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Quantum Computing for Effective Mineral Mining Workflows

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***Abstract* — The complexity in mineral exploration and extraction in modern era demanding high performance computing with large scale geo spatial data analysis. Quantum computing offers promising performance with parallelism, superposition and entanglement services to improve mining activities. In this paper we proposed a framework model with layered organization of service modules. Starting from encoding of data to knowledge pattern extraction from various kinds of smart devices using multi Qubits technology boosts the data handling and processing phases. Enabling Quantum Annealing, Variational Quantum Circuits, Quantum Optimization and Quantum Approximation procedures makes mineral mining pipeline computationally accurate and enriched.**

Keywords— Quantum Computing, Entanglement, Quantum Annealing, Quantum Circuits, Superposition, bits.

I. INTRODUCTION

Mineral Mining is becoming highly intensive data task. It is computationally and operationally placing many challenges [1]. Traditional computations suffer from high dimensional data with impurities generated from hyper spectral Imaging machines [6]. Also the mineral mining zones are equipped with plenty of IoT devices releasing variant data outputs in real time [3]. Many of the mining activities including core mining tasks, geological modeling, Ore exploration, field machinery functions, mine routings and resource scheduling are non linear in nature [7].

Quantum Computing can explore wide solution spaces concurrently to find optimal paths in less time with its superposition, entanglement and optimized algorithms [5]. Quantum technologies can accelerate 3D surface rendering more realistic with multi parameter based resolution methods [11]. This research aims to explore how quantum computing can enhance the efficiency, accuracy, and scalability of mineral mining workflows [4]. By evaluating quantum algorithms, designing hybrid computational pipelines, and simulating quantum-assisted mining tasks, the study outlines a transformative roadmap for next-generation intelligent mining systems [2][10]. Through this integration, mining operations can transition toward smarter, safer, and more sustainable practices driven by quantum-enabled decision-making [12]. Recent hybrid classical quantum architectures improve feasibility along with operational performance in long term applications [14].

In this paper Section II describes quantum computing technologies and their role in modern data handling. Section III showcases the proposed framework layered model and various services and modules support to mineral mining. In section IV provides an insight into comprehensive application view of QCMM model. Analysis is performed over quantum computing in contrast with traditional computing technology. In section V Conclusion and Future scope discussed.

II. QUANTUM COMPUTING

Quantum computing incorporates quantum mechanics principles mainly superposition and entanglement for fast exponential calculations. Quantum computers are more advanced than classical computers in solving complex problems. The fundamental principles of quantum computing are superposition, entanglement, and quantum interference. Superposition allows qubits to exist in multiple states simultaneously, enabling quantum computers to process many possibilities at once [11]. Entanglement links qubits so that the state of one instantly influences the state of another, regardless of distance, enabling highly coordinated and efficient calculations [9]. Quantum interference allows quantum states to combine in ways that amplify correct solutions and cancel out incorrect ones, improving computation accuracy.

Quantum interference improves algorithm accuracy by selectively improving the probability of correct solutions. The constructive interference performs reinforcement learning of quantum state towards correct answer. Whereas destructive interference reduces the likelihood of wrong solutions. Hence quantum algorithms avoid unnecessary calculations and improve power efficiency and accuracy. The Grover's approach improves searching efficiency by achieving quadratic speedup. The Quantum Fourier Transformation corrects prediction rate enabling exponential speed up. The quantum wave amplitude amplification increases success probability in choosing good states. Grover iterations applied to rotate quantum states in vector sub dimensional space.

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A. Quantum Entanglement

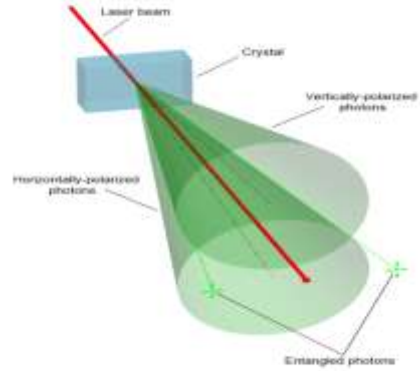

Fig. 1. Quantum Entanglement Principle.

B. Quantum Superposition

The superposition principle arises from the linearity of the Schrödinger equation, allowing any combination of valid quantum states to form another valid state. This enables qubits to represent both 0 and 1 at once, unlike classical bits, powering parallel computation in quantum algorithms. Measurement collapses the superposition into a single state probabilistically per each born rule.

