Quantum Computing for Databases: A Short Survey and Vision

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Abstract

With the development of quantum computing, significant advancements have been made since the 1980s, leading to the birth of quantum computers and sparking widespread enthusiasm in this emerging field. While quantum computing is still in its early stages of development, researchers are increasingly drawn to its magic power and have identified numerous compelling applications across various domains, ranging from cryptography, query optimization, and machine learning. Notably, one of the most promising applications lies within the realm of database management systems, giving rise to quantum computing for databases, which holds the potential to offer substantial advantages over classical databases, particularly in terms of query processing speed and efficiency, as well as saving memory space. This vision paper aims to provide an overview of the current research challenges and opportunities of quantum computing for the field of databases, as well as outline the potential for the development of a quantum multi-modal database.

Keywords

Quantum Computing, Quantum Database, Database Search, Database Manipulation, Query Optimization, Transaction Management, Database Query Language, Database Model

1. Introduction

Every update of quantum hardware (computer) attracts the attention of countless people, expecting it to provide more substantial computing power. The source of this expectation is the fact verified by proposed quantum algorithms: quantum computing, indeed, has the ability to solve certain problems more effectively than classical computing [1, 2]. Therefore, many researchers are spending lots of energy exploring quantum computing's applications (of academic or commercial interest) that can realistically be solved faster on a quantum computer than on a classical one (e.g., cryptanalysis [3, 4], materials science [5], and chemistry [6]). This is called practical quantum advantage, or quantum practicality for short [7]. One of the most promising applications is in the realm of database management systems [8], giving rise to the concept of *quantum databases*.

Quantum databases will be built upon the unique capabilities of quantum computing, which relies on the principles of quantum mechanics to perform computations. These principles allow quantum computers to process information in parallel, enabling them to solve certain problems more efficiently than classical computers. To fully exploit the potential of quantum computing in database management systems, researchers are currently exploring novel approaches for implementing quantum data structures and algorithms, as well as investigating interdisciplinary collaborations between the fields of quantum computing and database management. These efforts are paving the way for innovative solutions in areas such as quantum database search, database manipulation, query optimization, and transaction management.

This paper aims to provide an analysis of the current state of quantum databases by examining existing and mostly researched areas (see Table 1). Additionally, it will discuss the primary challenges that impede the growth of quantum databases, including the necessity for mature quantum computing hardware, limited coherence times, and the absence of well-established query languages and data models specifically tailored for quantum systems. Lastly, this paper will present a visionary outlook on quantum multi-modal databases, outlining their potential benefits. By tackling these challenges and unlocking the potential of quantum databases, our goal is to enhance database systems to support multi-modal storage, management, and search functionalities, among others.

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Table 1
An Overview of Current Development of Quantum Computing for Databases

Problems	Quantum-Enabled
Database Search	[1, 2, 9, 10, 11, 12, 13, 14, 15]
Database Manipulation	[16, 17, 18, 19, 20, 21, 22]
Query Optimization	[23, 24, 25, 26, 27, 28]
Transaction Management	[29, 30, 31]

The rest of the paper is organized as follows. Section 2 presents the current development of quantum hardware. Section 3 introduces the quantum-based methods applied in databases. Section 4 discusses the open challenges and vision. Section 5 concludes the paper.

2. Quantum Hardware

Quantum computing is a fast-growing technology. At the heart of it is quantum hardware, the physical devices, and components that allow quantum computers to function. This hardware – from the quantum bits (qubits) that hold and process quantum information to the circuits and cooling systems that make these qubits function – is very different from the classical computers we know well. Because of this difference, more attention is needed to promote the development of quantum hardware, so as to provide a better ecological environment for the development of its applications (e.g., databases). The key components of quantum hardware are:

Qubits [32] are the fundamental building blocks of quantum computers. Unlike classical bits, which can be either 0 or 1, qubits can be in a superposition of states (denoted in the form $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, a two-dimensional vector, where the coefficients α and β are called *probability amplitudes*), empowering them to hold and process more information than classical bits.

Quantum Gates [33] are the basic operations that are performed on qubits. Since qubits are represented by column vectors mathematically, a quantum gate is defined as a unitary matrix. They are the quantum equivalent of classical logic gates but with extra capabilities due to the unique properties of quantum mechanics.

Quantum Circuits [34] include networks of qubits, quantum gates, and measurements, which is the most widely used model of quantum computation. Based on the quantum circuit, we list two representative types of quantum computers built in recent years.

