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EDITORIAL

Quantum Computing and AI

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Quantum computing is currently in an important transitional stage: While quantum computers nowadays have reached a size and performance that cannot or only with restrictions be classically simulated, it remains to be investigated for which applications a quantum advantage can be reached. This defined an ideal entry point to look beyond the already proven acceleration of a few certain classical computing tasks such as unstructured search and prime factorisation by quantum computers with a keen focus at AI and its applications as some of the most important key technologies of our time.

In fact, *Quantum Artificial Intelligence* (QAI) aims to combine both worlds to their respective advantage. In other words, QAI research is concerned with the use of quantum computing for addressing computationally hard problems in AI, and vice versa, the use of AI to tackle challenges of building and operating quantum computing system. Of particular interest are the development of direct quantum or hybrid quantum-classical algorithms for problem solving *and* the investigation of their potential advantage over their best classical counterparts. Within AI, quantum AI is not just limited to quantum machine learning but also encompasses quantum planning and scheduling, quantum natural language processing, quantum computer vision, and quantum multi-agent systems.

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In the past decade, an impressive progress was made in both directions of QAI. Research on quantum-supported solutions of selected hard optimization problems in AI provided insights on the potential of quantum utility with use cases in various domains such as manufacturing, automated driving, transport and logistics, finance, and energy management. By 2030, the global market of quantum AI applications in general is actually estimated to be worth around eighteen billions of USD [1]. On the other hand, quantum computing can benefit from the use of AI methods, particularly from machine learning, for optimizing the control, performance and calibration of quantum computational devices.

In this special issue, we provide the reader with a first overview of quantum AI through an introductory survey to the field, a short collection of selected articles on recent research results in different subfields of QAI, relevant projects and systems, as well as an expert interview on quantum technologies and AI in general. In addition, the service part of this editorial may serve the reader as an entry point for further information on activities in quantum AI.

1 Content

1.1 Overview

In our contribution, *Quantum Artificial Intelligence: A Brief Survey*, we give an overview of the current state of research and development in quantum AI. After a short recall of quantum computing, we summarize selected key research results on the use of quantum computing for selected hard computational problems in different AI subfields together with related topics for future research. Then we do the same for the other direction of QAI, namely, the use of classical AI methods for quantum hardware engineering and operation.

1.2 Technical Contributions

Regarding the popular QAI subfield of quantum machine learning (QML), Antonio Macaluso presents an introductory overview of *Quantum Supervised Learning*, in terms of its selected methods, limitations and open research directions. In this context, the author distinguishes between two categories: (1) fault-tolerant QML methods like quantum support vector machines, quantum splines, and quantum linear regression, and (2) hybrid QML methods like quantum neural networks and quantum Kernels. While methods of the first category require error-corrected qubits and the capability to run arbitrarily long quantum circuits, those of the second are supposed to run on (contemporary) NISQ devices characterized by noisy and shallow quantum circuits. The author concludes that the state of research in this area does not definitely favor quantum models over classical ones yet but requires the availability of fault-tolerant quantum computers for this purpose.

Dominic Widdows reviews the current state of *Quantum Natural Language Processing* (QNLP) in QAI. The author describes how the fundamentals of gate-based quantum computing can be used to efficiently encode text as basic units of language and also higher-level concepts in classical NLP up to large language models. Among other, the author concludes that quantum methods being developed in this context at the small scale appear promising also for their use on intermediate scale problems of NLP.

Francesca De Falco and colleagues present two *Quantum Hybrid Diffusion Models for Image Synthesis* in the field of quantum vision (QV) in QAI. The first approach, QVU-Net, replaces the convolutional ResNet layers with hybrid quantum-classical variational quantum circuits only at the vertex, while the second, the QuanvU-Net, does so as well in the second block of the encoder part. The authors provide some experimental evidence for the benefit of this kind of quantum hybrid diffusion models, in the sense that these models (a) synthesize better-quality images and converge faster, and (b) do so with a lower number of parameters to train compared to the classical counterpart depending on the extent to which the vertex is hybridized.

Regarding quantum AI applications in the finance sector, Patrick Rebentrost and Seth Lloyd present and discuss *quantum algorithms for portfolio optimization*. The problem is to find an optimal investment strategy for input market data assets that achieves a certain desired return while risk is minimized. The authors show that their solution with poly(log(N)) runtime, where N is the number of input market data assets, can provide some polynomial speedup compared to poly(N) runtime of direct classical counterparts. As the authors state, the potential quantum utility in terms of even only a small speedup for financial calculations in principle can have a large impact in terms of financial reward in practice.

1.3 Project Reports

In the article *Q-Grid - Quantum Optimization for the Future Energy Grid*, Jonas Blenninger and colleagues summarize the key findings of the BMBF (German Federal Ministry for Education and Research)-funded Q-Grid project. Research in this project did focus on quantum AI for energy management in general, and optimal load balancing based on dynamic pricing, as well as micro-grid formation based on community detection directly or via prosumer coalition formation for optimal sharing, pooling and trading renewable resources in particular. The investigation revealed that for the selected optimization problems the use of variational quantum algorithms such as QAOA and hybrid quantum annealing solvers may provide better runtime scaling with similar solution quality.

