A Review on Quantum Computing

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Abstract - This literature review examines the evolution of quantum computing research over the past decade, from 2015 to 2025. Quantum computing, leveraging the principles of quantum mechanics to solve complex problems intractable for classical computers, has emerged as a transformative field with potential applications spanning medicine, materials science, artificial intelligence, and cryptography . Its relevance stems from the limitations of classical computing in addressing increasingly complex computational challenges, driving the need for alternative paradigms. The purpose of this review is to synthesize the key advancements, influential studies, persistent challenges, and emerging trends that have characterized quantum computing research during this period. By analyzing the trajectory of the field, this review aims to provide a comprehensive overview of the current state and future directions of quantum computing.

***Key Words*:** CiteSpace, quantum algorithms, quantum machine learning, scientometric analysis,Web of Science (WoS).

1. INTRODUCTION

Quantum computing, leveraging the principles of quantum mechanics to perform complex calculations beyond the capabilities of classical computers, has emerged as a transformative field with the potential to revolutionize various sectors, including medicine, materials science, finance, and artificial intelligence . Over the past decade, research in quantum computing has experienced exponential growth, marked by significant advancements in hardware development, algorithm design, and the exploration of potential applications . This surge in interest is driven by the promise of quantum computers to solve currently intractable problems, such as drug discovery, optimization challenges, and breaking modern encryption algorithms .

The relevance of quantum computing to the broader scientific and technological landscape cannot be overstated. As classical computing approaches its physical limits, quantum computing offers a fundamentally different approach to computation, promising unprecedented computational power . This potential has spurred substantial investment from governments, academic institutions, and private companies worldwide, fostering a vibrant and rapidly evolving research ecosystem . The development of fault-tolerant quantum computers could lead to breakthroughs in understanding complex systems, designing novel materials, and developing more efficient algorithms for machine learning .

This literature review aims to provide a comprehensive overview of the key developments and research trends in quantum computing over the past decade (2015-2025). It will highlight influential studies that have shaped the field, analyze the similarities and differences among various approaches, summarize the main findings, and identify gaps in current research, suggesting areas for future exploration. By examining the progress made in quantum hardware, algorithms, and applications, this review seeks to provide a valuable resource for researchers, policymakers, and anyone interested in understanding the current state and future prospects of quantum computing . The review will also touch upon the challenges that remain in realizing the full potential of quantum computing, including issues related to qubit stability, scalability, and error correction . Finally, the ethical and societal implications of this technology will be briefly considered, acknowledging the need for responsible development and deployment of quantum computing technologies .

Quantum Algorithms and Applications

Quantum algorithms leverage the principles of quantum mechanics to solve computational problems that are intractable for classical computers. This section reviews the progress made in quantum algorithms and their applications over the past decade, highlighting key achievements, influential studies, and potential future directions. The purpose of this review is to synthesize the diverse research efforts in this area, identify gaps in current knowledge, and suggest promising avenues for further exploration.

Shor's Algorithm and its Extensions

Shor's algorithm, developed in 1994, remains a cornerstone of quantum computing, demonstrating the potential for exponential speedup in factoring large numbers . This algorithm has significant implications for cryptography, as many widely used encryption schemes rely on the difficulty of factoring. Over the past decade, research has focused on improving the practical implementation of Shor's algorithm, including reducing the number of qubits required and increasing its resilience to noise . Furthermore, researchers have explored extensions of Shor's algorithm to solve related problems, such as computing discrete logarithms and finding the structure of hidden subgroups . These advancements have broadened the applicability of Shor's algorithm and solidified its importance in the field.

Grover's Algorithm and Search Problems

Grover's algorithm provides a quadratic speedup for searching unsorted databases compared to classical algorithms . While the speedup is not exponential like Shor's algorithm, Grover's algorithm has a wider range of applications, including optimization, machine learning, and data analysis . Recent research has focused on developing quantum search algorithms with improved efficiency and robustness, as well as exploring hybrid quantum-classical approaches that combine the strengths of both paradigms . For example, amplitude amplification, a generalization of Grover's algorithm, has been used to accelerate Monte Carlo simulations and improve the performance of machine learning algorithms .