1. In 2022, IBM [35] unveiled its most powerful quantum computer processor (Superconducting Circuits) to date, Osprey, a 433-qubit machine.
2. On June 22, 2023, IonQ [36], the world's first ion trap quantum computing company, launched the IonQ Forte system with 32 qubits, which users can access through the cloud on Amazon Braket, Microsoft Azure and Google Cloud, as well as through direct API access.

Adiabatic quantum computation [37] is another form of quantum computing. It works based on the adiabatic theorem. Efforts aimed at the realization of adiabatic quantum computation employing quantum physical systems are confronted with the challenge of non-ideal conditions, thereby impeding the fulfillment of the adiabatic theorem's potential. Quantum annealing, inhabiting an intermediary realm between the idealized assumptions of universal adiabatic quantum computation and the unavoidable compromises arising from experimental constraints, offers an alternative approach to identifying the minimum of an objective function without meeting the rigorous prerequisites set forth by adiabatic quantum computation [38, 39]. A quantum annealer uses a process, quantum annealing, to solve a hard optimization problem, whose method is evolving a known initial configuration at non-zero temperature towards the ground state of a Hamiltonian encoding a given problem [40]. A famous example of the quantum annealer is D-Wave [41].

- D-Wave Corporation (Canada) launched the world's first commercial quantum computer, "D-Wave One", on May 11, 2011. In 2023, D-Wave launched a 5000+ qubit computer.

Quantum Error Correction [42] is a set of techniques used to correct errors in quantum computations. Because qubits are extremely sensitive to noise and decoherence, these techniques are essential for creating reliable quantum hardware.

The advent of quantum computers has brought about a transformative impact on applications in various fields, offering more efficient and expedient resolutions to complex problems (e.g., Traveling Salesman Problem [43], Subset Sum Problem [44], and Boolean Satisfiability Problem [45]). Unfortunately, current quantum computers are Noisy Intermediate Scale Quantum (NISQ) devices [46], prone to substantial error rates and limited in size by the number of qubits in the system. However, luckily, NISQ computers are not our final goal. We firmly believe the ongoing research efforts of developing large-scale, fault-tolerant quantum computers indicate a bright future for quantum databases. Furthermore, developing efficient error correction mechanisms (e.g., surface code [47]) will be a huge aid to the development of quantum computing.

3. Quantum Computing for Databases

3.1. Quantum Database Search

The proposal of Grover's algorithm [1, 2] could help people know whether or not unsorted databases containing N records have one satisfying particular property by $O(\sqrt{N})$ operations instead of checking records one by one until finding the desired one. Based on this benefit of Grover's algorithm, people have made the following efforts in the hope of improving database query performance.

Grover [9] proposes an algorithm to locate the marked item in a single query. This algorithm is implemented by using enough subsystems, where each subsystem has an N dimensional state space like the system of the original Grover's algorithm [1, 2], and the number of subsystems (denoted as m) needs to be $\Omega(NlogN)$.

Terhal and Smolin [10] propose quantum algorithms for a class of problems (e.g., binary search and coin-weighing problems), which could retrieve a quantum database in a single query. The proposal of the algorithms is based on Bernstein and Vazirani's parity problem.

Boyer et al. [11] proposes an algorithm to find one result item that appears more than once in an N-items table, and the number of result items (denoted as t) is not known ahead of time. Besides, based on Grover's algorithm, Boyer combines it with Shor's algorithm [48] to design an algorithm for approximately counting the number of solutions.

Patel [12] proposes a factorized quantum search algorithm to find the wanted object in an unsorted database by $O(log_4 N)$ queries, which is much similar to the assembly process in DNA replication. This algorithm first digitizes the database with integer labels (i.e., a string of letters belonging to a finite alphabet), where the number of integer labels is N and $N = a^n$ (i.e., the alphabet has a letters, the length of the string is n letters, and set $a = 4$). With digitization, the algorithm could check one letter of integer labels at a time. Next, this algorithm utilizes the projection/measurement operator P_i to remove from the Hilbert space all the states whose i^{th} letter is not what we want, where P_i could be denoted using identity operators. That is, $P_i = I_1 \otimes \ldots (I_i)_{fix} \otimes \cdots \otimes I_n$. One by one, the algorithm looks over all the letters and finally locates the item with the wanted label.

Imre and Balázs [13] present a generalized Grover's search algorithm to find the desired result with high accuracy while letting the algorithm iterate as few times as possible. In detail, this algorithm replaces the Hadamard transformation with an arbitrary unitary transformation. Then, the generalized Grover operator ($\mathbb{Q}$) could preserve the 2-dimensional vector space spanned by the refined state vectors $|\alpha\rangle$ and $|\beta\rangle$. Next, the algorithm derives the optimal number of iterations l_{opt} during a search after knowing $\mathbb{Q}$. Besides, the algorithm could utilize the final state of the index register as an input to another circuit for extending the scale of quantum systems.

