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SURVEY

# Integration of Quantum Technologies into Metaverse: Applications, Potentials, and Challenges

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**ABSTRACT** Over the last few decades, technology has been improving dramatically and consequently transformed the standard of living and socio-economic conditions. The entire process will revolutionize when the next advanced technologies will be fully functional. Advanced technologies like the metaverse, Web 3.0, and others necessitate high computing power, invincible security, and ultra-fast internet. Despite increasing demand, traditional computing methods have limitations and are not capable of satisfying the requirements. To solve these tribulations, quantum computing is shining a light of hope. This survey aims to analyze the methodology, constraints, and potential of integrating quantum computing with the metaverse. We begin with an overview of quantum computing and related terms. We then investigate the feasibility of applying quantum-enabled technologies to enhance the metaverse. Furthermore, this survey also considers middleware for seamless conversion between traditional and quantum computing with the metaverse. In the subsequent phase of this survey, our objective is to discern and delineate the prospective application domains for the quantum-enabled metaverse. In essence, the difficulties of integrating quantum computing with the metaverse, present research approaches, and open research issues with consequences for additional in-depth investigations are highlighted.

**INDEX TERMS** Artificial intelligence, blockchain, metaverse, quantum computing, security.

## I. INTRODUCTION

This current world situation is undergoing a period of transition, where every aspect is being influenced by the swift development of information technology. For instance, the current Internet or Web 2.0 is transitioning toward a blockchain-based decentralized World Wide Web 3 (Web 3.0), and there are advancements in healthcare known as Healthcare 4.0, advancements in autonomous vehicles to Level 5, and Industrial revolution 5 (Industry 5.0). Notably, among these advancements, the part of Web 3.0, the metaverse stands out as one of the most substantial interests within both academic and technological spheres following Facebook's rebranding as "Meta" in 2021 [1]. Indeed, not only Meta but also other major tech giants, including Microsoft, NVIDIA, Google, Tencent, Epic Games, Roblox, Unity Technologies, and other companies, demonstrate a substantial interest in the development of the metaverse.

The word metaverse is a fusion of two different phrases, the prefix "meta" means transcending, and the suffix "verse" is a short form of the universe [2]". Nevertheless, it is worth noting that the concept of the metaverse is not a recent development, as its origin can be traced back to Neal Stephenson's science fiction novel, Snow Crash, published in 1992, merely a year after the advent of the internet. The metaverse is an advanced technology that facilitates

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three-dimensional and immersive interactions between virtual and physical environments, where avatars serve as the virtual representation of humans. The metaverse integrates a range of cutting-edge technologies to provide a real-world experience within the virtual environment. In this sense, it serves as a vast simulation that produces a mirroring world. Artificial intelligence (AI), digital twins (DT), blockchain, augmented reality (AR), virtual reality (VR), and the Internet of Things (IoT) are the bassic requirement for functioning the metaverse. Metaverse is expected to revolutionize various aspects of our lives, including working patterns, entertainment, socialization, education, and business. Within the metaverse, users possess the ability to engage in virtual activities that mirror real-life experiences.

**TABLE 1. List of abbreviations.**

| | |
|---|---|
| AI | Artificial Intelligence |
| AR | Augmented Reality |
| CV-QKD | Continuous-variable Quantum Key Distribution |
| CNOT | Controlled-NOT gate |
| DT | Digital Twins |
| DV-QKD | Discrete-variable Quantum Key Distribution |
| FTQC | Fault-tolerant Quantum Computers |
| HMD | Head-mounted Displays |
| IoE | Internet of Everything |
| IoT | Internet of Things |
| LSTM | Long Short-Term Memory |
| MIMO | Multiple-input Multiple-output |
| MCM | Multicarrier Multiplexing |
| NFT | Non-fungible Token |
| NISQ | Noisy Intermediate-scale Quantum |
| NLP | Natural Language Processing |
| NN | Neural networks |
| OTP | One-time Pad |
| QAOA | Quantum Approximate Optimization Algorithm |
| QDPoS | Quantum Delegated Proof of Stake |
| QLSTM | Quantum Long Short-Term Memory |
| QML | Quantum Machine Learning |
| QPU | Quantum Processing Unit |
| Qubit | Quantum Bit |
| QKD | Quantum Key Distribution |
| SISO | single-input single-output |
| THz band | Terahertz Band |
| UC | Unit Commitment |
| VR | virtual reality |
| XAI | Explainable Artificial Intelligence |

From a broad stance, the development of the metaverse comprises three distinct steps: (1) digital twins, (2) digital natives, and (3) surreality [3], [4]. The first step of metaverse development is digital twins, which is mirroring the real world in virtual space. In this step, the meta-human activity mirrors the real-world user. Digital twins are used for smart planning, AI-assisted industrial system design, and product design [5], [6]. The second phase emphasizes the creation of virtual content and products within the digital world. These digital products or content do not exist physically in the real world. The maturity level reaches its peak in the third stage of the metaverse development process. This phase embodies the seamless integration and mutually beneficial relationship between the physical and virtual worlds. Here, the virtual world expands more than the real world, covering a broader scope and enabling the existence of numerous scenes and lives that transcend physical reality and reside virtually.