Quantum Simulation

Quantum simulation aims to use quantum computers to simulate the behavior of other quantum systems, which is often intractable for classical computers . This has applications in various fields, including materials science, drug discovery, and fundamental physics . Significant progress has been made in developing quantum algorithms for simulating molecular systems, condensed matter systems, and quantum field theories . Researchers are also exploring the use of quantum simulation to study complex phenomena such as high-temperature superconductivity and quantum phase transitions . The development of more powerful quantum computers will enable the simulation of increasingly complex systems, leading to new scientific discoveries and technological advancements.

Quantum Machine Learning

Quantum machine learning is an emerging field that explores the potential of quantum computers to enhance machine learning algorithms . Quantum algorithms have been developed for various machine learning tasks, including classification, clustering, and dimensionality reduction . These algorithms offer the potential for speedups compared to classical machine learning algorithms, particularly for large datasets . However, the development of practical quantum machine learning algorithms is still in its early stages, and further research is needed to overcome challenges such as noise and limited qubit connectivity. As quantum computers become more powerful, quantum machine learning is expected to play an increasingly important role in data analysis and artificial intelligence.

Near-Term Applications and Hybrid Algorithms

With the advent of near-term quantum devices, also known as Noisy Intermediate-Scale Quantum (NISQ) computers, research has shifted towards developing quantum algorithms that can be implemented on these devices . Variational quantum algorithms (VQAs) are a prominent example of such algorithms, which combine classical optimization techniques with quantum computations to solve optimization problems . These algorithms have been applied to various problems, including quantum chemistry, materials science, and combinatorial optimization. Hybrid quantum-classical algorithms, which leverage both classical and quantum resources, are also gaining traction as a promising approach for near-term quantum computing . These algorithms offer the potential to achieve quantum advantage for specific problems, even with limited qubit resources and high noise levels.

Gaps and Future Directions

Despite the significant progress made in quantum algorithms and applications, several gaps remain in current research. One major challenge is the development of quantum algorithms that are robust to noise and can be implemented on near-term quantum devices. Another challenge is the need for more efficient quantum algorithms for specific problems, as many existing algorithms still require a large number of qubits or quantum gates. Future research should focus on developing new quantum algorithms that are tailored to the capabilities of near-term quantum devices, as well as exploring new applications of quantum computing in various fields. Furthermore, more research is needed to understand the fundamental limits of quantum computation and to develop new theoretical tools for analyzing the performance of quantum algorithms. As quantum computers continue to evolve, quantum algorithms and applications will play an increasingly important role in solving some of the world's most challenging problems.

2. Quantum Hardware and Architectures

Quantum computing's potential hinges on the successful development of robust and scalable quantum hardware. This section reviews the major hardware platforms and architectural approaches that have dominated the field over the past decade. We aim to provide an overview of their strengths, weaknesses, and the key research trends shaping their evolution.

Superconducting Qubits

Superconducting qubits have emerged as a leading platform for quantum computing, largely due to their compatibility with existing microfabrication techniques and their demonstrated scalability . These qubits, based on Josephson junctions, exhibit macroscopic quantum behavior, allowing for the creation of quantum superposition and entanglement . Early work focused on transmon qubits, which offer reduced sensitivity to charge noise . Researchers have explored various architectural designs, including 2D lattices and 3D integration , to increase qubit connectivity and density. Companies like Google, IBM, and Rigetti have heavily invested in superconducting qubit technology, achieving significant milestones in qubit count and coherence times . However, challenges remain in improving qubit fidelity, reducing crosstalk, and developing sophisticated control electronics for large-scale systems . Recent research explores novel materials and fabrication techniques to enhance qubit performance and address these limitations .

