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A SURVEY OF GROVER'S ALGORITHM AND ITS MODIFICATIONS FOR EFFICIENT UNSTRUCTURED SEARCH

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Abstract
One of the fundamental algorithms of quantum computing is known as Grover's quantum search algorithm, which gives a quadratic speedup over classical search methods in unstructured databases. The authors present a survey of the research on Grover algorithm since 2003 and describe some important modifications and improvement over the years. Adaptive variants, hardware-specific implementations and usage in optimization, artificial intelligence etc. are discussed. In this paper, we review the different variants of Grover's algorithm, discuss their working principles and implementation strategies. These are compared so as to discover possible modifications that increase the efficiency and performance of unstructured search. Also, current issues such as error mitigation in quantum devices and adaptation of algorithms to variable database size are discussed. This survey will be a useful overview of the state of the art in quantum search algorithms, and suggest lines for future research. The development of Grover's algorithm is an important step in the field of quantum computing, and as research in the field continues to progress, the algorithm will be further refined and improved to enable more practical applications in the future.

I. INTRODUCTION AND DOMAIN OVERVIEW

In computer science searching in a collection of data is a large problem. It can be found in things such as database retrieval, cryptography, artificial intelligence, and making things go better. Using computers to search through a very large database that is not sorted is time consuming. This problem can be addressed with quantum computers. This allows quantum computers to accomplish tasks much quicker than traditional computers. One such example of the advantages that quantum computers can offer is Grover's search algorithm [1].

$T_{classical} = O(N), T_{Grover} = O(\sqrt{N})$ (1)

Grover's algorithm is a fundamental quantum search algorithm. It makes the assumption that every item in searching space is equally likely to be the desired item. Not all reality is like this. When we use the Grovers algorithm with things that're not all equally likely, it does not work very well. We need to change how we make the search stronger to make Grovers algorithm work, with these kinds of things [2]. But the problem is, we do not have good quantum hardware at the moment.

If we use these computers to do a thing called Grover's algorithm, it's okay when we only have a qubits.

