9.70
23. Kartashov, V. M., Tikhonov, V. A., Voronin, V. V., Tymoshenko, L. P. (2016). Complex models of random signals in problems of acoustic sounding of atmosphere. *Telecommunications and Radio Engineering, 75 (20),* 1885–1892. https://doi.org/10.1615/telecomradeng.v75.i20.80
24. Kartashov, V. M., Tikhonov, V. A., Voronin, V. V. (2017). Features of construction and application of complex systems for the atmosphere remote sounding. *Telecommunications and Radio Engineering, 76 (8),* 743–749. https://doi.org/10.1615/telecomradeng.v76.i8.70
25. Oleynikov, V. N., Zubkov, O. V., Kartashov, V. M., Korytsev, I. V., Babkin, S. I., Sheiko, S. A. (2019). Investigation of detection and recognition efficiency of small unmanned aerial vehicles on their acoustic radiation. *Telecommunications and Radio Engineering, 78 (9),* 759–770. https://doi.org/10.1615/telecomradeng.v78.i9.20
26. Semenets, V. V., Kartashov, V. M., Leonidov, V. I. (2018). Registration of refraction phenomenon in the problem of acoustic sounding of atmosphere in airports zone. *Telecommunications and Radio Engineering, 77 (5),* 461–468. https://doi.org/10.1615/telecomradeng.v77.i5.90
27. Muradyan, P., Coulter, R. (2020). *Radar Wind Profiler (RWP) and Radio Acoustic Sounding System (RASS) Instrument Handbook.* Environmental Science Division, Argonne National Laboratory, 20. Available at: https://www.arm.gov/publications/tech_reports/handbooks/rwp_handbook.pdf Last accessed: 14.11.2025

DOI: 10.15587/2706-5448.2026.356886

DEVELOPMENT OF A DECISION SUPPORT MODEL FOR MULTI-STAGE INVESTMENT DECISIONS IN PRODUCTION SYSTEMS UNDER RISK

pages 92–97

Oksana Mulesa, *Doctor of Technical Sciences, Professor, Department of Physics, Mathematics and Technologies, University of Prešov, Prešov, Slovakia; Department of Software Systems, Uzhhorod National University, Uzhhorod, Ukraine, e-mail: oksana.mulesa@unipo.sk, ORCID: https://orcid.org/0000-0002-6117-5846*

Olga Kachmar, *PhD, Associate Professor, Independent Researcher, Uzhhorod, Ukraine, ORCID: https://orcid.org/0009-0007-5139-7801*

Svitlana Baloha, *PhD, Associate Professor, Department of Computer Systems and Networks, Uzhhorod National University, Uzhhorod, Ukraine, ORCID: https://orcid.org/0000-0002-1221-9072*

Hanna Tiutiunnykova, *Senior Lecturer, Department of Computer Systems and Networks, Uzhhorod National University, Uzhhorod, Ukraine, ORCID: https://orcid.org/0000-0003-0859-6382*

Dmytro Shevchuk, *PhD Student, Department of Computer Systems and Networks, Uzhhorod National University, Uzhhorod, Ukraine, ORCID: https://orcid.org/0009-0003-6518-9473*

The object of research is the process of making investment decisions in production systems under conditions of risk and uncertainty.

In modern enterprise conditions, making investment decisions requires choosing between several options for production development. Their effectiveness depends on possible states of the external environment. A feature of these processes is that investment decisions can have several stages, and their effectiveness depends on the conditions of implementation.

The work focused on developing a decision support model that takes into account the step-by-step implementation of investment projects and evaluates alternatives considering possible environmental scenarios. The analysis showed that traditional approaches are mostly based on one-stage decision models, which limits the ability to consider changes in project implementation conditions.

The model for supporting investment decision-making developed in the research combines single-stage and multi-stage approaches to evaluating the effectiveness of alternatives under conditions of risk. A feature of the obtained results is that they allow determining the expected result of applying multi-stage alternatives and identifying rational investment strategies. An approach to evaluating the efficiency reserve of investment projects in production was also proposed.