Ju et al. [15], an extension of [14], use the quantum Boolean circuits to implement Grover's algorithm. The implementation of Grover's algorithm is made up of two parts: selective-inversion $I_{|x_0\rangle}$, and inversion-about-average $I_{|\psi_0^{\perp}\rangle}$. Besides, they summarize these problems and offer a template of quantum circuits for applying in the following situation: Give a one-way function $f : \{0,1\}^n \longrightarrow \{0,1\}^m$ and a m-bit integer M, the aim is to find an n-bit integer x for satisfying $f(x) = M$.

3.2. Database Manipulation

We all know that one of the abilities of database management systems (DBMSs) is to manipulate data. The basic processes in database systems involving data manipulation encompass a range of operations that include but are not limited to insertion, deletion, selection, and projection. In this part, we will introduce current research on applying quantum computing in this area.

Cockshott [16] mentions that the basic operations (selection, projection, and join) could be implemented in the quantum relational database. In detail, the primary key selection could be achieved with the help of Grover's algorithm [1, 2]. Relational database projection in the quantum database can be performed by only keeping the qubits that encode the domains of the projected relation and having the rest qubits discarded. The join operation could be implemented by cooperation with a similarity operator, a combining operator, and Grover's algorithm [1, 2].

Younes [17] defines some operations of a Quantum Query Language (QQL) used to manipulate a database file. Specifically, a way to insert records (one or several records) into the superposition in a single step is presented based on the tensor product. Then, a permutation operator is defined to achieve updating records. Next, by utilizing Boolean functions and global conditions, certain sets of records can be selected and conditional operations can be executed on the intersection of the selected records. And finally, backing up and restoring a required portion of the database file is given based on the oracle operator and partial diffusion operator.

Liu and Long [18] propose a quantum algorithm to delete a marked item, with a single query, from an unsorted database without knowing anything about the marked state. This algorithm is made up of the following iterative process: (i) Take phase rotations with a fixed value of $\pi/3$ to every basis state while the marked state $|\tau\rangle$ keeps unchanged; (ii) Do the n-qubit Hadamard transformation; (iii) Take phase rotations with a fixed value of $\pi/3$ to the $|0\rangle$ state; (iv) Do the n-qubit Hadamard transformation again. With this fixed phase angle $\pi/3$, the proposed deletion algorithm could nearly completely delete the marked state. Besides, this deletion operation is periodic, whose period is 3.

Pang et al. [19] propose a quantum algorithm combining Grover's algorithm, classical memory, and classical iterative computation for getting intersection. Specifically, the algorithm consists of two parts. The first part is a subroutine finding an element in set $X = A \bigcap B$, similar to the algorithm [11]. The second part is for getting $X = A \bigcap B$, which works by repeatedly calling the subroutine until there is no output from the subroutine.

Gueddana et al. [20] give a quantum database design. For the relational database, it consists of several relations (tables), where each table could be represented by a circuit (e.g., a CNOT-based circuit). Then, a quantum database associated with a relational database can be regarded as a collection of quantum circuits. Next, they design circuits to implement table, insert (i.e., inserting records into a quantum table), delete, and select, respectively. Here, they concentrate on selecting from naturally joined quantum tables instead of retrieving records from a single table.

Salman and Baram [21] propose an algorithm to pick any member of the intersection set $X = A \bigcap B$, which is based on the oracle f_A (i.e., $f_A(x) = 1, x \in A, otherwise f_A(x) = 0$), the oracle $f_B(x)$ (i.e., $f_B(x) = 1, x \in B$), the intersection oracle $f_{A \bigcap B}(x)$, and a Toffoli gate. Then the algorithm obtains an element in the intersection set X by using Grover's algorithm [1, 2].

Jóczik and Kiss [22] propose four quantum algorithms, for basic set operations (intersection, difference, union, projection), with the help of Grover's algorithm. The first one is to define an appropriate oracle function O_f to determine the intersection set X of set A and B. Then it uses the method of Grover's algorithm to locate X. The second algorithm is to obtain the set difference, which uses the previous intersection algorithm to obtain the result. The third one is to get a union. The last algorithm is to obtain projection, which consists of two parts. One is to remove the duplicate attributes, whose main idea is to convert a multiset to a set. The other one is to acquire the elements of the specific column, which is implemented based on Grover's algorithm.

3.3. Database Query Optimization

Query optimization is finding an optimal way to conduct a provided query by considering the possible query plans, which tends to explore large search spaces for solving this problem. In this part, we will introduce current research on applying quantum computing to the optimization problem.