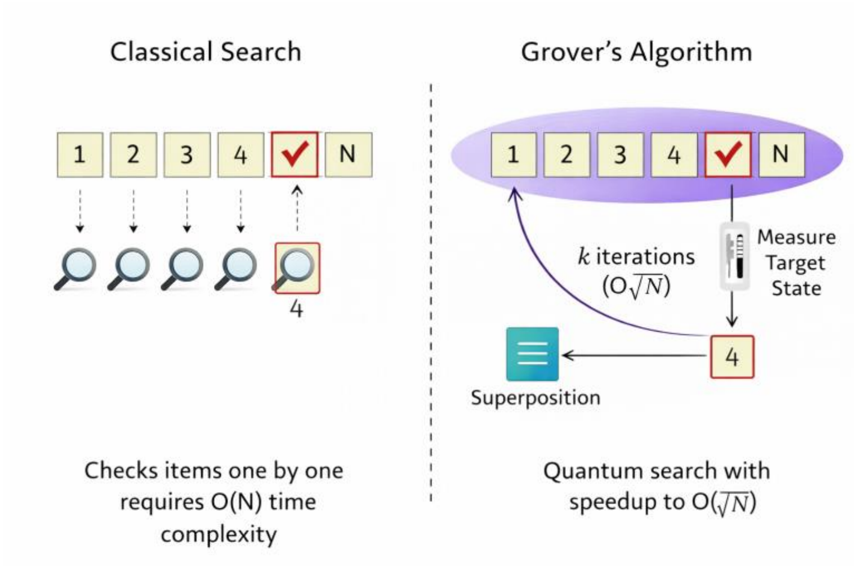

Fig. 1. Comparing classical and Grover's search algorithms

When we add more qubits the accuracy of Grover's algorithm gets worse. We are also looking for ways to decrease the number of errors in these computers. It is very difficult to obtain the correct result most of the time when employing actual quantum devices. Quantum computers, like these, are just not very reliable [3]. To get around these problems people have thought of ways to make the Grovers algorithm better. They've thought of ideas such as changing their approach or their schedule to searching in a way that may vary over time. They also have algorithms that will search exactly, which means that they don't fail sometimes like the old algorithms did. Some have been trying to search using quantum stuff, meaning that they get the correct answer every time, but also more complicated circuits. They've also been working on optimizations and creating frameworks to make the Grovers algorithm useful in real world problems such as finding the optimal solution on a map and searching through a set of combinations. Grovers algorithm is still being improved with these methods, such as optimizationbased approaches and hybrid quantum-classical frameworks to make it work better for complex problems like global optimization and combinatorial search, with Grovers algorithm [4]. Additionally, new techniques in algorithm design are much more concerned with increasing the efficiency of circuits and reducing the amount of hardware required. Optimized implementations of the oracle and diffusion operators, which reduce the circuit depth and gate count, are quite useful. This results in an overall improvement in performance. Also makes it more feasible to use on NISQ devices. These advancements indicate that individuals are actively working on making quantum algorithms effective in practice, not theory, and on bringing on quantum speedup on NISQ devices, both in the form of quantum algorithm design, as well as in the form of quantum algorithm design advancements. The Grovers algorithm is very significant beyond the improvement of algorithms. It's also used for cryptography in things like quantum cryptography. This is a good deal, since Grover's algorithm can make it easier to break classical cryptographic systems, and make brute force attacks easier. Grovers algorithm is aiding in the development of novel methods of maintaining communications secure with quantum technology. Grovers algorithm is also being employed to Quantum-Classical systems. This is interesting in that it allows us to solve hard problems that are hard for computers to solve without having to do so and also helps with large searches. Grovers algorithm is useful, for these things [3]. A number of research efforts are underway on search algorithms based on Grover. This paper is trying to do that by looking at what people have found out about Grover-based search algorithms from 2003, to 2026. Make a list of all the types of Grover based search algorithms and Compare them. The aim of this paper is to make people understand what is happening with Grover-based search algorithms right here and how we will be going forward to make them useful. We want to be sure that Grover based search algorithms can accomplish things that normal computers cannot accomplish, and that's what we're using them for

II. Existing Work

Quantum search algorithms, such as Grover's algorithm, have drawn a considerable amount of interest as they can search things much quicker than classical search methods. There is a period of time since they have been studying Grovers algorithm, studying its workings, real-life applications, limitations of the algorithm, ways to improve the algorithm. Some tests on small quantum systems have been performed and they demonstrated that Grover's algorithm could be implemented. For instance, for the case of three qubits, quantum search has been shown to be able to locate things quicker than the methods. Quantum search algorithms, like Grovers algorithm are very important [5]. In 2026 [6], a new algorithm that uses a qudit, known as the high-dimensional Grover Adaptive Search algorithm, was proposed to improve the efficiency of unstructured search and optimization problems. The suggested extension generalizes Grover's algorithm to QD systems of larger dimensions and is tested on highly nontrivial optimization problems, showing it to be efficient for these problems.

TABLE I

Summary of Quantum Research Works

Area	Description	Reference
Early quantum speedup	Quantum speedup was shown with a small quantum system (3 qubits) using Grover's algorithm.	[5]
Qudit-based improvement	Qudit-based Grover search improves optimization and unstructured search.	[6]
NISQ performance issue	Degradation of superconducting qubits due to noise and decoherence.	[7]
Quantum control methods	Methods developed to control quantum dynamics and improve performance.	[8]
Non-uniform data handling	Grover's algorithm can be adapted for realistic data using modified amplitude amplification.	[2]
Search strategy limitation	Improper search strategies decrease the likelihood of success.	[9]