The rapid progress in quantum hardware and algorithms has led to the expectation that quantum computing will imminently transition from the noisy intermediate-scale quantum (NISQ) era to the fault-tolerant quantum computer (FTQC) era. Preskill [7] provide an initial definition of current NISQ computers and outline the subsequent steps required to attain FTQC. The present quantum computing paradigm is commonly referred to as NISQ, denoting noisy intermediate-scale quantum computers that exhibit the capability to address real-world problems with enhanced efficiency and speed compared to classical supercomputers. A quantum race is underway to construct FTQC, with projections indicating a staggering 500% expansion in the quantum computing market by 2028. However, this extraordinary invention also has a dark side. Current cryptosystems, financial systems, and security mechanisms will become obsolete in front of powerful quantum computers, this event is referred to as Q-Day, signifying the moment when quantum machines breach prevailing encryption protocols [8], [9]. Quantum technology will apply several vital technologies, such as quantum AI, quantum internet, quantum cryptography, quantum super computing, quantum simulation, etc. Many of these technologies have direct relevance to metaverse development and service. To cope with future quantum challenges, the metaverse should consider integrating quantum-enabled systems in metaverse development and metaverse-provided services.

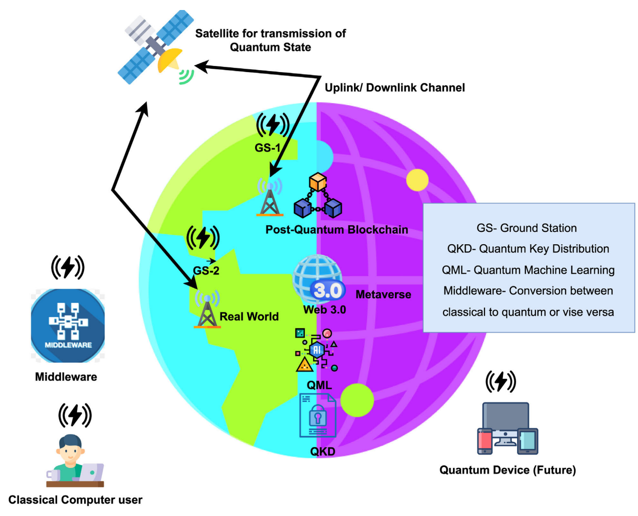


**FIGURE 1. Exploring potential quantum-enabled technologies for the metaverse.**

### *A. MOTIVATION*

The operation of metaverse platforms leans upon multiple enabling technologies, incorporating AI, big data, blockchain, Web 3.0, semantic communications, as well as edge and cloud computing. Sensitive data is stored in the metaverse and poses serious consequences if security is compromised. An instance of this type of data includes the user's biometric information employed in secure authentication or avatar generation. Consequently, prioritizing information security is crucial. However, existing security encryption protocols are insufficient against quantum computing threats. Integrating quantum security measures offers resilience against both classical and quantum attacks. As the metaverse correlates with 3D virtual object handling, necessitating substantial network traffic, leveraging quantum-enabled terahertz band (THz band) communication emerges as a promising solution for metaverse applications. The exponential growth of quantum computing foreshadows a quantum revolution, showcasing its computational superiority over classical computers despite hardware constraints. This supremacy spans diverse application domains, from intricate simulations to AI, security, and other disciplines. This paradigm shift underscores the potential for integrating quantum technology into the metaverse, signifying prospects, constraints, and direction for further research. For a more comprehensive view of the review path, let's consider the metaverse platform illustrated in figure 1, showcasing various possibilities for integrating quantum techniques into the metaverse. An individual can connect to the metaverse using either a quantum personal computer, a classical computer, or other devices. The internet connectivity may be quantum internet or hybrid internet [10], [11]. The internet connection can be evolve into a quantum internet utilizing satellite communication technology [12], [13], [14]. Middleware to facilitate the conversion between quantum and classical computing or vice versa [15]. A quantum-enabled edge device to perform computing tasks and offload functions between the user and the metaverse server [16], [17]. To optimize metaverse workload, the quantum optimization algorithm can be applied. In order to facilitate decentralized navigation, Web 3.0 can utilize the integration of quantum-enabled blockchain technology [18]. To manage large amounts of data, the use of quantum big data will be beneficial. Earlier mentioned quantum-enabled facilities are for operating metaverse platforms. Also, we investigate the scope of emerging quantum-enabled metaverse to solve problems, providing services, facilities, and other application areas.