Trapped Ions

Trapped ions represent another prominent approach to quantum computing, known for their high fidelity and long coherence times . In this approach, individual ions are confined using electromagnetic fields and their internal energy levels are used to encode quantum information . Quantum gates are implemented using lasers to manipulate the ions' quantum states and induce entanglement . Trapped ion systems have demonstrated impressive gate fidelities and all-to-all connectivity, making them suitable for implementing complex quantum algorithms . Research efforts are focused on scaling up the number of trapped ions while maintaining high fidelity, which requires advanced ion trapping techniques and precise laser control . Architectures based on shuttling ions between different zones within a trap are being explored to overcome connectivity limitations . Companies like IonQ and Honeywell (now Quantinuum) are actively developing trapped ion quantum computers, pushing the boundaries of performance and scalability .

Neutral Atoms

Neutral atom qubits, particularly those based on Rydberg atoms, have gained increasing attention in recent years . These qubits utilize the internal energy states of neutral atoms trapped in optical lattices or tweezer arrays . Rydberg atoms, with their highly excited electronic states, exhibit strong interactions, enabling the implementation of quantum gates via controlled collisions . Neutral atom systems offer advantages in terms of scalability and connectivity, as large arrays of atoms can be readily created and manipulated . Research is focused on improving the coherence times of Rydberg qubits and developing efficient methods for entangling multiple atoms . Several research groups and companies, including ColdQuanta and Atom Computing, are pursuing neutral atom quantum computing, demonstrating promising results in terms of qubit count and gate fidelity .

Photonic Qubits

Photonic qubits, encoded in the properties of photons, offer unique advantages for quantum communication and distributed quantum computing . Photons are naturally mobile and exhibit low decoherence, making them ideal for transmitting quantum information over long distances . Quantum gates can be implemented using linear optical elements or nonlinear optical processes . While photonic qubits have shown promise in demonstrating quantum key distribution and other quantum communication protocols, scaling up photonic quantum computers remains a significant challenge . Recent research focuses on developing integrated photonic circuits and novel sources of entangled photons to overcome these limitations . Companies like PsiQuantum are pursuing photonic quantum computing, aiming to build large-scale fault-tolerant systems .

Other Emerging Architectures

Beyond the four leading platforms, several other quantum computing architectures are under active investigation. These include:

- **Topological Qubits:** Based on exotic states of matter that are inherently robust to noise .
- **Silicon Qubits:** Leveraging the well-established silicon manufacturing infrastructure .
- **Nitrogen-Vacancy (NV) Centers in Diamond:** Utilizing the spin states of NV centers as qubits .

These emerging architectures offer unique advantages and face distinct challenges in terms of scalability, coherence, and control. Continued research and development are crucial to assess their potential and determine their role in the future of quantum computing.

GRAPH_DESCRIPTION: Comparison of different quantum computing hardware platforms (Superconducting, Trapped Ion, Neutral Atom, Photonic) based on key metrics such as coherence time, gate fidelity, scalability, and connectivity.

Collaborative Efforts and Industry Investments

Quantum computing's rapid advancement over the past decade has been significantly fueled by collaborative efforts between academic institutions, government agencies, and private sector companies, alongside substantial industry investments. This section reviews these collaborations and investments, highlighting their impact on the field's progress and identifying future trends.

Academic-Industry Partnerships

Academic-industry partnerships have become a cornerstone of quantum computing research. These collaborations leverage the fundamental research expertise of universities with the engineering and commercialization capabilities of industry . For example, the partnership between the University of California, Berkeley, and Google has led to significant advancements in superconducting qubit technology . Similarly, collaborations between universities like MIT and companies such as IBM have accelerated the development of quantum algorithms and software . These partnerships often involve joint research projects, shared facilities, and the exchange of personnel, fostering a synergistic environment for innovation. The Quantum Economic Development Consortium (QED-C), established in 2018, plays a crucial role in fostering these collaborations by bringing together stakeholders from academia, industry, and government to identify and address key challenges in quantum computing .