Circuit optimization	Improved oracle and diffusion operator design reduces quantum gate complexity.	[10]
Multi-target search	Extended Grover's algorithm enables multiple target search.	[11]
Hybrid optimization methods	Grover-based hybrid approaches for solving optimization problems.	[12]
Structured search applications	Quantum search applied to structured problems like pathfinding.	[13]
Entanglement role	Quantum coherence plays a key role in Grover's algorithm performance.	[4]
Cryptography impact	Grover's algorithm impacts classical cryptographic security systems.	[14]
Physical implementation	Cavity-based systems and quantum state preparation implementations.	[15]

III. TAXONOMY OF GROVER VARIANTS

There are many versions of Grovers algorithm. These implementations of Grovers algorithm can be organised in a meaningful way. They can be categorized according to their working, what they do with phases and how they use oracles. That's a convenient way to organise them. It helps us understand how the different versions of Grovers algorithm deal with problems. These problems are anything that can't be done often enough, such as scaling up Grovers algorithm, or getting hardware to be successful. A. Mechanism-Based Classification There are algorithms based on Grover which can be classified based on their modification of the basic amplitude amplification process or their extension.

1) Standard Amplitude Amplification: This class deals with the Grovers algorithm. The Grovers algorithm is quite good at searching for what we want. It does this by using the oracle and diffusion operator over again. This helps to increase the chances of finding the target state. The Grovers algorithm is much faster than search. It can locate things a lot faster which is an excellent deal. The Grovers algorithm achieves this by being much faster, than search, which is a big improvement [16].

$G = (2|\psi\rangle\langle\psi| - I)\, O$ (2)

Where

O = oracle

D = Diffusion operator

2) Phase Control Variants:

The changes in these methods involve the different ways in which the phase is rotated when increasing the amplitude of the signal. They don't employ a specific phase of π. Instead, they take advantage of various phase shifts to improve the process and to minimise the risk of errors. The phase shifts can be modified to suit the situation, so the process goes more smoothly, and is less sensitive to errors. In order to get better results and make the results more reliable, the methods that change the phase of the rotation while the process of amplitude amplification, in particular the amplitude amplification, is performed are used [1]. There is the equations of phase grover and phase rotation.

$G(\phi) = D(\phi) \cdot O(\phi)$ (3)

$R\phi = e\ i\phi$ (4)

3) Oracle Parallelism:

In this version oracles are used simultaneously to speed up searching.When used in parallel, oracles can make things work better.It also makes the circuit more complicated.The idea is that oracles working together can find what we need quicker.This is because they can consult the answer key at the moment.It's important that the circuit can accommodate it.Consider multiple oracles and circuit complexity.Oracles are useful in searching. Circuits are important, for getting the results [16]. The scaling intuition is:

Tparallel ≈ √ N p (5)

where p = no of parallel oracles

4) Hybrid Search Algorithms:

The Grovers algorithm and techniques are used in Hybrid methods.The optimization and stochastic search techniques are used.They are able to solve problems effectively. One approach is Grover Adaptive Search or GAS. It searches with Pure Adaptive Search. The ultimate objective is to solve optimization problems based on Grovers algorithm and Pure Adaptive Search. A different method is to perform Grovers algorithm optimized techniques.This can be used to solve optimization problems. There are also stochastic (random) search methods that can be employed with Grovers algorithm. This combination is useful, for solving optimization problems. The trick is to determine the combination of Grovers algorithm and other methods.This combination can be useful for getting the solutions with efficiency.

5) Hardware-Aware Search:

These methods have been created with the issues associated with quantum computers in mind. There are some problems with quantum computers, such as noise and decoherence [17]. They have limited number of qubits. The techniques attempt to simplify the circuits and to perform them better on NISQ devices. They do so by making the circuits shallower, and ensuring they run correctly when executed on NISQ devices [8].