### B. CONTRIBUTIONS

The field of quantum computing and its underlying technologies have been the subject of various surveys and reviews. Existing surveys and reviews have focused on specific aspects and research results, yet a comprehensive overview of the field remains elusive. The core contributions of this paper are outlined as follows:

- We provide a brief overview of quantum computing and relevant background terms that are essential for an easy understanding of the foundational concepts of this technology.
- In our research, we conducted a comprehensive survey of state-of-the-art quantum technologies with a particular focus on their potential integration within the metaverse. Quantum technology, proving its outstanding powers in various fields, emerged as a promising candidate for empowering the metaverse with cutting-edge features. The six prominent quantum applications examined in our survey include quantum machine learning (QML), blockchain, quantum internet, security, middleware, and supercomputing. These technologies have been at the forefront of quantum advancements, showcasing their potential to revolutionize various industries, including healthcare, finance, and information technology. By investigating their applicability in the context of the metaverse. We aimed to shed light on the transformative possibilities they may bring to the metaverse environment.
- Moreover, we discuss future research directions and limitations of integrating quantum computing within the metaverse.

### C. PAPER ORGANIZATION

Table 2 and figure 2 show the structural flow of the paper. The remainder of this paper is structured as follows: Section II introduces the fundamental concepts of quantum computing, covering its basic principles and terminology. Section III reviews quantum-enabled technologies essential for the metaverse, while Section IV explores various practical application fields of the quantum-enabled metaverse. In Section V, the challenges related to the integration of quantum computing with the metaverse are investigated. Section VI provides a concise outline of ongoing projects involving the metaverse and quantum computing. Section VII presents a diverse range of research directions, and, finally, Section VIII concludes the article.

## II. QUANTUM COMPUTING: PRELIMINARIES

The fundamental nature of our universe is intrinsically rooted in the principles and laws of quantum mechanics. However, the idea of quantum mechanics combined with computation was first put forth by Nobel laureate Richard Phillips Feynman in 1982 as a result of his struggles in simulating quantum phenomena using classical computers. He realised that, due to the exponential slowdown incurred, it was not possible to simulate quantum phenomena through classical computing methods and that a new device incorporating quantum properties was necessary. The classical computer is rooted in semiconductor technology, utilizing electrical flow as a binary switch, represented by either a 0 or 1. This processing of information is guided by the principles established in Shannon's Noiseless Coding Theorem (1948). Conversely, quantum computers operate with quantum bits, or qubits, and the processing of information takes place in a Hilbert space ($\mathcal{H}$) of eight dimensions, with the potential for infinite dimensional extension. Quantum computing represents a convergence of the disciplines of quantum physics and computer science. Quantum physics has proven to be effective in a wide range of scientific domains, including