Trummer and Koch [23] propose an algorithm to solve the problem of Multiple Query Optimization (MQO) with an adiabatic quantum computer, where MQO aims to choose a combination of query plans for minimizing the cost of running a set of queries. To reach this purpose, the algorithm first transforms an MQO problem instance into a Quadratic Unconstrained Binary Optimization (QUBO) problem instance. After that, the algorithm will use the quantum annealer to minimize the physical energy formula by finding an optimal value assignment. Then, the algorithm passes the solution returned by the quantum annealer back step by step. It uses the returned solution to obtain the answer and address the original MQO problem.

Fankhauser et al. [24] present an approach according to the Quantum Approximate Optimization Algorithm (QAOA), which could find quasi-optimal solutions for the MQO problem on a gate-based quantum computer. The approach comprises two parts: one is to explore the search space by parametrized quantum computing, and the other is to optimize the parameters by classical computing with the heuristic strategies [49].

Schönberger [25] investigates solving the MQO problem with QAOA on the gate-based 27-qubit quantum computer and analyses MQO problems with different numbers of plans per query. Besides, a multi-step reformulation is presented for the join ordering problem so that it can run on the quantum circuit/annealer. And finally, the related experiment results are given.

Schönberger et al. [26] present a quantum implementation of join ordering optimization based on a reformulation to QUBO problem. According to insights gained from the experimental analysis, authors identify design criteria for shaping quantum processing units (QPU) as special-purpose devices tailored to specific applications (e.g., databases). Furthermore, the authors conduct numerical simulations for tailored custom QPU designs and suggest minor architectural improvements on which the usefulness of custom co-designing QPUs for join ordering can be substantially enhanced.

Nayak et al. [27] propose to formulate the join order optimization problem as a QUBO problem and then solve this QUBO problem to find the best solution for the more general bushy join trees instead of the previous approach [26] finding the best solution among the left-deep join trees.

Winker et al. [28] develop a quantum machine learning approach to predict efficient join orders by learning from past join orders, which uses a variational quantum circuit (VQC) [50]. It is worth noting that this approach has been integrated into an open-source relational database management system.

3.4. Transaction Management with Quantum Machine

Transaction management is a critical component in database systems, ensuring data integrity and consis-

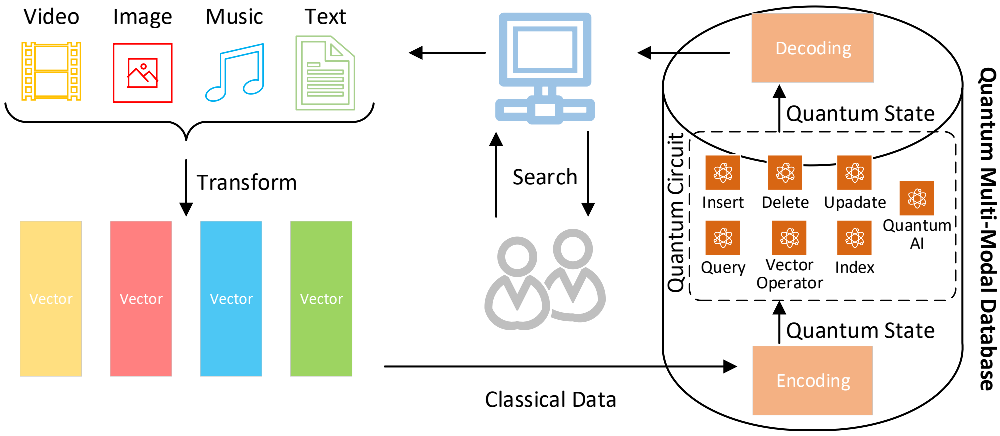

Figure 1: A Vision of Quantum Multi-Modal Databases

tency. However, the application of quantum technology and quantum computers in transaction processing is still in its nascent stages, with limited research conducted in this domain [51]. Currently, the primary focus is on modeling transaction processing as a general resource scheduling problem and leveraging quantum computing techniques to enhance its efficiency. This part introduces some techniques by quantum methods to speed up the transaction process of the concurrent controls.

Bittner et al. [29, 30] introduce an optimal quantum algorithm by leveraging quantum annealing to optimally schedule transactions over a two-phase locking database such that the performance of a quantum annealer outperforms traditional ones and isolation property is still guaranteed.

Groppe et al. [31], similar to [29, 30], leverage Grover's search algorithm in solving combinatorial optimization problems to optimally schedule transactions. Firstly, concerning the transaction lengths and conflicts between the transactions, the code generation modular is proposed for the black box function of Grover's search algorithm. And estimating the optimal solutions can further accelerate Grover's search algorithm. The authors also provide a detailed complexity analysis of the comparison between a quantum method and traditional ones in terms of preprocessing and execution time, space, and code length.