6) Analytical Characterization:

This category is about math analysis of Grover variants. It explores how they are used. Success probability How fast they converge behavior. We want to know how good Grover variants are, at solving problems. Grover variants are tested to determine if they are reliable. The aim is to get an understanding of Grover variants performance. It helps in choosing the Grover variant [3]. Such classification reflects the evolution of things over time. The models have been replaced by practical adaptations and in turn, the practical adaptations have been replaced by hardware-aware implementations. This definitely demonstrates that research into quantum search has progressed to a more mature phase. The power of quantum search research is continually improving.

B. Phase Strategy-Based Classification

It's very important for Grovers algorithm to know how it works, and how often it succeeds, but more importantly, the rotation of phases. There are some suggestions that have been made for making it more effective. The efficiency and success of the algorithms depend on how the phases are rotated. Grovers algorithm goes about its goals through the use of phase rotation. There are various ways suggested to enhance its performance. People who study this stuff have found out that some methods are really good for working with quantum systems that're not perfect. These methods are called fixed-point phase strategies. They are better because they can handle noise in the system. This makes them more useful, for things we want to do in the world [8].

Approach	Phase Strategy	Impact
Standard Phase	The system uses a fixed phase shift of π in both oracle and diffusion operators.	Ensures correct processing but may cause instability if not properly configured [16].
Fixed-Phase	Uses a phase ϕ where $0 < \phi < \pi$.	Improves adaptability to system constraints [1].
Adaptive Phase	Phase values are dynamically adjusted during iterations.	Improves success rate and reduces failure cases in search process.

Fixed-Point Search	Phase shifts are carefully designed so the system converges steadily toward the solution using oracle and diffusion phase control with parameter ϕ.	Ensures stable convergence and avoids oscillation, but increases runtime [9].

C. Oracle Usage-Based Classification

The oracle is very crucial to Grovers algorithm. The use of the oracle makes a difference in how effective the oracle is, and what we can use the oracle for. But we need to consider how to utilise the oracle to obtain good results, Grovers algorithm.

Oracle Strategy	Description
Single Oracle	The standard approach where a single oracle marks the target state in each iteration. It is the simplest and most widely used method.
Multiple Parallel Oracles	Multiple oracle functions are executed simultaneously to accelerate the search process. This improves efficiency but increases hardware complexity.
Adaptive Oracle	The oracle dynamically changes based on intermediate results or probabilistic regions of the search space. Commonly used in optimization problems.
Optimized Oracle Design	Focuses on reducing circuit depth and gate complexity during oracle construction to improve performance on NISQ devices.

III. COMPARATIVE ANALYSIS

The various trade-offs between Grover-based algorithms are considered as computational complexity, success probability, and hardware feasibility. The benefits and disadvantages of various Grover variants in their implementation. These points are crucial to take into account when choosing a Grover algorithm, as they ensure its performance and compatibility with existing quantum hardware. One factor to consider is that Grover-based algorithms are computationally complex. One other issue is the success rate of Grover-based algorithms. In addition, hardware feasibility of Grover based algorithms needs to be considered. Research gaps and open challenges. However, there remain some issues scientists have to address regarding Grover algorithms. Despite progress some Groverbased algorithms are not actually used in the real world due to these issues. There is a tremendous potential for Grover based algorithms. It is necessary to find a way to make them work better. This is impeding the use of Grover based algorithms.

A. Hardware Scalability These platforms are not so scalable as they are when it comes to size, as is the case with current quantum hardware, such as those based on superconducting and trapped-ion systems. The above mentioned quantum hardware platforms have more number of errors and decoherence, which does not allow us to use them to make large versions of Grover variants [17].

B. Oracle Design Complexity Grovers algorithm is an interesting algorithm to work with. One of the parts of using Grovers algorithm is building a good oracle. Our goal is to create oracles that can deal with lots of target states, search limited spaces, optimization problems involving a mixture of optimization types. Such an oracles construction for Grovers algorithm is extremely costly, when it comes to computer power. It is often said that the speed benefits offered by Grovers algorithm are cancelled out by it [11].