Tobias Stollenwerk and colleagues present in $Q(AI)^2$ *- Quantum Artificial Intelligence for the Automotive Industry* the results of the BMBF-funded QAI2 project on quantum AI for selected automotive use cases. In particular, the project delivered first insights on the potential of QAI methods for selected hard optimisation and classification problems each with a selected application in the automotive domain such as capacitated vehicle routing, safe navigation of autonomous vehicles, bin packing and flexible job-shop scheduling, as well as quality assessment classification of finite-element networks in engineering. In many cases, the theoretical and experimental analysis revealed evidence for quantum utility for the specific problem at hand. The developed QAI solutions are tailored to D-Wave quantum (annealer) hardware and frameworks such as Qiskit and Pennylane, and are publicly available.

The article *QUASIM - Quantum Computing Enhanced Service Ecosystem for Simulation in Manufacturing* by Wolfgang Maass and colleagues reports on the current state of the BMBF-funded project QUASIM on QAI for manufacturing. Their research on the potential of QML algorithms for manufacturing processes focuses on two use cases: the FEM-aided simulation and optimization of milling processes in the production of blade integrated disks (blisks) for jet engines, and the laser cutting of metals with a focus on heat dispersion and thermal expansion. The ongoing project QUASIM envisions the development of a comprehensive service-oriented framework of end-to-end software packages that seamlessly integrate quantum algorithms with manufacturing processes in an user-friendly and accessible way for industry professionals.

1.4 System Descriptions

Michael Falkenthal and colleagues present in *PlanQK - Platform and Ecosystem for Quantum Applications* the serverless API-driven service-oriented software platform PlanQK in support of an open community-driven ecosystem for quantum computing. The publicly available platform is the key result of the BMWK (German Federal Ministry for Economic Affairs and Climate Action)-funded lighthouse project PlanQK and offers an increasing number of QML algorithms and implementations for various use cases. PlanQK acts as a hub for users allowing them to access selected quantum backends provided by multiple clouds, such as AWS Braket and Microsoft Azure, with just one PlanQK account. The PlanQK platform software also enables users to model, train, evaluate, deploy and orchestrate quantum services into higher-level quantum solutions, and offers a marketplace for their trading and exchange.

The article *Benchmarking Quantum Generative Learning: A Study on Scalability and Noise Resilience using QUARK* by Florian J. Kiwit and colleagues introduces the QUARK framework for the benchmarking of QML algorithms in terms of scale, quality, and speed. The authors used QUARK to investigate the effects of statistical and quantum noise in QML applications, focusing on the training of selected quantum generative models, namely, the quantum computing Born machine (QCBM) and the quantum generative adversarial network, as well as the effects of quantum noise in the training of QCBMs. The QUARK framework was developed in part in the BMBF-funded project $Q(AI)^2$ and is publicly available.

1.5 Expert Interview

Finally, in our interview on *Quantum Technologies and AI* with professor Tommaso Callarco from the Research Center Julich in Germany, we discuss the relations between quantum computing and AI in general, and the current status and potential impact of quantum AI research worldwide. Tommaso is well-known for his work in quantum technologies, as well as for his leading role in the European Quantum Community Network, and the initiation of the European Quantum Industry Consortium and the European Quantum Technology flagship program. .

2 Service

The field of Quantum AI is currently researched within both the physics and computer science communities. This is reflected in its academic cultures: While conferences in physics are often broad and inclusive and journals are the most prominent venue for publications, computer science conferences are often focused and selective and represent the top destinations for papers.

2.1 Scientific Events

The interdisciplinary nature of QAI research papers calls for conferences and workshops in the fields of quantum computing and AI with relevant topics. Currently, there are a few such scientific events but a clear need for more that are specifically devoted to QAI, and which would address relevant communities to join forces in this regard.

- European Quantum Technologies Conference (EQTC)
- International Conference on Quantum Techniques in Machine Learning (QTML)
- IEEE International Conference on Quantum Software (QSW)
- IEEE International Conference on Quantum Computing and Engineering (QCE) / Quantum Week
- Adiabatic Quantum Computing (AQC)
- International Network on Quantum Annealing Conference (INQA)
- Quantum Information Processing (QIP)
- International Conference on Computational Science (ICCS)
- ACM International Conference on Computing Frontiers (CF)
- European Conference on Artificial Intelligence (ECAI)
- International Joint Conference on Artificial Intelligence (IJCAI)
- International Workshop on Quantum Algorithms, Optimization, and AI (QAI)

2.2 Journals

Journals exclusively dedicated to Quantum AI are extremely rare, the international journal on Quantum Machine Intelligence published by Springer appeared to be the first one in this respect. After all, every now and then special issues of scientific journals on QAI-relevant topics are published, such as the present issue. In the world of physics journals, some general journals are picking up Quantum AI, but there has also been an emergence of journals more dedicated to quantum information processing.

