

UDC 81'322:004.912

SPECIFICS OF HYBRID MATHEMATICAL PROGRAMMING METHODS APPLIED TO MACHINE TRANSLATION WITHIN CONTEMPORARY LINGUISTIC

Krasniuk S.O.*senior lecturer*

ORCID: 0000-0002-5987-8681

*Kyiv National University of Technologies and Design,
Mala Shyianovska Street 2, Kyiv, Ukraine*

Abstract. *This paper investigates hybrid mathematical optimization as a key approach to enhancing machine translation systems. By integrating continuous neural network representations with discrete decoding algorithms and expert linguistic constraints, these systems overcome the limitations of isolated statistical or neural methods. The study analyzes implementation mechanisms, such as multi-criteria quality functions and various algorithmic combination strategies, which allow for the simultaneous minimization of lexical, syntactic, and semantic losses. The findings demonstrate that hybrid models provide superior accuracy, interpretability, and adaptability, particularly in specialized domains or under conditions of data scarcity. Ultimately, the synthesis of mathematical tools and cognitive-linguistic knowledge is presented as the foundation for the next generation of human-oriented translation technologies*

Keywords: *computational linguistics, machine translation, hybrid mathematical optimization, neural networks, linguistic constraints, multi-criteria optimization, semantic adequacy*

Introduction.

The rapid digitalization of society, the exponential growth of multilingual information arrays and the strengthening of global communication processes have led to a noticeable increase in interest in the automation of complex interlingual interaction [1], [2]. Machine translation from an auxiliary software tool has gradually turned into a strategically important element of the digital economy, e-government, international scientific cooperation and commercial activity [3], [4]. Modern translation platforms are used in search engines, corporate information environments, management decision support services, educational technologies and the infrastructure of electronic government services. Large technology corporations such as Google, DeepL SE and OpenAI systematically invest significant financial and scientific resources in the creation of intelligent neural network large-scale language models [5], which confirms the high applied and economic value of this area. However, improving the quality of automatic translation is impossible without

improving the mathematical tools that underlie learning algorithms, parametric tuning and text decoding. Traditional concepts - statistical, neural network or strictly/rigidly linguistically rigged - when used in isolation demonstrate certain limitations: the first take into account mainly frequency patterns and surface correlations, the second require large amounts of data [6] and computing power, the third are characterized by high labor intensity. In this regard, hybrid mathematical optimization, which combines discrete and continuous procedures, probabilistic constructions and heuristic methods [7], which allows simultaneously taking into account the formal-structural and semantic characteristics of the language, becomes particularly relevant. Considering the above, the purpose of this publication is to reveal the specifics of hybrid mathematical optimization for machine translation systems, to analyze its theoretical and methodological foundations, implementation mechanisms, advantages, limitations and practical prospects in modern linguistics and applied intellectual technologies.

Main Part.

1. Theoretical foundations of method integration. Machine translation can be interpreted as a complex task of transforming a sequence of signs of one language into an equivalent sequence of another while preserving the meaning, structure of the utterance, and communicative function of the text. From a formal point of view, this problem is interpreted as finding the optimal mapping:

$$\hat{y} = \arg \max_y P(y/x) ,$$

where X denotes the original utterance, and Y denotes the set of possible translation options.

Classical statistical approaches use probabilistic decomposition through Bayes' rule, separating the language model and the transformation model. However, such systems take into account long-term dependencies and contextual connections to a limited extent. Neural architectures, on the contrary, provide end-to-end learning, forming continuous representations, but often function as a "black box", which complicates the interpretation of decisions and error control.

Hybrid optimization is a compromise paradigm in which formal search

algorithms, stochastic evaluations, neural network representations and linguistic constraints are combined into a single structure. As a result, a multi-level architecture is formed, where each method solves specific subproblems and compensates for the weaknesses of other components.

2. The essence of hybrid mathematical optimization. Hybrid mathematical optimization is understood as a set of methods that combine different classes of algorithms:

- 2.1. continuous optimization procedures (gradient methods, adaptive parameter update algorithms);
- 2.2. discrete strategies (dynamic programming, branch and bounds, integer programming);
- 2.3. probabilistic constructs (Bayesian networks, Markov processes, hidden models);
- 2.4. a family of heuristic and metaheuristic algorithms (where the effectiveness of evolutionary optimization technologies is particularly worth highlighting [8], [9], [10]);
- 2.5. expert linguistic rules and constraints.

In the context of machine translation, this manifests itself in the combination of neural representations of words, sentences, or entire documents in the form of numerical vectors (lists of numbers) with optimal decoding algorithms, post-processing based on grammatical patterns, and multi-objective parameter tuning. Thus, the text transformation task turns into a complex multi-extreme optimization problem, where lexical, syntactic, and semantic losses need to be minimized simultaneously/synchronously.