C. Quantum Computing Models

Gate-based quantum computing:
Logic gates incorporated in quantum computing named as circuit model 'Hadamard' for superposition, 'CNOT' for entanglement applied sequentially to qubits which enables universal computations using circuits.
Quantum annealing:
Slowly evolves a quantum system's Hamiltonian to find global energy minima, ideal for optimization problems with larger qubit counts but limited scope.
Measurement-based (1-way) quantum computing:
It is based on measuring pre-entangled cluster states to perform operations through quantum gate teleports. Where computations are driven entirely by performing a series of adaptive single-qubit measurements on a highly entangled resource state, typically a cluster state or graph state. The process is "one-way" because the entangled resource state is gradually consumed and destroyed by the measurements, rather than applying sequences of quantum gates as in the circuit model.
Adiabatic quantum computing:
Gradually transforms an initial Hamiltonian to a problem specific one, preserving the ground state solution

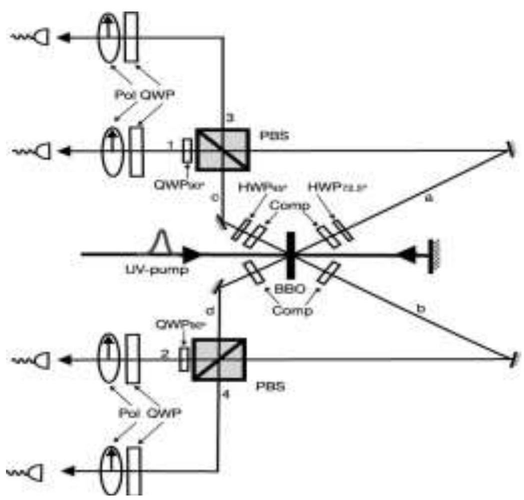

Fig. 1. 1-Way Quantum Computing circuit

D.

III. Proposed Model

In this work we proposed a model for mineral mining fused with quantum computing benefits. Figure 1 shows the proposed framework model for mineral mining which is a collection of three layers.

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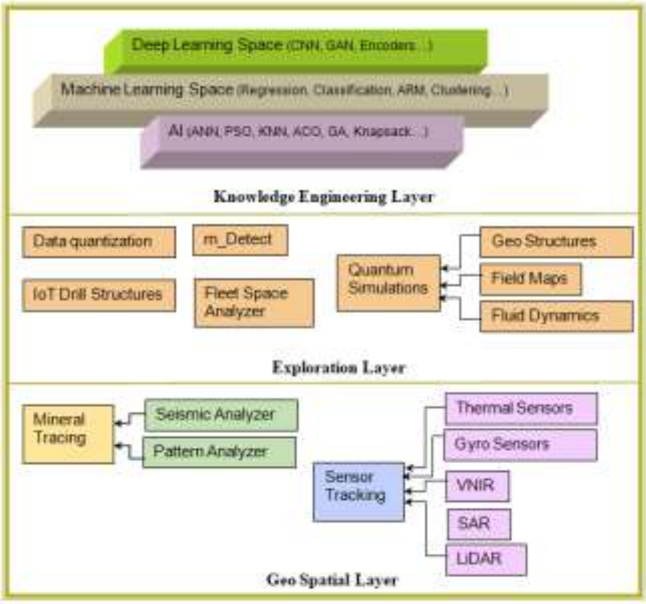

Fig. 2. Framework of Quantum Computing based Mineral Mine Model.

The model is a collection of phased process to evaluate player skill assessment using variety of machine learning techniques.

A. Geo Spatial Layer

This is the foundation layer in our model. It plays key role in data Extraction, Transformation and Loading. The quantum computing technology introduces Q-bits having multi-state selection feature to perform extensive parallel processing enabling exponential speed of computation. The Mineral Tracing module focus over geo sensor inputs extracts the geo patterns and seismic wave forms into digital quantization space. Large volume of data can be handled effectively using quantum computing. The Sensor tracking module coordinates with all the IoT smart devices equipped with variety of sensors. Supporting auto-encoding algorithms computationally fast in converting from wave signals to quantum digits. The layer is scalable to handle broad tasks related to mineral resource data ETL process.

$$\Delta = \frac{X_{max} - X_{min}}{2^B} \; where \;\; \Delta = qunatization\ Interval$$
$$B = number\ of\ bits;\ X_{max}, X_{min} signal\ limts$$

B. Exploration Layer

In Exploration Layer some important modules included for effective mineral mining activity support. Table 1 show the various modules interlaced in this layer and their role in Quantum Mineral Mining (QMM) approach.

TABLE 1: QMM Exploration Layer

Modules	*Application*
Data Handling	➢ Seismic Signal processing ➢ Earth Density measurements ➢ Magnetic Flux reading ➢ Gyro Compass measures ➢ SAT/DRONE image processing ➢ Drill Machinery IoT data ➢ Wi-Fi Data
mDetect	➢ 3D Imaging ➢ Infrared Imaging ➢ X-ray Imaging ➢ AI enabled reconstructs ➢ Subsurface Modelling ➢ Exploration Analysis
Fleet Space Analyzer	➢ Full Stack IDE ➢ Mineral Exploration Libraries ➢ 3D Imaging

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	➢ Surveying Tools ➢ Landscape Analyzers ➢ AI Maps
Quantum Simulations	➢ Geo Structures ➢ Field Maps ➢ Thermal Mapping ➢ Fluid Dynamics ➢ 2D/3D Rendering tools