During the experimental verification, it was shown that the developed model allows taking into account the staged implementation of alternatives and the information that follows from this. Thanks to this, it provides the possibility of adjusting managerial decisions depending on the actual state of the environment at different stages of the implementation of the adopted decisions.

The developed model can be used in the process of substantiating investment decisions in production systems under conditions of risk.

Keywords: adaptive decision-making, efficiency reserve, Bayesian decision analysis, expected utility.

References

1. Stanton, M. C. B., Roelich, K. (2021). Decision making under deep uncertainties: A review of the applicability of methods in practice. *Technological Forecasting and Social Change, 171,* 120939. https://doi.org/10.1016/j.techfore.2021.120939

2. Teece, D. J., Pisano, G., Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal, 18 (7),* 509–533. https://doi.org/10.1002/(sici)1097-0266(199708)18:7<509::aid-smj882>3.0.co;2-z
3. Rosenhead, J. (1968). Introduction to Operations Research. *Journal of the Operational Research Society, 19 (3),* 329–330. https://doi.org/10.1057/jors.1968.78
4. Saaty, T. L., Vargas, L. G. (2013). *Decision making with the analytic network process: Economic, political, social and technological applications with benefits, opportunities, costs and risks.* Vol. 195. Springer, 363. https://doi.org/10.1007/978-1-4614-7279-7
5. Kahneman, D., Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. *Econometrica, 47 (2),* 263–292. https://doi.org/10.2307/1914185
6. Izonin, I., Tepla, T., Danylyuk, D., Tkachenko, R., Duriagina, Z., Lemishka, I. (2020). Towards an Intelligent Decision Making of Ti-based Powders Selection for Medical Manufacturing. *2020 International Conference on Decision Aid Sciences and Application (DASA).* IEEE, 1–5. https://doi.org/10.1109/dasa51403.2020.9316866
7. Hou, H. (Cynthia). (2025). Utility Theory Application in Decision-Making Behavior for Energy Use and Management: A Systematic Review. *Energies, 18 (8),* 2125. https://doi.org/10.3390/en18082125
8. Bakır, N. O., Tekin, S., Keleş, B. (2026). Expected utility-based maintenance planning under risk aversion for a two-state deterioration model. *Reliability Engineering & System Safety, 270,* 112169. https://doi.org/10.1016/j.ress.2025.112169
9. Wu, F., Li, H. Z., Chu, L. K., Sculli, D., Gao, K. (2008). An approach to the valuation and decision of ERP investment projects based on real options. *Annals of Operations Research, 168 (1),* 181–203. https://doi.org/10.1007/s10479-008-0365-7
10. Castro, J., Tito, E., Brandão, L. (2021). Optimization of a Portfolio of Investment Projects: A Real Options Approach Using the Omega Measure. *Journal of Risk and Financial Management, 14 (11),* 530. https://doi.org/10.3390/jrfm14110530
11. Panayi, S., Trigeorgis, L. (1998). Multi-stage real options: The cases of information technology infrastructure and international bank expansion. *The Quarterly Review of Economics and Finance, 38 (3),* 675–692. https://doi.org/10.1016/s1062-9769(99)80096-9
12. Mulesa, O., Snytyuk, V., Myronyuk, I. (2019). Optimal alternative selection models in a multi-stage decision-making process. *EUREKA: Physics and Engineering, 6,* 43–50. https://doi.org/10.21303/2461-4262.2019.001005
13. Berger, J. O. (1985). *Statistical Decision Theory and Bayesian Analysis.* Springer Series in Statistics. Springer New York. https://doi.org/10.1007/978-1-4757-4286-2
14. Hnatiienko, H., Tmienova, N., Kruglov, A., Shkarlet, S., Morozov, A., Palagin, A. (Eds.) (2020). Methods for Determining the Group Ranking of Alternatives for Incomplete Expert Rankings. *Mathematical Modeling and Simulation of Systems (MODS'2020).* Springer, 217–226. https://doi.org/10.1007/978-3-030-58124-4_21