3. Key components of hybrid systems.

3.1. Neural network representations. Modern solutions are based on distributed vector representations of words, phrases and sentences, encoders/decoders, attention mechanisms, transformer structures. These elements implement continuous optimization of parameters based on large parallel corpora, forming deep semantic dependencies and ensuring knowledge transfer between contexts.

3.2. Discrete decoding. After the training stage, the task of selecting the most probable text sequence arises. At this level, combinatorial search methods are used: beam search, dynamic programming, bounded search, integer optimization. Here, continuous probable estimates are converted into a discrete symbolic result, which emphasizes the need to integrate different mathematical approaches.

3.3. Linguistic constraints. The use of morphological, syntactic and terminological rules allows for additional correction of the result. Specialized dictionaries, ontologies, matching patterns and structural constraints are introduced into the system. Such elements reduce the probability of errors arising from lack of data or ambiguity of the context.

3.4. Multi-criteria quality functions. The quality of the translation is assessed by a set of indicators: probabilistic model assessment, metrics such as BLEU and TER, semantic similarity, stylistic adequacy, domain relevance. Therefore, optimization becomes multi-criteria in nature and requires finding a balanced compromise between competing goals.

4. Algorithmic combination strategies. In practical developments, various integration schemes are used:

- a) Sequential scheme - generation of translation by a neural network with subsequent grammatical correction.
- b) Parallel scheme - combining several models and ensemble of their results.
- c). Iterative optimization - cyclic retraining on detected errors.
- d). Hierarchical organization - division of tasks by levels of analysis: lexical, syntactic, semantic and pragmatic.

Each strategy aims to reduce the accumulation of inaccuracies and increase the system's robustness to rare words, polysemy, and structural ambiguity.

5. Advantages of the hybrid approach. Key advantages include: - increased accuracy and reliability of translation in specialized subject areas; - resistance to limited training data; - increased interpretability of solutions; - the possibility of introducing expert knowledge; - rational use of computing resources; - high adaptability to new domains and languages.

Of particular importance is the ability of hybrid systems to combine statistical patterns with cognitive and semantic factors, which brings automatic translation closer to human perception of meaning.

6. Limitations and problematic aspects. Along with the advantages, hybrid methods are characterized by a number of difficulties: complicated architecture, increased development effort, the need to coordinate heterogeneous modules, difficulties in scaling and formalizing rules. Additional problems are created by multi-criteria optimization, when different quality indicators may conflict and require compromise solutions.

7. The value of modern linguistics. Modern linguistics plays an important role in the design of hybrid systems. Corpus studies provide an empirical database, cognitive theories explain the mechanisms of meaning formation, formal grammars specify strict syntactic structures, and pragmatic approaches take into account the communicative context. The integration of this knowledge into mathematical models reduces semantic and stylistic distortions and makes translation more natural.

8. Prospects for further development. Further improvement of hybrid approaches is associated with automatic rule extraction from corpora, the use of reinforcement learning, self-adaptive tuning of hyperparameters, the implementation of multimodal architectures, federated learning, and the development of energy-efficient algorithms. It is assumed that new generation systems will combine large-scale language models with point-by-point linguistic adjustments and intelligent optimization mechanisms.

Conclusions.

Thus, hybrid mathematical optimization is one of the most promising areas of machine translation development, which allows overcoming the limitations of exclusively statistical or purely neural network methods. Combining continuous and discrete procedures, probabilistic estimates, heuristics and linguistic rules forms a complex mechanism for searching for the best translation option, which takes into account a variety of linguistic factors.

The analysis demonstrates that hybrid models provide higher accuracy, stability and adaptability, especially in conditions of specialized domains and data scarcity. At

the same time, their implementation requires significant computational and organizational resources, as well as close interdisciplinary interaction between specialists in the fields of mathematics, computer science and linguistics.

In modern linguistics and intelligent technologies, hybrid optimization is becoming a key tool for improving the quality of automated interlingual communication. Further development of this direction is associated with the deepening of the synthesis of mathematical methods and linguistic knowledge, which opens up the possibility of creating more accurate, interpretable and human-oriented machine translation systems, which is confirmed in [11-14].