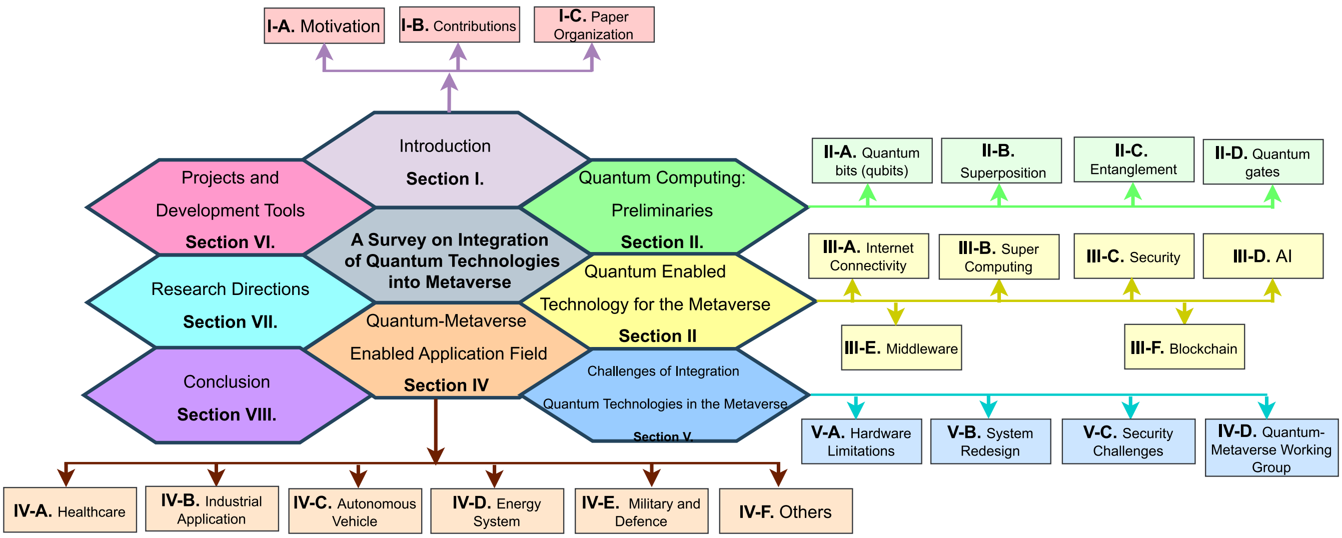


**FIGURE 2.** Overview of the survey paper.

**TABLE 2.** Survey paper outline.

| Survey Paper Outline | |
|---|---|
| Section I. | Introduction |
| I-A. | Motivation |
| I-B. | Contributions |
| I-C. | Paper Organization |
| Section II. | Quantum Computing: Preliminaries |
| II-A. | Quantum bits (qubits) |
| II-B. | Superposition |
| II-C. | Entanglement |
| II-D. | Quantum gates |
| Section III. | Quantum Enabled Technology for the Metaverse |
| III-A. | Internet Connectivity |
| III-B. | Super Computing |
| III-C. | Security |
| III-D. | AI |
| III-E. | Middleware |
| III-F. | Blockchain |
| Section IV. | Quantum-Metaverse Enabled Application Field |
| IV-A. | Healthcare |
| IV-B. | Industrial Application |
| IV-C. | Autonomous Vehicle |
| IV-D. | Energy System |
| IV-E. | Military and Defence |
| IV-F. | Others |
| Section V. | Challenges of Integration Quantum Technologies in the Metaverse |
| V-A. | Hardware Limitations |
| V-B. | System Redesign |
| V-C. | Security Challenges |
| V-D. | Quantum-Metaverse Working Group |
| Section VI. | Projects and Development Tools |
| Section VII. | Research Directions |
| Section VIII. | Conclusion |

but not limited to life sciences, chemistry, and military applications [12].

Quantum computing, rooted in the principles of quantum mechanics, has emerged as a topic of significant interest and acquisition in both academia and industry. Multiple well-known technology corporations have made significant investments in the pursuit of developing quantum computing technology. For instance, IBM is slated to launch its 1,121-qubit processor, known as Condor, in 2023 [19]. Additionally, there are plans to establish a quantum-based cloud data center in Ehningen, Germany, supporting 100+ qubits, expected to be operational by 2024 [20]. Microsoft has established a cloud platform, Azure, which hosts various quantum-related platforms such as QCI, IONQ, and 1Qloud [21]. Meanwhile, Google's Quantum AI Lab has already succeeded in creating a quantum computer capable of solving real-world problems. Processor manufacturer Intel has also been focusing on constructing quantum hardware [22]. According to data from Yahoo Finance, the quantum computing market is to raise by 500% by 2028. As of 2021, the market is valued at USD 490.51 million. However, it is anticipated to experience significant growth in the near future, with projections indicating a substantial compound annual growth rate (CAGR) of 30.70% by 2028. As a result of this expected growth, the global quantum computing market is estimated to reach a value of USD 2,930.67 million by 2028, representing a whopping increase of 497% over 7 years. This growth is a testament to the increasing adoption and integration of quantum computing technologies in various industries and applications and highlights the potential of this emerging market to shape the future of computing and technology as a whole [23].

The swift advancement of quantum computing has necessitated a comprehensive examination of its influence on various aspects of information technology. In the upcoming era of quantum computing, it is important to consider how the formation of new technologies, such as Web 3.0, the metaverse, artificial intelligence, big data processing, and semantic communication, will be impacted.

### *A. QUANTUM BITS (QUBITS)*

The fundamental building block of quantum information is the qubit, which can be physically implemented in various

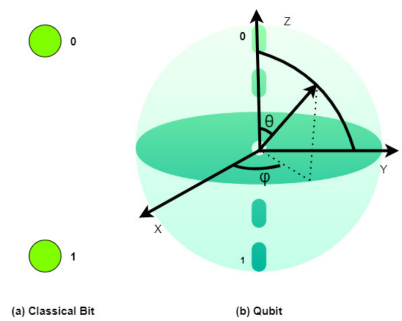


**FIGURE 3.** The difference between classical bit and qubit: (a) classical bits can only represent 0 or 1 and (b) the pure quantum state of a qubit is represented by a Bloch sphere in geometry. The superposition principle enables a qubit to exist simultaneously at any point between $|0\rangle$ and $|1\rangle$.

forms, including individual atoms, electrons, photons (light particles), or complex systems like superconducting electrical circuits. The bits can be represented graphically using a Bloch sphere, as illustrated in figure 3. Here $\theta$ is referred to as the polar angle and $\phi$ is referred to as the azimuthal angle. Qubits state mathematically represented as bra-ket notation ($|.\rangle$). A pure quantum state $|\psi\rangle$ can be expressed as

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \tag{1}$$

where $\alpha$ and $\beta$ are complex numbers from the set of complex numbers $\mathbb{C}$ as $\alpha, \beta \in \mathbb{C}$, referred to as probability amplitudes, which satisfy the condition $|\alpha^2| + |\beta^2| = 1$.