DOI: 10.15587/2706-5448.2026.357488

DEVELOPMENT OF A HYBRID ARTILLERY FIRE CONTROL SYSTEM BASED ON NEURAL NETWORKS AND UNCERTAINTY QUANTIFICATION METHODS

pages 98–105

Yurii Rubel, *PhD Student, Assistant, Department of Software, Lviv Polytechnic National University, Lviv, Ukraine, e-mail: yurii.b.rubel@lpnu.ua, ORCID: https://orcid.org/0009-0003-1891-2446*

Yurii Hrytsiuk, *Doctor of Technical Sciences, Professor, Department of Software, Lviv Polytechnic National University, Lviv, Ukraine, ORCID: https://orcid.org/0000-0001-8183-3466*

The object of research is the process of controlling the fire of artillery installations in a hybrid ballistic modeling system. The problem addressed lies in the lack of comprehensive studies of systems that combine neural network forecasting with physical iterative refinement and stochastic assessment of projectile dispersion within a single operational pipeline. This paper examines the specific features of developing a hybrid artillery fire control system based on the integration of neural networks, numerical refinement of aiming angles, and methods for quantifying the uncertainty of the ballistic model. A modular system architecture is proposed and investigated, integrating a ballistic simulator with a 4-DOF model in accordance with NATO STANAG 4355. The system is supplemented by a neural network, which generates an initial approximation of the aiming angles. For the subsequent calculation of the aiming angles, an algorithm was implemented using iterative elevation angle refinement via the Brent method and gradient azimuth correction. To assess uncertainty, polynomial chaos expansion (PCE) and Monte Carlo methods were integrated. A synthetic ballistic dataset consisting of 121107 records was generated based on 24 configurations of artillery systems. Validation of the neural network demonstrated a narrowing of the search space for aiming angles to a corridor of ±3–5°, ensuring further rapid convergence of the iterative refinement algorithm. Testing for the 2S22 "Bohdana" artillery system at a range of 20 km showed a deterministic error of 0.68 m. The PCE method achieved an error of 0.47 m, outperforming the Monte Carlo method (5.28 m) by a factor of 11.2. Analysis using the PCE method revealed anisotropic projectile dispersion: $\sigma_x = 168.85$ m, $\sigma_z = 80.84$ m, $CEP50 = 147.3$ m. The viability of the hybrid system has been demonstrated under ballistic simulation conditions, laying the groundwork for further validation with real-world firing data.

Keywords: ballistic modelling, hybrid ballistic pipeline, ballistic dataset, neural networks, uncertainty quantification.

