ABSTRACT
for the dissertation of Aksultan Mukhanbet
submitted for the degree of Doctor of Philosophy (PhD)
in the educational program 8D06102 – Computer Engineering
on the topic: " Research and Development of Hybrid Quantum-Classical Algorithms for Pattern Recognition"

Relevance of the Research Topic.

The intersection of quantum computing and machine learning has emerged as one of the most rapidly advancing and strategically significant domains in contemporary science and technology. This interdisciplinary field integrates the computational advantages of quantum mechanics with the data-driven methodologies of machine learning, aiming to address increasingly complex problems that are beyond the reach of classical approaches. Over the past decade, classical deep learning techniques - particularly deep neural networks such as Convolutional Neural Networks (CNNs) - have demonstrated remarkable success in a wide range of applications, including computer vision, pattern recognition, natural language processing, and large-scale data analytics. These models have become the backbone of modern artificial intelligence systems, achieving state-of-the-art performance across numerous benchmarks.

Despite these achievements, fundamental limitations of classical approaches are becoming increasingly evident. One of the primary challenges lies in the continuous growth of data volumes and the corresponding increase in computational demands. As datasets become larger and more complex, classical architectures struggle to scale efficiently. This scalability issue is further exacerbated by the architectural complexity of modern deep learning models. State-of-the-art networks such as CNN, ResNet, and VGG often consist of hundreds of millions or even billions of trainable parameters.

The exponential growth in the number of parameters leads directly to increased computational costs, raising critical concerns regarding efficiency, sustainability, and accessibility. In many real-world scenarios, particularly in resource-constrained environments, deploying such large models is impractical. Furthermore, the reliance of these models on vast amounts of labeled data presents an additional limitation, as high-quality annotated datasets are not always readily available.

In parallel, Quantum Neural Networks (QNNs) have been proposed as a novel class of models that leverage quantum mechanical principles to enhance computational capabilities. However, at the current stage of development, pure QNNs still face several limitations. In particular, their performance in complex tasks, such as the classification of high-resolution or multi-channel images, remains constrained. On Noisy Intermediate-Scale Quantum (NISQ) devices, the achievable accuracy is typically limited - for instance, approximately 82.78% in certain image classification tasks. This suggests that, while quantum models hold significant theoretical promise, they are not yet fully mature for widespread practical deployment.

Quantum Machine Learning (QML) is widely regarded as a promising pathway to overcoming these limitations. By exploiting the fundamental principles of quantum mechanics - such as superposition, entanglement, and interference - QML introduces fundamentally new mechanisms for information representation and processing. These quantum phenomena enable the encoding of information in high-dimensional Hilbert spaces, potentially allowing for more

efficient data representations. For instance, superposition facilitates the compact encoding of large-scale data, while entanglement enables the modeling of complex, non-classical correlations that are difficult to capture using classical methods.

Nevertheless, the practical realization of QNNs is hindered by several technical and technological constraints. NISQ-era quantum hardware is inherently limited by a relatively small number of qubits, high levels of noise, and decoherence effects that degrade quantum states over time. These limitations directly affect the reliability and accuracy of quantum computations. Additionally, restrictions on circuit depth and gate fidelity impose further constraints on the complexity of implementable quantum models. Consequently, there is a pressing need for the development of quantum algorithms and architectures that are both efficient and robust under realistic hardware conditions.

To address these challenges, hybrid quantum-classical architectures have been proposed as a practical and scalable solution. These models combine classical neural networks with parameterized quantum circuits, allowing each component to compensate for the limitations of the other. In such hybrid frameworks, classical layers can handle data preprocessing and feature extraction, while quantum circuits are employed to capture complex correlations and enhance model expressivity. Hybrid QNN models have demonstrated the ability to achieve high classification accuracy while significantly reducing the number of trainable parameters. Importantly, they are designed to operate within the constraints of current quantum hardware, making them suitable for near-term applications.