C. Phase Optimization Problem Flexible and adaptive phase variants can be used to enhance the performance, but determination of the best phase parameter for the data set remains a challenge. At present, there is no general and automatic method to determine the optimal phase, as different areas of problems require different phases [1]. The sensitivity of noise and error is discussed below. Grover variants need phase rotations but they are very sensitive to quantum noise. With NISQ devices, things like gate errors, decoherence and measurement errors have a significant impact on their success rate. There are ongoing efforts to minimize errors and make them fault-tolerant [8]. The integration with Classical Optimization is also considered, as detailed below. The Hybrid quantum-classical methods, such as the Grover Adaptive Search are quite efficient solvers of NP- problems. But there is a problem we do not have a system to combine the Grover algorithm with other methods, such, as genetic algorithms or simulated annealing to solve big optimization problems. For example the Hybrid quantum-classical approaches, including the Grover Adaptive Search need to be used with the heuristics like genetic algorithms and simulated annealing to solve the large-scale optimization problems. In this section, the gap between theory and practice will be discussed. If we consider a quantum system, we often assume it to be idealized model, however real world quantum computers are not perfect and are affected by various physical limitations. This is an issue since it prevents the implementation of quantum search algorithms in the real world [17].

Grover Variant	Success Probability	Noise Robustness	Circuit Depth	Scalability
Standard Grover	High (≈ 1 ideal)	Low	Medium	Medium
Fixed-Phase Grover	High (0.85 — 0.95)	Medium	Medium	Medium
Adaptive Phase Grover	Very High (0.9 — 0.98)	High	High	High
Multi-Oracle Grover	High (0.85 — 0.95)	Low-Medium	Very High	Low
Hybrid Grover (Quantum-Classical)	High (0.9 — 0.97)	High	High	High
Hardware-Aware Grover (NISQ)	Medium (0.7 — 0.9)	Very High	Low	High

IV. Future Directions

Implementing more quantum hardware-efficient and errorresilient versions for noisy intermediate-scale quantum (NISQ) devices will be the primary area of focus for future research on Grover-based quantum search algorithms. One important area of research is the automatic optimization of phase parameters, for which there exists no general method of choosing optimal phase parameters for different problems. Also, reducing the complexity of the oracles is important, as it can have a major impact on the overall circuit cost. In addition, there are potential applications of combining Grover's algorithm with hybrid quantum-classical optimization methods and to multi-oracle and higher dimensional (qudit) systems, which are potential routes to practical quantum search in real-world applications.

V. Conclusion

When searching an unorganized large database, Grover algorithm is an important tool for quantum computing. Much quicker than methods. People have worked on it for 20 years

to make it better. Various approaches have been attempted to
make it better, such as fixed phases, varying number of iterations by multiple oracles, quantum and classical computing etc [16]. These changes are intended to correct some of the algorithmic issues, such as its performance being limited to database sizes that are powers of two, requiring knowledge of the number of items to be marked before running, and its sensitivity to noise and errors in the hardware [1]. People have tried Grovers algorithm on simulated computers and with real quantum devices, and found it does not perform as they had hoped, particularly with larger systems where there are more opportunities for noise and errors to occur [17]. Also, the necessity that Grovers algorithm only works probably the limits in choosing phases, and the difficulty in making oracles remain large issues [18]. This survey looks at fifteen studies from 2003 to 2026. It provides a list of all the variants and discusses the phase strategies, oracle use and hardware requirements. The survey demonstrates the strengths and weaknesses of each version and, therefore, what is required in the future. What inspired the creation of new quantum search algorithms are the gaps that were identified, such as the ability to handle databases of any size, optimize phases and get it working on quantum hardware. [1]. To conclude Grovers algorithm has come a long way and has many potential applications, but yet still much work to be done to make it more reliable, flexible and useful in the real world. To fix these problems we need to make hardware-aware versions of Grovers algorithm, which will help bridge the gap between quantum search theory and practical applications in big unstructured databases [17]. Existing approaches attempt to achieve this by tuning the phases of the waves involved and by making use of a flexible database handling system to facilitate efficient and reliable searching in the modern quantum systems.