- Quantum Machine Intelligence (Springer)
- Artificial Intelligence (Elsevier)
- Transactions on Quantum Engineering (IEEE)
- Physical Review Letters, Physical Review A, Physical Review X Quantum (American Physical Society)

- Nature, NPJ Quantum Information, European Physical Journal Quantum Technology, Quantum Information Processing (Springer Nature)
- Quantum Science and Technology (Institute of Physics Publishing)

2.3 Quantum Programming and Simulation

There are a number of freely available software tools and frameworks for the programming and simulation of quantum algorithms.

- Xanadu Pennylane [4]
- IBM Qiskit [5]
- OpenQASM (Open Quantum Assembly Language)[6]
- Google Cirq and TensorFlow Quantum [7]
- Microsoft Azure Quantum [8]
- Amazon Braket [9]
- Rigetti Forest [10]

2.4 QAI Research Landscape

There is an increasing number of academic institutions, companies, and organisations related to QAI research worldwide of which we list but a few.

- Quantum Group at University of Oxford, UK [11]
- Centre for Quantum Information and Quantum Control—Quantum Computing and Algorithms at University of Toronto, Canada [12]
- NASA Quantum Artificial Intelligence Laboratory (QuAIL), USA [13]
- Applied Quantum Algorithms Group (aQa) at Leiden University, The Netherlands [14]
- Center for Quantum Science and Engineering (QSE) at EPFL, Switzerland [15]
- Quantum Information & Computation—AI and Science Group at Innsbruck University, Austria [16]
- Quantum Applications and Research Lab at (QAR-Lab) at Ludwig-Maximilians-University Munich, Germany [17]
- Quantum Algorithms Group at Research Center Jülich (FZJ), Germany [18]
- Quantum AI research at German Research Center for AI (DFKI) in Saarbrücken, Kaiserslautern and Bremen, Germany
- Quantum Computer Vision Group at Max-Planck-Institute for Informatics in Saarbrücken, Germany [28]
- Quantum Machine Learning at Fraunhofer Institute IAIS in Bonn, Germany [29]
- Multiverse Computing [19]
- Google Quantum AI Lab [20]
- Microsoft Azure Quantum team [21]
- IBM Quantum ML Research [22]
- Xanadu Quantum Technologies [23]
- European Quantum Community Network (QCN) [26]
- Quantum Computing User Network in Deutschland (QuCUN) [27]
- Special Interest Group on Quantum Computing of the German Society for Informatics (GI-FGQC) [24]
- AI Chapter of German Society for Informatics (GI-FBKI) [25]

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6. Open Quantum Assembly Language (OpenQASM), IBM Qiskit part: openqasm.com
7. Google Cirq: quantumai.google/cirq, TensorFlow Quantum www.tensorflow.org/quantum
8. Microsoft Azure Quantum. quantum.microsoft.com
9. AWS Amazon Braket: aws.amazon.com/de/braket
10. Rigetti Forest SDK: qcs.rigetti.com/sdk-downloads
11. Quantum Group at University of Oxford, UK: www.cs.ox.ac.uk/activities/quantum
12. Centre for Quantum Information and Quantum Control - Quantum Computing & Algorithms at University of Toronto, Canada: cqiqc.physics.utoronto.ca/research/research-areas/quantum-computing-and-algorithms/
13. NASA Quantum Artificial Intelligence Laboratory (QuAIL), USA: www.nasa.gov/intelligent-systems-division/discovery-and-systems-health/nasa-quail

14. Applied Quantum Algorithms Group (aQa) at Leiden University, The Netherlands: aqa.liacs.nl
15. Center for Quantum Science and Engineering (QSE) at EPFL, Switzerland: www.epfl.ch/research/domains/quantum-center
16. Quantum Information & Computation - AI and Science Group at Innsbruck University, Austria: www.uibk.ac.at/th-physik/qic-group
17. Quantum Applications and Research Lab at (QAR-Lab) at Ludwig-Maximilians-University Munich, Germany: qarlab.de
18. Quantum Algorithms Group at Research Center Jülich (FZJ), Germany: www.fz-juelich.de/en/pgi/pgi-12/groups/quantum-algorithms
19. Multiverse Computing: multiversecomputing.com
20. Google Quantum AI Lab. quantumai.google
21. Microsoft Azure Quantum team: azure.microsoft.com/en-us/blog/quantum
22. IBM Quantum ML Research. research.ibm.com/topics/quantum-machine-learning
23. Xanadu Quantum Technologies (Xanadu Research - Quantum algorithms): www.xanadu.ai/research
24. Special Interest Group on Quantum Computing of the German Society for Informatics (GI-FGQC): fg-qc.gi.de
25. AI Chapter of the German Society for Informatics (GI-FBKI): fb-ki.gi.de
26. European Quantum Community Network (QCN): qt.eu/structure-governance/quantum-community-network
27. Quantum Computing User Network in Germany (QuCUN): www.qucun.de
28. Quantum Computer Vision Group at Max-Planck-Institute for Informatics in Saarbrücken, Germany: 4dqv.mpi-inf.mpg.de
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