Another promising direction in this field is the use of evolutionary optimization techniques, particularly genetic algorithms, for the design of quantum circuit architectures. Genetic algorithms are well-suited for exploring high-dimensional, non-convex, and combinatorial search spaces, which are characteristic of quantum circuit design problems. By encoding circuit structures as individuals in a population and iteratively applying selection, crossover, and mutation operations, these algorithms can efficiently discover high-performing architectures. The application of genetic algorithms to quantum circuit optimization enables the automated synthesis of NISQ-compatible circuits, reducing the reliance on manual design and expert intuition. In recent years, this approach has gained significant attention and has shown promising results in improving both performance and efficiency.

In this context, the optimization of quantum circuit architectures in Quantum Convolutional Neural Networks (QCNNs) represents a particularly relevant and challenging research problem. QCNNs extend classical convolutional architectures into the quantum domain, offering a structured approach to processing high-dimensional data using quantum circuits. In this dissertation, a novel hybrid quantum-classical neural network architecture, referred to as HQCNN, is proposed. Furthermore, an enhanced version of this architecture, termed HQCNN-REGA, is developed using a genetic algorithm-based optimization framework. The proposed models are evaluated through comprehensive experimental studies on widely used benchmark datasets, including MNIST, FashionMNIST, and CIFAR-100.

The experimental results demonstrate that the proposed approaches achieve competitive classification accuracy while maintaining significantly lower model complexity. In addition, the models exhibit improved computational efficiency and adaptability to hardware constraints, highlighting their practical applicability. Overall, this work contributes to bridging the gap between theoretical advancements in quantum machine learning and their real-world

implementation, providing a foundation for the development of next-generation intelligent systems based on hybrid quantum-classical paradigms.

Aim of the Dissertation

Development and optimization of hybrid quantum-classical neural networks based on quantum circuits, with the goal of improving the accuracy of quantum algorithms and reducing the number of trainable parameters in image recognition tasks.

Research Objectives:

– to conduct a systematic and critical review of current research in the field of Quantum Machine Learning (QML) and Quantum Convolutional Neural Networks (QCNN), and to analyze their advantages and limitations;

– to study and systematize the main methods for encoding classical data into quantum states (angle encoding, amplitude encoding, basis encoding, etc.), and to comparatively evaluate them in terms of computational complexity and efficiency;

– to investigate the theoretical foundations of the Data Re-uploading method, which is based on multiple data injections into quantum circuits, and to identify its application features in quantum models;

– to develop a hybrid quantum-classical neural network architecture (HQCNN) that effectively integrates classical and quantum layers, including QConv2D layers;

– to design and implement a genetic algorithm for the simultaneous optimization of key quantum circuit parameters, including the number of layers, the set of quantum gates, and the entanglement structure between qubits;

– to develop a comprehensive evaluation methodology for assessing the performance of the proposed hybrid model and its genetically optimized version (HQCNN-REGA);

– to conduct extensive experimental studies on the MNIST, FashionMNIST, and CIFAR-100 datasets, and to perform a thorough comparative analysis of the obtained results against classical and purely quantum models in terms of accuracy, robustness, and computational efficiency.

Research Methods:

Systematic literature review, quantum computing, design and training of parameterized quantum circuits (PQC), quantum neural networks, hybrid quantum-classical neural networks, genetic algorithms, data re-uploading.

Object of Research

Hybrid quantum-classical neural networks for image recognition tasks.

Subject of Research

Methods for optimizing quantum circuits in quantum neural networks.

Scientific Novelty of the Results Obtained:

1. A hybrid quantum-classical algorithm for image recognition tasks has been developed, based on a novel architecture that jointly employs quantum convolutional (QConv2D) and fully connected (QDense) layers. In this unified architecture, parameterized quantum circuits are effectively used as filters and measurement operators.
2. A new evolutionary approach to quantum circuit architecture optimization under limited qubit constraints has been proposed. By combining quantum encoding with genetic algorithms, the number of trainable parameters in the neural network has been significantly reduced and the computational efficiency of the model has been improved.