References:

1. Puzyrko, S. (2023). Literary translation as cross-cultural communication. *Ukrainian Cultural Studies*, 1(12), 16–30.
[https://doi.org/10.17721/UCS.2023.1\(12\).16](https://doi.org/10.17721/UCS.2023.1(12).16)
2. Савицька, Л. В., Ковальова, К. Л., & Безугла, І. В. (2023). Вплив перекладу на міжкультурну комунікацію: аспекти філології та лінгвістики. *Вісник науки та освіти*, 8(14), 279–292. [https://doi.org/10.52058/2786-6165-2023-8\(14\)-279-292](https://doi.org/10.52058/2786-6165-2023-8(14)-279-292)
3. Goncharenko S. Intelligent technologies for modern sociolinguistics / S. Goncharenko (2025). *Science: Development and Factors its Influence* : Proceedings of the 6th International Scientific and Practical Conference (October 6-8, 2025; Amsterdam, Netherlands). - Amsterdam: Scientific Collection «InterConf», 2025. - pp. 61-64.
4. Goncharenko S. (2025). Intelligent information technologies for innovative management of advanced philology projects. *Innovations and New Directions in Scientific Research* : Proceedings of the 2nd International Scientific Conference (Manchester, United Kingdom, 20 September 2025). - Lulu Press, Inc., 2025. - pp. 176-179.
5. Goncharenko S. (2025). Big semi-structured data & deep ANN in computational linguistics. *Science and Global Challenges in the Modern World* :

Proceedings of the 2nd International Scientific Conference (Leicester, United Kingdom, 5 October 2025). - Lulu Press, Inc., 2025. - pp. 133-136.

6.Goncharenko S. (2025). Big data & ML in contemporary education / S. Goncharenko. *Science: Development and Factors its Influence* : Proceedings of the 6th International Scientific and Practical Conference (October 6-8, 2025; Amsterdam, Netherlands). - Amsterdam: Scientific Collection «InterConf», 2025. - pp. 34-37.

7.Krasnyuk, M. (2014). Hibrydyzatsiia intelektualnykh metodiv analizu biznesovykh danykh (rezhym vyivlennia anomalii) yak skkladovyi instrument korporatyvnoho audytu [Hybridization of intelligent methods of business data analysis (anomaly detection mode) as a standard tool of corporate audit]. *Stan i perspektyvy rozvytku oblikovo-informatsiinoi systemy v Ukraini - Stan i perspektyvy rozvytku oblikovo-informatsiinoi systemy v Ukraini : materialy III Mizhnar. nauk.-prakt. konf. [m. Ternopil, 10-11 zhovt. 2014 r.] - The state and prospects of the development of the accounting and information system in Ukraine: materials of the III International science and practice conf. [m. Ternopil, October 10-11. 2014]*. TNEU, 2014. pp. 211-212 (in Ukrainian).

8.Kulynych Y., Krasnyuk M., Krasniuk S. (2022). Efficiency of evolutionary algorithms in solving optimization problems on the example of the fintech industry. *Grail of Science*, №14-15, May 2022, (pp. 63-70) DOI: <https://doi.org/10.36074/grail-of-science.27.05.2022>

9.Krasnyuk M.T., Naumenko M.A. (2024) Efektyvne zastosuvannia henetychnykh alhorytmiv u vyrishenni bahatoekstremumnykh optymizatsiinykh zadach v menedzhmenti konkurentnoho pidpriemstva [Effective application of genetic algorithms in solving multi-extremum optimization problems in the management of a competitive enterprise]. *Grail of Science*, №41, June 2024, pp. 65-73. URL: <https://archive.journal-grail.science/index.php/2710-3056/issue/view/05.07.2024/29> [in Ukrainian].

10.Maxim Krasnyuk, Svitlana Krasniuk (2024). CHAPTER 6. Evolutionary technologies and genetic algorithms in machine translation. *Innovation in modern science: Education and Pedagogy, Philosophy, Philology, Art History and Culture*,

Medicine and Healthcare. Monographic series «European Science». Book 30.

Part 3. 2024. pp. 91-98, Published by: ScientificWorld-NetAkhatAV, Lußstr.

1376227 Karlsruhe, Germany

<https://desymp.promonograph.org/index.php/sge/issue/view/sge30-03/sge30-03>

11.Wu, Z., Wei, D., Chen, X., Shang, H., Guo, J., Li, Z., Luo, Y., Yang, J., Rao, Z., & Yang, H. (2025). Combining the best of both worlds: A method for hybrid NMT and LLM translation. *Proceedings of Findings of the Association for Computational Linguistics: ACL* 2025, 5140–5148.

<https://doi.org/10.18653/v1/2025.findings-acl.266>

12.Wang, Y., Li, X., Yang, Y., & Anwar, A. (2021). Hybrid system combination framework for Uyghur–Chinese machine translation. *Information*, 12(3), 98.

<https://doi.org/10.3390/info12030098>

13.Chang, C. C. (2025). Integrating hybrid AI approaches for enhanced translation quality for low-resource languages. *Applied Sciences*, 15(16), 9039.

<https://doi.org/10.3390/app15169039>

14.Costa-Jussà, M. R., & Fonollosa, J. A. R. (2015). Latest trends in hybrid machine translation and its applications. *Computer Speech & Language*, 32(1), 3-10.

<https://doi.org/10.1016/j.csl.2014.11.001>

Article sent: 18.02.2026

© Krasniuk S.O.