### B. SUPERPOSITION

Heisenberg's uncertainty principle forms the foundation of the principle of superposition. According to this principle, it is impossible to measure a particle's position and momentum simultaneously with complete accuracy. This is due to the inherent quantum property of a particle that exists in a superposition of states prior to measurement [24]. Similarly to a classical bit, a qubit possesses two distinct states, 0 and 1. However, in contrast to a classical bit, a qubit can exist in a weighted superposition of these two states, thereby enabling the simultaneous evaluation of specific functions for both input values. The renowned thought experiment on the paradoxical state of a cat by the physicist Erwin Schrodinger is widely recognized for its explication of superposition. In this experiment, a feline specimen is enclosed in a box containing a lethal particle with a fifty percent likelihood of killing the cat. In accordance with our conventional understanding, the cat is presumed to be either alive or deceased. However, in quantum superposition, until the box is opened, the cat exists in a state of indeterminacy, simultaneously poised between life and death [25]. The polarised state of a photon provides a useful visualisation of the concept of superposition. Specifically, when a photon is polarised at an angle of 45 degrees, it manifests itself as being concurrently vertically and horizontally polarised, representing both states simultaneously [26]. As previously stated, a single qubit state may be expressed mathematically as:

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \tag{2}$$

$$|1\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \tag{3}$$

consequently,

$$|0\rangle = \langle 0|^{\dagger} = \begin{bmatrix} 1, 0 \end{bmatrix}^{\dagger}, \tag{4}$$

and

$$|1\rangle = \langle 1|^{\dagger} = \begin{bmatrix} 0, 1 \end{bmatrix}^{\dagger}, \tag{5}$$

where $\dagger$ represents the Hermitian transpose operation applied to the matrix. Hence, the superposition state of a single qubit may be expressed as,

$$c_1|0\rangle + c_2|1\rangle = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}, \tag{6}$$

where $c_1$ and $c_2$ refers to the probability amplitude [27].

### C. ENTANGLEMENT

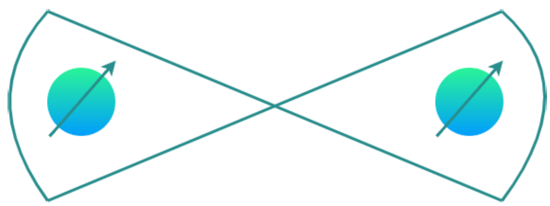

**FIGURE 4.** In the context of quantum entanglement, when two particles are entangled, the measurement of the spin state of one particle can instantaneously affect the spin state of the other particle, regardless of how far apart they are in space. This phenomenon is a fundamental feature of quantum mechanics and has been experimentally observed in various systems.

Quantum entanglement is a highly complex and captivating phenomenon in the natural world. Its potential utility has been empirically demonstrated in various applications, such as quantum teleportation, quantum cryptography, quantum dense coding, quantum computation, and information processing [28]. Quantum entanglement, illustrated in figure 4 is a strange occurrence in the universe where two subatomic particles become interconnected in such a way that altering one particle also alters the other, regardless of their physical distance. In the context of our discussion, let us analyse a state of polarization entanglement that involves two particles. This particular state is created through the utilization of a type-II parametric down-conversion crystal and may be represented in the following manner:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|z+\rangle X^{|z-\rangle} Y^{+} e^{i\alpha}|z-\rangle X^{|z+\rangle} Y), \tag{7}$$

where the variable $\alpha$ represents a birefringent phase shift of the crystal. The symbols $|z+\rangle$ and $|z-\rangle$ refer to the spin eigenstates, which can also be interpreted as the eigenstates of horizontal and vertical polarization, respectively. Finally, the subscripts $X$ and $Y$ are used to distinguish between the two particles under consideration [29]. By applying suitable birefringent phase shifts and polarization conversions, it is possible to transform the aforementioned state into any of the four Bell states [30]

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|z+\rangle X^{|z+\rangle} Y^{\pm|z-\rangle} A^{|z-\rangle} Y), \tag{8}$$

and

$$|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|z+\rangle X^{|z-\rangle} Y^{\pm|z-\rangle} A^{|z+\rangle} Y). \tag{9}$$

The notion of entanglement, initially proposed in the 1930s, challenged the principle of "local realism," which can be summarized by two fundamental assertions. Realism posits that every particle possesses well-defined properties for all conceivable measurements, while locality asserts that communication between particles cannot exceed the speed of light [31]. Einstein et al. [32] presented a thought experiment in 1935, based on a certain theory that it is possible for one point in the universe to instantaneously influence another point that is located arbitrarily far away. He referred to this peculiar occurrence as *spooky action at a distance*. In the same year, Schrödinger originally called this phenomenon an entanglement (Verschränkung) in paper [33].