Mapping Physics to Qubits done by Jordan –Wigner transformer.

$$a_i = \left(\prod\nolimits_{k<j}\right)\frac{X_j+iY_j}{2}$$

The Trotter–Suzuki Approximation is a key to quantum simulations. It comes under first order to higher orders. High ordering minimizes the error rate.

$$e^{-i(H_1+H_2)t}$$

C. Knowledge Engineering Layer

The Knowledge Engineering Layer comprised with Machine Learning, Deep Learning and AI algorithms as services. This module acquires data from Exploration Layer. The adoption of quantum computing techniques improves the performance and accuracy of algorithms. The prediction quality is improved to exponential. The computations over large data sets are made easy with quantum computing. Various machine learning algorithms applied over data to derive variety of knowledge patterns. The autonomous decision making ability in machines greatly enhanced with AI interfaces. Deep learning models used to assess SAT/Drone generated real-time images effectively in mineral mining.

IV. Applicational View

Fig. 3 shows the quantum superposition analysis over SAT image data. Major applications of this technique in mineral mining are

- Spectral band analysis
- Time series based overlaying frames
- Combining, Comparing, Normalization operations
- GIS layer analysis
- Mathematical superposition of values
- Multi spectral analysis
- Change detection
- Classification
- Geo statistics monitoring

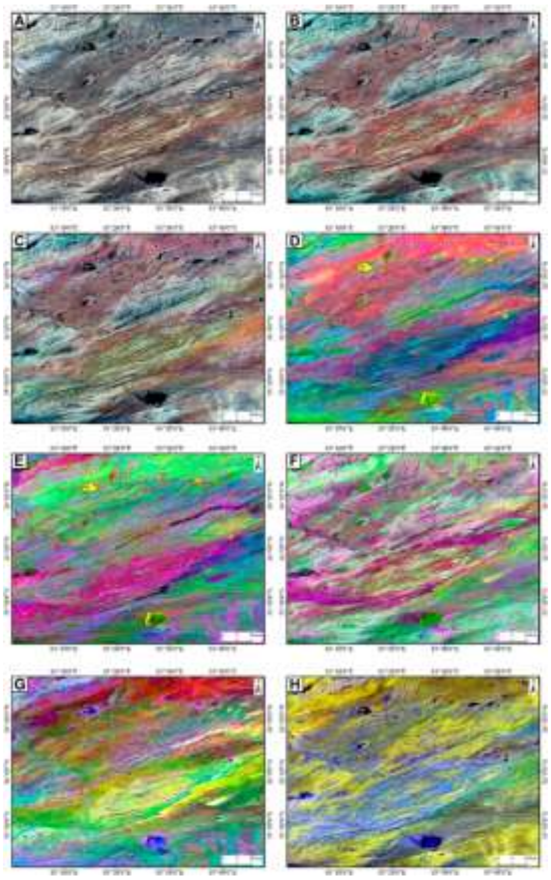

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Fig. 3. Quantum Superposition Analysis from SAT images

Fig. 4 shows the comparative analysis over quantum computing model to classical computation model. It is clear that adoption of quantum computing extremely improved performance and computational efficiency in mineral mining system.

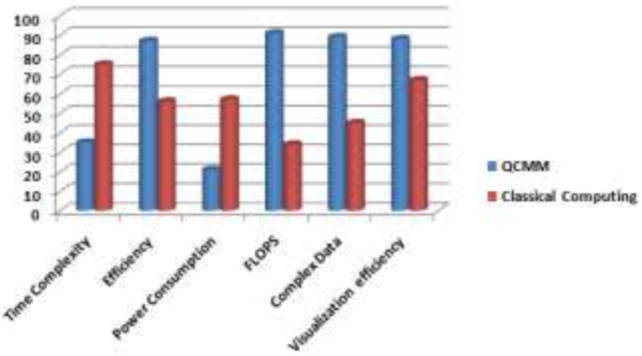

Fig. 4. QCMMM Vs Classical MMM

V. Conclusion And Future Scope

Quantum computing has the potential to significantly enhance the accuracy, speed, and efficiency of mineral mapping workflows by addressing the computational bottlenecks inherent in traditional geospatial and spectral analysis techniques. Its ability to process high-dimensional datasets through quantum parallelism, optimize complex inversion and classification models, and simulate geological systems with greater fidelity offers a transformative pathway for mineral exploration. By integrating quantum algorithms with remote sensing, hyper spectral imaging, and geo statistical modeling, mineral mapping can evolve into a more data-driven, predictive, and resource-efficient process.

Although practical large-scale quantum hardware is still emerging, early hybrid quantum–classical approaches already demonstrate promising improvements in feature extraction, mineral identification, and spatial optimization tasks. As quantum technologies mature, they are expected to become a central component of next-generation mineral exploration workflows enabling faster decision-making, reducing operational costs, and improving the overall precision of subsurface resource characterization.

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