Propositions Submitted for Defense:

3. The proposed hybrid quantum-classical algorithm based on quantum convolutional (QConv2D) and quantum fully connected (QDense) layers achieves a classification accuracy of 97.4% on the CIFAR-100 dataset, which is 9–10% higher than the performance of existing comparable quantum methods.

4. The evolutionary algorithm for automatic quantum circuit architecture determination under resource constraints reduces the number of trainable parameters with angle encoding to 18,690 while maintaining minimum circuit depth. This reduces the parameter count by a factor of 47 compared to traditional classical convolutional neural networks (CNNs) and significantly improves computational efficiency.

Theoretical and Practical Significance of the Research

Theoretical significance:

This study makes a significant contribution to the development of the theoretical foundations for optimizing Parameterized Quantum Circuits (PQC). In particular, the architectural parameters of quantum neural networks - such as the number of layers, gate configurations, and entanglement structure - are considered as a unified system, and the problem of their simultaneous optimization is investigated in depth. This approach enables a transition from traditional empirical design methods toward more systematic and formalized methodologies for quantum model development.

Furthermore, the work extends the mathematical capabilities of heuristic optimization methods, such as genetic algorithms, within the context of Quantum Machine Learning. The problem of efficient search in high-dimensional, discrete, and continuous parameter spaces is addressed, and new approaches for the automated synthesis of quantum circuits are proposed. These results establish a theoretical foundation for the design of quantum algorithms, particularly for developing compact and efficient architectures tailored to the constraints of the NISQ era. In addition, the study contributes to a deeper understanding of the expressivity and generalization capabilities of hybrid quantum-classical models.

Practical significance:

The developed hybrid quantum-classical neural network architectures (HQCNN and HQCNN-REGA) demonstrate high practical efficiency and can be applied to real-world tasks. The proposed models significantly reduce the number of trainable parameters compared to classical deep learning architectures, which in turn leads to reduced training time, lower computational costs, and decreased energy consumption. This is especially advantageous in resource-constrained environments and in applications where energy efficiency is critical. The proposed architectures are designed with consideration of the limitations of modern NISQ quantum devices, including constraints on circuit depth, number of quantum gates, and qubit connectivity. This ensures their compatibility with existing quantum hardware platforms (such as IBM Quantum, Rigetti, and others). Therefore, the results of this research provide not only theoretical contributions but also practically applicable solutions suitable for deployment in real computational environments.

Volume and Structure of the Dissertation

The dissertation consists of an introduction, four main chapters, a conclusion, and a list of references. The total volume of the work is approximately 80 pages, including tables, figures, and formulas. The reference list contains more than 50 entries.

Chapter 1 presents a literature review on quantum machine learning, the mathematical foundations of quantum computing, and quantum convolutional neural networks.

Chapter 2 covers the fundamentals of parameterized quantum circuits for image recognition tasks: data encoding methods, PQC structure, and variational algorithms.

Chapter 3 describes the hybrid HQCNN architecture, the Data Re-uploading method, and the design of QConv2D and QDense layers.

Chapter 4 presents the development of the genetic algorithm for quantum circuit optimization, the results of experimental studies on the MNIST, FashionMNIST, and CIFAR-100 datasets, and a comparative analysis.

Approbation of the Work

The results of the work were discussed at scientific seminars of the Faculty of Information Technologies and Artificial Intelligence at Al-Farabi Kazakh National University, and were also presented at international conferences:

- International Conference of Computational and Information Technologies in Science, Engineering and Education (CITech-2025), Almaty, Kazakhstan, 2025;
- IEEE International Scientific Conference on Smart Information Systems and Technologies, Astana, Kazakhstan, 2024.

Publications.

7 printed works have been published on the topic of the dissertation, including 4 in publications recommended by the Committee for Control in Education and Science of the Republic of Kazakhstan, 3 in peer-reviewed journals indexed in international citation databases (Web of Science and/or Scopus), and 1 in proceedings of international conferences.

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