References

1. Xie, J., Yang, G., Wang, L., Li, L. (2024). Multi-Stage Multidisciplinary Design Optimization Method for Enhancing Complete Artillery Internal Ballistic Firing Performance. *Computer Modeling in Engineering & Sciences, 140 (1),* 793–819. https://doi.org/10.32604/cmes.2024.048174
2. Baranowski, L., Szymonik, J., Majewski, P. (2024). Dynamic calculation of the fire zone for anti-aircraft artillery. *Journal of Theoretical and Applied Mechanics, 62 (4),* 787–798. https://doi.org/10.15632/jtam-pl/194401
3. Masluk, L., Havalko, V., Dzhygomon, S. (2022). Main problematic questions and ways of their solution in the development of automated management systems for rocket troops and artillery. *Modern Information Technologies in the Sphere of Security and Defence, 45 (3),* 63–68. https://doi.org/10.33099/2311-7249/2022-45-3-63-68
4. Budaretskiy, Y., Schavinskiy, Y. (2016). Synthesis of structure and optimization of algorithms of work of the decision support system of at a fire-control artillery subdivisions of tactical link. *2016 13th International Conference on Modern Problems of Radio Engineering, Telecommunications and Computer Science (TCSET).* Lviv: IEEE, 312–316. https://doi.org/10.1109/tcset.2016.7452043
5. Li, D., Guo, L. H. (2012). The application of digital signal processing (DSP) for the real time solving of artillery fire control exterior trajectory. *2012 IEEE International Conference on Computer Science and Automation Engineering.* Beijing: IEEE, 32–35. https://doi.org/10.1109/icsess.2012.6269399
6. Hao, B., Tegang, L., Zhengzheng, Y., Sheng, Z., Wufan, S. (2024). Design of a Software-Defined Artillery System Architecture. *Journal of Physics: Conference Series, 2891 (11),* 112009. https://doi.org/10.1088/1742-6596/2891/11/112009
7. Rothe, H., Kuhrt, A., Schroeder, S., Trebing, S.; Sánchez-Gálvez, V., Brebbia, C. A., Motta, A. A., Anderson, C. E. (Eds.) (2005). Fire control algorithms and software for the modular naval artillery concept (MONARC) of the German navy. *Computational Ballistics II.* WIT Press, 40, 406–416. Available at: https://www.witpress.com/elibrary/wit-transactions-on-modelling-and-simulation/40/14941
8. Qian, L., Chen, G., Tong, M., Tang, J. (2022). General design principle of artillery for firing accuracy. *Defence Technology, 18 (12),* 2125–2140. https://doi.org/10.1016/j.dt.2022.09.001
9. Bragado, A. C., Solera-Rico, A., Gómez, M. A. (2023). Implementation of Trajectory Propagator for Artillery Projectiles Based on Artificial Neural Networks. *New Technologies and Developments in Unmanned Systems,* 187–192. https://doi.org/10.1007/978-3-031-37160-8_29
10. Liu, H., Shan, G., Mei, W. (2014). Analysis on the kill probability of two Shooting Modes for fire control system of antiaircraft artillery. *Proceedings of the 33rd Chinese Control Conference.* Nanjing: IEEE, 9075–9081. https://doi.org/10.1109/chicc.2014.6896529
11. Pan, W., Sun, Y., Jing, Y. (2016). Artillery firepower selection based on chaos genetic algorithm. *2016 Chinese Control and Decision Conference (CCDC).* Yinchuan: IEEE, 1588–1593. https://doi.org/10.1109/ccdc.2016.7531237
12. Papp, Z., Rožnjik, A.; Kovács, T. A., Nyikes, Z., Fürstner, I. (Eds.) (2022). A Method for Approximating Circular Error Probable. *Security-Related Advanced*

ISSN-L 2664-9969; E-ISSN 2706-5448

Technologies in Critical Infrastructure Protection. Dordrecht: Springer, 29–42. https://doi.org/10.1007/978-94-024-2174-3_3