Government Initiatives and Funding

Government initiatives and funding have played a pivotal role in supporting quantum computing research and development. Recognizing the strategic importance of quantum technologies, governments worldwide have launched ambitious programs to foster innovation and maintain a competitive edge . The National Quantum Initiative Act in the United States, signed into law in December 2018, has provided significant funding for quantum research across various government agencies, including the Department of Energy, the National Science Foundation, and the National Institute of Standards and Technology . Similarly, the European Union's Quantum Technologies Flagship, launched in 2018, aims to foster a European quantum industry through collaborative research and development projects . China has also made substantial investments in quantum computing, with a focus on developing quantum communication networks and building large-scale quantum computers . These government initiatives not only provide funding for research but also help to establish national quantum strategies and promote international collaboration .

Private Sector Investments and Commercialization

Private sector investments in quantum computing have surged in recent years, driven by the potential for transformative applications across various industries. Major technology companies, including Google, IBM, Microsoft, and Amazon, have made significant investments in developing their own quantum computing platforms and services . These companies are not only building quantum computers but also developing quantum software and cloud-based quantum computing services, making quantum computing resources more accessible to researchers and businesses . Venture capital firms have also invested heavily in quantum computing startups, focusing on areas such as quantum algorithms, quantum software, and quantum hardware components . As of today, November 3, 2025, the increasing availability of quantum computing resources and the growing ecosystem of quantum software and tools are accelerating the commercialization of quantum technologies . However, significant challenges remain in scaling up quantum computers and developing practical quantum algorithms that can outperform classical computers for real-world applications .

3. CONCLUSIONS

Quantum computing has emerged as a transformative field with the potential to revolutionize computation and information processing .This literature review has explored the evolution of quantum computing research over the past decade, highlighting key advancements, influential studies, and persistent challenges. The purpose of this review was to synthesize the diverse body of knowledge in the field, identify gaps in current research, and suggest potential directions for future exploration as of November 3, 2025.

Summary of Main Findings

The literature reveals significant progress in several areas. Quantum algorithms, such as Shor's algorithm for factoring and Grover's algorithm for searching , have demonstrated the potential for exponential speedups compared to their classical counterparts. Significant effort has been devoted to developing and improving quantum hardware platforms, including superconducting circuits , trapped ions , photonic systems , and topological qubits . Each platform possesses unique strengths and weaknesses in terms of coherence, scalability, and gate fidelity. Quantum error correction (QEC) remains a critical area of research, with various encoding schemes and fault-tolerant architectures being actively investigated . Furthermore, quantum simulation has shown promise in tackling complex scientific problems in fields like materials science and drug discovery . The development of quantum software and programming languages is also advancing, aiming to make quantum computers more accessible to a wider range of users .

Influential Studies and Comparative Analysis

Several studies have profoundly shaped the field. The experimental demonstration of Shor's algorithm on a small-scale quantum computer was a landmark achievement, solidifying the practical potential of quantum computation. Research on topological quantum computation , while still in its early stages, offers the promise of inherently fault-tolerant qubits, which could significantly simplify the task of QEC. The development of variational quantum eigensolver (VQE) and quantum approximate optimization algorithm (QAOA) has provided near-term quantum algorithms suitable for implementation on noisy intermediate-scale quantum (NISQ) devices. These algorithms, while not providing exponential speedups, offer potential advantages for specific optimization and simulation problems. A comparison of different quantum computing platforms reveals a trade-off between coherence times and connectivity . Superconducting qubits generally offer high connectivity but are susceptible to decoherence, while trapped ions exhibit longer coherence times but have limited connectivity.

Gaps in Research and Future Directions

Despite the remarkable progress, several challenges remain. Building large-scale, fault-tolerant quantum computers is a formidable engineering challenge. Improving qubit coherence times, gate fidelities, and scalability are crucial for realizing the full potential of quantum computing . Furthermore, the development of efficient quantum algorithms for a wider range of problems is essential. Research on quantum machine learning is still in its early stages, and exploring the potential of quantum algorithms for machine learning tasks is an active area of investigation . Another gap lies in the development of robust quantum software tools and programming languages that can effectively harness the power of quantum computers . Future research should focus on addressing these challenges, exploring novel quantum computing architectures, and developing new quantum algorithms and applications. As quantum computing technology matures, it is poised to transform various aspects of science, technology, and society .

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