REFERENCES

[1] X. Li and Z. Li, “Quantum search algorithms: Recent advances and applications,” Quantum Information Processing, vol. 22, no. 3, pp. 1– 25, 2023.
[2] Y. Sun and L.-A. Wu, “Quantum search algorithm on weighted databases,” Scientific Reports, vol. 14, no. 1, p. 30169, 2024.
[3] R. Bhatt et al., “Quantum search algorithm improvements and applications in noisy intermediate-scale quantum devices,” Quantum Information Processing, vol. 24, no. 2, pp. 1–20, 2025.
[4] M. Tariq, R. Abdelrahim, O. Alhussein, and S. Muhaidat, “Hybrid quantum-classical maximum-likelihood detection via grover-based adaptive search for ris-assisted broadband wireless systems,” arXiv preprint arXiv:2505.03914, 2025.
[5] C. Figgatt, D. Maslov, K. A. Landsman, N. M. Linke, S. Debnath, and C. Monroe, “Complete 3-qubit grover search on a programmable quantum computer,” Nature communications, vol. 8, no. 1, p. 1918, 2017.
[6] S. Gund ¨ uz and I. Yılmaz, “Leveraging qudits: high-dimensional grover ¨ adaptive search algorithm for solving quadratic and higher-order unconstrained binary optimization problems,” The European Physical Journal Plus, vol. 141, no. 4, p. 368, 2026.
[7] M. AbuGhanem, “A hardware-efficient m {\o} lmer-s {\o} rensen gate for superconducting quantum computers,” arXiv preprint arXiv:2510.07352, 2025.
[8] B. Pokharel and D. A. Lidar, “Better-than-classical grover search via quantum error detection and suppression,” npj Quantum Information, vol. 10, no. 1, p. 23, 2024.
[9] S. Lee and S. Y. Nam, “Finding all solutions with grover’s algorithm by integrating estimation and discovery,” Electronics, vol. 13, no. 23, p. 4830, 2024.

[10] R. A. Gut¸oiu, A. Tan˘ asescu, and P. G. Popescu, "Simple exact quantum ˘ search: Ra gut¸oiu et al." Quantum Information Processing, vol. 23, no. 10, p. 356, 2024.
[11] M. A. Naranjo and L. A. Fletscher, "Review quantum circuit synthesis for grover's algorithm oracle," Algorithms, vol. 17, no. 9, p. 382, 2024.
[12] S. Zhong, W. Li, G. Dai, and D. Wu, "The optimization of exact multitarget quantum search algorithm based on mindspore," arXiv preprint arXiv:2412.18306, 2024.
[13] C. Grange, M. Poss, E. Bourreau, V. T'kindt, and O. Ploton, "Moderate exponential-time quantum dynamic programming across the subsets for scheduling problems," European Journal of Operational Research, vol. 320, no. 3, pp. 516–526, 2025.
[14] M. L. Wu, "A grover-based quantum algorithm for solving perfect mazes via fitness-guided search," arXiv preprint arXiv:2507.21937, 2025.
[15] S.-Q. Zhou, H. Jin, J.-M. Liang, S.-M. Fei, Y. Xiao, and Z. Ma, "Coherence fraction in grover's search algorithm," Physical Review A, vol. 110, no. 6, p. 062429, 2024.
[16] N. Mehendale, "Implementation of grover's search algorithm using qiskit," arXiv preprint arXiv:1703.04792, 2017.
[17] R. Sai Prasath et al., "Analysis and improvement of grover's quantum search algorithm for multiple solutions," Quantum Information Processing, vol. 22, no. 6, pp. 1–18, 2023.
[18] A. Younes, "Strength and weakness in grover's quantum search algorithm," arXiv preprint arXiv:0811.4481, 2008.