### D. QUANTUM GATES

Several approaches to building future quantum computers have been being investigated, including gate-based architecture, photonic architecture, and annealing architecture. These approaches differ in the type of qubits employed, noise and crosstalk properties, and the connectivity among them. As a result, each approach has its own collection of benefits and limitations. Among these, gate-based architecture is considered to be more flexible and allows for a wider range of computation, making it a popular choice for companies like Google, IBM, and Rigetti in the development of quantum computers [34], [35]. Deutsch demonstrated in 1985 that 2-state systems can undergo any unitary evolution by using a small set of simple operations, which can simulate the evolution of any physical system [36] This concept was later termed a quantum gate. Quantum gates are analogous to classical logic gates and are fundamental building blocks in quantum computing systems. They play a crucial role in manipulating and altering the state of qubits. A quantum computer is composed of quantum circuits, consisting of wires and gates, which allow for the manipulation of the qubit's stored information. The utilization of various quantum gates enables the construction of quantum circuits and ultimately the creation of a functional quantum computer. In the physical layer, quantum gates can be implemented in several ways, such as superconducting circuits using Josephson junctions [37], [38], trapped atomic ions [39], [40] or silicon quantum dots [41], [42]. The behaviour and action of a quantum gate can be described mathematically using unitary matrices as

$$U = \begin{pmatrix} u_{00} & u_{01} \\ u_{10} & u_{11} \end{pmatrix}, \tag{10}$$

where $n \epsilon 0, 1, 2, \ldots$ refers to the $n+1$ bit ($2^{(n+1}$-dimensional) operator [43]. Let us start with a quantum gate for a single qubit system. Pauli matrices, which rotate the qubit state on the corresponding axis and produce the phase shift, are considered one of the usable single-qubit systems given by [44] and [45]:

$$\sigma_0 = I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \tag{11}$$

where $\sigma_0$ is Pauli matrices and $I$ denotes the identity matrix. Pauli matrices of $X$, $Y$, and $Z$ axis is given below:

$$\sigma_1 = X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \tag{12}$$

$$\sigma_2 = Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \tag{13}$$

$$\sigma_3 = Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \tag{14}$$

The Pauli gate on the X-axis in equation (12), is referred to as a "NOT gate" like a traditional logic gate. Another useful single qubit gate is Hadamard gate represented as:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}, \tag{15}$$

$$T = \begin{pmatrix} e^{i\pi/8} & 0 \\ 0 & e^{-i\pi/8} \end{pmatrix}, \tag{16}$$

For a single-qubit operation, the U gate is employed, while for a two-qubit function, the controlled-U gate is utilized. The controlled-U gate is composed of a control qubit and a target qubit. The gate applies the $U$ operation to the target qubit only when the control qubit is in the state $|1\rangle$. Otherwise, the target qubit remains unchanged. The controlled-Z (CZ) and controlled-NOT (CNOT) gates are examples of the controlled-U gate. The $C^nU$ gates are multi-qubit gates that consist of $k$ control qubits and one target qubit. The gate $U$ is executed on the target qubit if and only if all $k$ control qubits are in state $|1\rangle$. Otherwise, the gate has no effect on the target qubit. One of the most well-known examples of a $C^kU$ gate is the Toffoli gate, also referred to as the $C^2NOT$ gate. The matrix representation of the $CNOT$ gate and the $C^2NOT$ gate can be expressed as:

$$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \tag{17}$$

$$C^2NOT = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}. \quad (18)$$

The depiction of the circuit representation of controlled gates is presented in Table 1.

**TABLE 3. Circuit representation of quantum gates and matrices.**

| Gate | Symbol | Matrix |
|---|---|---|
| Identity | I | $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ |
| Pauli-X | X | $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ |
| Pauli-Y | Y | $\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$ |
| Pauli-Z | Z | $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$ |
| Hadamard | H | $\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$ |
| CNOT | | $\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$ |
| Toffoli | | $\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$ |

## III. QUANTUM ENABLED TECHNOLOGY FOR THE METAVERSE

The metaverse represents an amalgamation of leading-edge technologies, including AI, blockchain, networking, internet connectivity, and various others. Quantum technology, despite hardware constraints, has already demonstrated its superiority across multiple sectors, including those crucial for the metaverse's functioning. This section investigates the state-of-the-art advancements in quantum AI, quantum-enabled blockchain, quantum internet (QI), quantum computing prowess, security techniques, and their potential integration within the metaverse, as depicted in figure 5.