4. Open Challenges and Vision

The core vision of quantum databases is to harness the unique capabilities of quantum computing to revolutionize the field of database management systems. In particular, quantum databases aim to offer significant advantages in terms of query processing speed. To achieve this vision, researchers need to overcome several challenges related to quantum computing hardware and software, as well as develop new query languages and data models tailored for quantum systems.

One of the main challenges in realizing the vision of quantum databases is the development of mature quantum computing hardware. Although recent advances in quantum computing have led to the creation of several prototype quantum computers, these machines still suffer from issues such as limited coherence times, a lack of error correction mechanisms, and I/O bandwidth. For one, when accessing classical data in databases, current classical computers could do it faster than quantum computers. That is to say, fundamental I/O bottleneck (bounds for data input and output bandwidths) limits quantum computers in their interaction with the classical world [7]. To enable practical quantum database applications, researchers need to continue working on improving the stability and reliability of quantum computing hardware, as well as developing large-scale, fault-tolerant quantum computers. Of course, people could also regard quantum computing as a specialized hardware component of classical databases (e.g., [26]) to accelerate data processing. We call this *quantum accelerated databases*.

Another challenge lies in the development of query languages [52] and data models specifically designed for quantum database systems. Quantum databases require a new set of tools and techniques to handle the unique properties of quantum information, such as superposition and entanglement. Researchers should focus on creating intuitive query languages that can efficiently represent and manipulate quantum data, as well as designing data models that can effectively store and organize quantum information. This calls for interdisciplinary collaborations between the fields of quantum computing and database management, which are crucial for realizing the vision of quantum databases.

In this paper, we present a vision for the development of a quantum multi-modal database, as illustrated in Figure 1. This innovative approach aims to enable efficient and precise similarity searches, as well as data retrieval based on quantum vector distance or similarity. A vector database is designed to store data in the form of high-dimensional vectors, which serve as mathematical representations of various features or attributes. Vectors are commonly used to encode multi-modal data, encompassing diverse forms such as video, image, music, and text, into numerical representations. Leveraging the power of quantum circuits, the numerical values within these vectors can be efficiently encoded using quantum techniques. A straightforward approach is using multiple qubits to encode the numerical value of the vector and use controlled gates to determine the elements of the vector. Then we may apply quantum multipliers or adders on these vectors to accelerate processing. By combining the principles of quantum computing with the concept of vector databases, we anticipate advancements in the fields of similarity search and data retrieval. This approach holds the potential to revolutionize the way we process and analyze multi-modal data in quantum computing environments.

Additionally, it is crucial for this framework to encompass an accessible interface, enabling operations such as insertion, deletion, and updating of quantum data. Furthermore, there is a need to develop a quantum multi-modal query algorithm capable of efficiently accessing and processing multi-modal data. And it is feasible to develop the corresponding operations and query algorithms by building upon the extant works introduced in the previous section (e.g., [1, 20, 28, 30]). For example, we could use the following format to preserve the value located at index i in the v-th vector:

$$|v\rangle_{Vector\_ID}|i\rangle_{Index\_ID}|value\rangle_{Data},$$

where the three quantum registers storing qubits are used to save the ID of the vector, the index ID of the vector, and the value of the data, respectively. Next, we apply CNOT gates on these quantum registers to store the i-th data's value of the v-th vector, with the third register being the target qubits and the first two as control qubits. Besides, it could be extended as the storage format of relational tables. In summary, these could be interesting attempts in the future. On top of it, the utilization of Grover's algorithm [1], amplitude amplification, or quantum counting can be employed to perform various forms of queries. With references [18, 20], we could also attempt to design the corresponding deletion operation. Of course, exploring the utilization of quantum machine learning techniques within quantum databases also presents an intriguing avenue for further investigation [53]. Finally, as data is stored within quantum vector databases, a compelling direction to explore is the provision of multi-modal data services within a cloud environment [54]. Investigating the feasibility and effectiveness of deploying quantum vector databases in the cloud can pave the way for scalable and accessible multi-modal data management.

5. Conclusion

Quantum Computing has the potential to significantly enhance the performance of various applications. The vision of quantum computing for databases relies on the successful integration of quantum computing into database management systems, the development of novel query languages, and the design of quantum systems specifically tailored for multi-modal data. Overcoming these challenges and harnessing the potential of quantum computing for databases promises to usher in a new era of database management systems that surpass the existing levels of power and efficiency.

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