13. Ghosh, A. K., Prakash, O. (2004). Neural Models for Predicting Trajectory Performance of an Artillery Rocket. *Journal of Aerospace Computing, Information, and Communication, 1 (2),* 112–115. https://doi.org/10.2514/1.3398
14. Gao, Z., Zhang, D., Yi, W. (2025). Projectile trajectory and launch point prediction based on CORR-CNN-BiLSTM-Attention model. *Expert Systems with Applications, 275,* 127045. https://doi.org/10.1016/j.eswa.2025.127045
15. Roux, A., Changey, S., Weber, J., Lauffenburger, J.-P. (2023). LSTM-Based Projectile Trajectory Estimation in a GNSS-Denied Environment. *Sensors, 23 (6),* 3025. https://doi.org/10.3390/s23063025
16. Wang, L., Chen, Z., Yang, G. (2021). An Uncertainty Analysis Method for Artillery Dynamics with Hybrid Stochastic and Interval Parameters. *Computer Modeling in Engineering & Sciences, 126 (2),* 479–503. https://doi.org/10.32604/cmes.2021.011954
17. Herbut, A., Brząkała, W. (2024). Polynomial chaos expansion vs. Monte Carlo simulation in a stochastic analysis of wave propagation. *Wave Motion, 130,* 103390. https://doi.org/10.1016/j.wavemoti.2024.103390
18. Wang, M., Qian, L., Chen, G., Lin, T., Shi, J., Zhou, S. (2024). High-dimensional uncertainty quantification of projectile motion in the barrel of a truck-mounted howitzer based on probability density evolution method. *Defence Technology, 32,* 209–221. https://doi.org/10.1016/j.dt.2023.03.004
19. Jacewicz, M., Lichota, P., Miedziński, D., Głębocki, R. (2022). Study of Model Uncertainties Influence on the Impact Point Dispersion for a Gasodynamicaly Controlled Projectile. *Sensors, 22 (9),* 3257. https://doi.org/10.3390/s22093257
20. Ilg, M., Rogers, J., Costello, M. (2011). Projectile Monte-Carlo Trajectory Analysis Using a Graphics Processing Unit. *AIAA Atmospheric Flight Mechanics Conference.* https://doi.org/10.2514/6.2011-6266
21. Du, A. (2021). *A comparative study between 6 degree-of-freedom trajectory model and modified point mass trajectory model of spinning projectiles.* [Master's thesis; Embry-Riddle Aeronautical University]. Available at: https://commons.erau.edu/edt/594/
22. Baranowski, L. (2013). Feasibility analysis of the modified point mass trajectory model for the need of ground artillery fire control systems. *Journal of Theoretical and Applied Mechanics, 51 (3),* 511–522. Available at: http://www.ptmts.org.pl/jtam/index.php/jtam/article/view/v51n3p511
23. Šilinger, K., Blaha, M. (2017). The New Automated Fire Control System for Artillery Units based on Interoperability and Standards. *Proceedings of the 14th International Conference on Informatics in Control, Automation and Robotics.* Madrid, 332–337. https://doi.org/10.5220/0006468003320337
24. Shchavinskyi, Y. V. (2015). Vidpratsiuvannia alhorytmiv rozrakhunku danykh dlia pidvyshchennia efektyvnosti vohnevoho urazhennia velykorozmirnykh tsilei. *Bionika intelektu, 2 (85),* 120–126. Available at: http://nbuv.gov.ua/UJRN/bioi_2015_2_21
25. Majstrenko, O. V., Makeev, V. I., Prokopenko, V. V., Andreiev, I. M., Kamentsev, S. Y., Onofriychuk, A. Y. (2024). An improved mathematical model of the method of fully preparing the determination of firing units for hitting the information and calculation component of the automated fire control system of combat vehicles of reactive artillery. *Radio Electronics, Computer Science, Control, 4,* 195–209. https://doi.org/10.15588/1607-3274-2024-4-19
26. Maksymova, O., Boltyonkov, V., Gultsov, P., Maksymov, O. (2023). Improvement of the model and method of artillery installation target damage control with minimal combat capability loss. *Odes'kyi Politechnichnyi Universytet Pratsi, 2 (68),* 98–115. https://doi.org/10.15276/opu.2.68.2023.11
27. Rubel, Y., Hrytsiuk, Y. (2025). Intelektualne koryhuvannia strilby v avtomatyzovanykh systemakh upravlinnia vohnem artyleriiskykh ustanovok. *1st International Scientific and Practical Conference "Science and Technology: New Horizons of Development".* Prague, 192–198. Available at: https://isu-conference.com/wp-content/uploads/2025/07/Prague_Czech-Republic_14.05.25.pdf