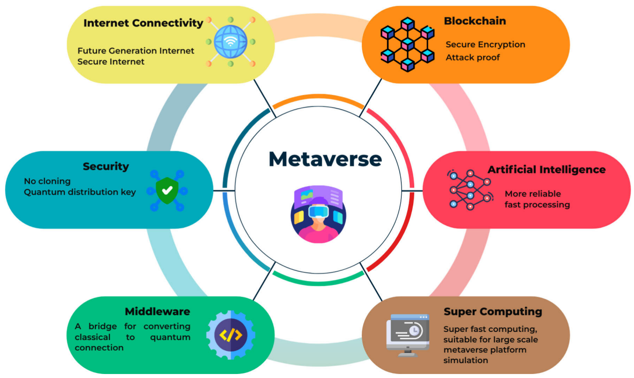


**FIGURE 5. Primary application field of quantum computing in the metaverse.**

### A. INTERNET CONNECTIVITY

Internet connectivity is the fuel for the metaverse. For better service and user satisfaction, internet service should be reliable, low-latency, and secure. Users may need to connect to the metaverse through wearable devices, sensors, or electronic equipment. These smart devices can collect and process information, sending it to an edge or cloud server. In addition, these smart devices often have the capability to collect various types of sensitive information, such as personal habits, preferences, and health conditions. This continuous and ubiquitous monitoring or recording poses risks to user privacy and security [3]. A crucial challenge for future communications is to overcome the limits of Shannon's channel capacity. Shannon's channel capacity is the reliable maximum data rate for transmission in a communication channel with specific bandwidth and noise level. The next-generation QI, which enables satellite-to-ground communication, has the potential to mitigate these issues.

Quantum evolution introduces a new era of the internet known as the QI, wherein the fundamental principles of quantum physics, including teleportation, superposition, and entanglement, are leveraged for networking purposes. It is believed that the future internet system will be an interconnection between classical and quantum internet. With the development of research technology and hardware, the quantum internet is not only a theoretical concept but also an under-construction reality. Quantum communication networks are categorized into two different classifications: unentangled and entangled [10]. The links between quantum nodes in an unentangled quantum network are created by unentangled quantum states. These networks can be utilized to implement short-range point-to-point quantum key distribution (QKD) protocols. A detailed study of QKD networks associated with the physical layer and the network layer, as well as the development paths of application and protocol, is discussed in [13]. QKD does not guarantee secure quantum communication, rather than it generates a quantum random number, which can be shared by two parties via a quantum communication channel. Data will be passed through classical communication channels and QKD shared between the two via the quantum channel. As a result, QKD is a good option for one-time pad (OTP) encryption. In [46], propose a lightweight QKD authentication protocol combining universal polynomial hashing, XOR universal Toeplitz hashing, and OTP encryption. The proposed method uses key recycling by utilizing only one authentication key, and a post-processing refund mechanism. Since both classical data and quantum data are utilized in the QKD scheme, it would be beneficial if the same channel could accommodate both quantum and classical communication. Paper [47] proposes a wavelength allocation scheme for the simultaneous transmission of classical data and QKD over multi-core fiber, significantly enhancing the coverage distance for secure QKD transmission.

The distribution of QKD between two parties can be divided into two types: discrete-variable quantum key distribution (DV-QKD) and continuous-variable quantum key distribution (CV-QKD). Numerous practical experiments have been performed on DV-QKD, including one that covered a 1200 Km distance [48]. Until now, in practical experiments, DV-QKD has been found to cover higher distances than CV-QKD. Nevertheless, CV-QKD distinguishes itself by employing coherent homodyne detection as opposed to single photon detection, which makes it a promising candidate for integration with next-generation communication systems especially in Millimeter (mm)-waves and terahertz (THz). Millimeter (mm)-waves and terahertz (THz) communication have until now been considered for indoor communications, inter-satellite communication, deep space communication, and short-range communications. Zhang et al. [49] have successfully exhibited the feasibility of employing millimeter-waves (mm-waves) and terahertz (THz) CV-QKD in both single-input single-output (SISO) and multiple-input multiple-output (MIMO) systems at cryogenic temperatures of $T = 4$ K. This experiment instills optimism regarding the prospects of establishing a quantum internet for facilitating intersatellite and deep space communications. Paper [50], utilizes CV-QKD with multicarrier multiplexing (MCM) across Gaussian subchannels. The findings reveal the system's robustness against optimal collective Gaussian attacks in both indoor environments and inter-satellite links. For short-distance indoor environments, CV-QKD can be applied for THz band wireless quantum communication. As demonstrated in paper [51], the authors achieve wireless quantum key distribution over a span of 1.95 m, employing a 5-cm diameter antenna and operating within the bandwidth of 0.1–1 THz. The paper [52], demonstrates a practical measurement of the CV-QKD distance obtaining rate for high-speed metropolitan networks in different communication bandwidths.