28. Rubel, Y., Hrytsiuk, Y. (2025). Current state of automated fire control systems for artillery systems. *Herald of Khmelnytskyi National University. Technical Sciences, 355 (4),* 520–530. https://doi.org/10.31891/2307-5732-2025-355-73
29. Rubel, Y., Hrytsiuk, Y. (2026). Arkhitekturnyi pidkhid do realizatsii hibrydnoi systemy upravlinnia vohnem artylerii. *4th International Scientific and Practical Conference.* International Scientific Unity, 125–130. https://doi.org/10.70286/isu-14.01.2026.006
30. Katalinić, I. (2021). Implementation of MPMM ballistic model for calculation of differential coefficients for TFTs according to NATO STANAG 4119. *Strategos, 5 (1),* 169–196. Available at: https://hrcak.srce.hr/en/file/379956
31. *ISO 2533:1975 Standard Atmosphere* (2024). International Organization for Standardization. Available at: https://www.iso.org/standard/7472.html
32. Stull, R. B. (Ed.) (1988). *An Introduction to Boundary Layer Meteorology.* Dordrecht: Springer, 670. https://doi.org/10.1007/978-94-009-3027-8
33. Tobin, J., Fong, R., Ray, A., Schneider, J., Zaremba, W., Abbeel, P. (2017). Domain randomization for transferring deep neural networks from simulation to the real world. *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems,* 23–30. https://doi.org/10.48550/arXiv.1703.06907
34. Dormand, J. R., Prince, P. J. (1980). A family of embedded Runge-Kutta formulae. *Journal of Computational and Applied Mathematics, 6 (1),* 19–26. https://doi.org/10.1016/0771-050x(80)90013-3
35. Hairer, E., Norsett, S. P., Wanner, G. (1993). *Solving Ordinary Differential Equations I: Nonstiff Problems.* Heidelberg: Springer Berlin, 528. https://doi.org/10.1007/978-3-540-78862-1
36. Brent, R. P. (2013). *Algorithms for Minimization Without Derivatives.* Dover Publications, 208. Available at: https://www.perlego.com/book/111565/algorithms-for-minimization-without-derivatives-pdf
37. Press, W. H., Teukolsky, S. A., Vetterling, W. T., Flannery, B. P. (2007). *Numerical recipes: The art of scientific computing.* Cambridge University Press, 1235. Available at: https://numerical.recipes/
38. Xiu, D., Karniadakis, G. E. (2002). The Wiener – Askey Polynomial Chaos for Stochastic Differential Equations. *SIAM Journal on Scientific Computing, 24 (2),* 619–644. https://doi.org/10.1137/s1064827501387826
39. Eldred, M., Burkardt, J. (2009). Comparison of Non-Intrusive Polynomial Chaos and Stochastic Collocation Methods for Uncertainty Quantification. *47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition.* https://doi.org/10.2514/6.2009-976
40. Yaro, A. S., Maly, F., Prazak, P. (2023). Outlier Detection in Time-Series Receive Signal Strength Observation Using Z-Score Method with Sn Scale Estimator for Indoor Localization. *Applied Sciences, 13 (6),* 3900. https://doi.org/10.3390/app13063900
41. Goodfellow, I., Bengio, Y., Courville, A. (2016). *Deep Learning.* MIT Press book. Available at: http://www.deeplearningbook.org
42. Zhao, Q., Tang, Q., Han, J., Yang, M., Chen, Z. (2019). Efficient Method of Firing Angle Calculation for Multiple Launch Rocket System Based on Polynomial Response Surface and Kriging Metamodels. *Mathematical Problems in Engineering, 2019 (1),* 1–15. https://doi.org/10.1155/2019/7689860
43. Gao, Z., Yi, W. (2025). Prediction of projectile impact points and launch conditions based on extreme learning machine. *Measurement, 252,* 117308. https://doi.org/10.1016/j.measurement.2025.117308
44. Sivaprasad, G., Mathur, G., Rajesh, G. (2025). Physics informed neural network (PINN) for trajectory estimation of artillery shells from target location. *34th International Symposium on Ballistics.* Jacksonville. https://doi.org/10.12783/ballistics25/37082