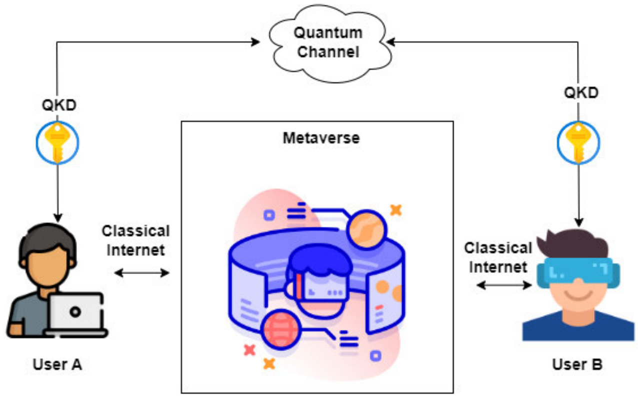


**FIGURE 6.** A conceptual secure metaverse authentication framework leveraging QKD over classical communication channels. In this setup, data transmission occurs via the classical network, while the quantum channel exclusively carries the QKD.

However, the complex and scalable QI is mainly based on an entangled quantum network with the help of quantum repeaters [11]. End-to-end entangled states that span long distances offer significant potential for application in various quantum networking architectures. These entangled quantum networks can be effectively deployed as quantum local area networks (QLANs), quantum metropolitan area networks (QMANs), quantum wide area networks (QWANs), and even as global quantum networks. The interconnection approach for entangled quantum networks can be classified into two categories. The first category is the linear quantum network scheme, which utilizes bipartite entanglement derived from Bell states. The second category involves a 2D quantum network using multipartite entanglement with (Greenberger–Horne–Zeilinger) GHZ states [53]. Paper [11], presents a mathematical model to analyze the dynamic effects on the weakly entangled and strongly entangled quantum network. The study also examined the impact of noise on the equilibrium states of these entangled networks. Caleffi and Cacciapuoti [54], conducted a theoretical analysis of the feasibility of integrating a quantum switch for entangled quantum teleportation through a noisy quantum channel. Quantum repeaters are used to facilitate the teleportation or swapping of entangled qubits across quantum nodes in an entangled quantum network.

QI provides enhanced security and privacy compared to the traditional Internet due to its quantum physics nature. It is impossible to measure a property of a qubit without altering its state, ensuring that qubits cannot be copied or any attempt to do so could be detected [55]. QI can be considered a highly compatible choice for the metaverse, providing unparalleled security, particularly in the context of military-oriented metaverse environments and the industrial metaverse.

### B. SUPER COMPUTING

Over the course of the last fifty years, Moore's law has remained a consistent phenomenon, where computing power has doubled every two years through the continual downsizing of transistors in integrated circuits. Recent cutting-edge transistors have reached a thickness of just a few atoms [56]. Hence, the electronics industry is confronting intrinsic physical limitations that hinder the augmentation of speed and performance. However, the need for high-speed computing is still increasing for advanced technologies like the metaverse. Quantum computing is the next solution to complex computing problems. Metaverse incorporates many technologies, for example AL, blockchain, etc. As a consequence, metaverse needs more computational power than the current web 2.0.

Besides, the metaverse entails potential environmental challenges, including the generation of excessive e-waste, an amplified carbon footprint, and substantial demands for immersive data storage, processing, and transmission [57]. Quantum computers, operating with lower energy consumption than classical computers, hold the promise of mitigating costs and lessening the environmental burden associated with metaverse operations. Quantum computers exhibit enhanced computational efficiency in comparison to their classical counterparts, primarily attributable to their quantum mechanical attribute of superposition. This quantum state of superposition permits the simultaneous existence of multiple possibilities, thereby engendering accelerated processing capabilities when contrasted with classical computers. The inherent property of superposition enables a qubit to represent manifold values in parallel, whereas a bit in classical computers denotes either 0 or 1 exclusively. Moreover, entanglement, another distinctive facet of quantum mechanics, contributes to exponential gains in computing potency. Through the entanglement of multiple qubits, computations can be carried out concurrently. This parallel processing capacity inherent to quantum computers imparts a distinct advantage that is not present in classical computers [58].

### C. SECURITY

The metaverse would not only be confined within the boundaries of the virtual world but would also exert an influence on the social, economic, and cultural aspects of the tangible reality. This virtual world with unrestricted time and space will open a new way for criminals to commit crimes that may have a direct impact on the real world. Since the metaverse is considered would not bound by geographical borders, a single crime may lead to conflicts among several nations. The crime type would be new, and as a result, it may be even more difficult to detect and apply traditional laws. Possible crimes that could occur using the metaverse are theft of virtual assets with real-world monetary value, money laundering through the metaverse, tax violations in the metaverse, real-world location tracking of a user for criminal purposes, sensitive and private data leakage, gambling, physical assault of an avatar, simulation of sensitive events, and many more. If an assailant takes control of an individual's identity and engages in the unlawful actions previously outlined, there exists the possibility that an innocent party in the physical world could face undeserved penalties [59]. Furthermore, the metaverse is susceptible to a range of potential cyberattacks, encompassing diverse forms such as identity theft, man-in-the-middle attacks, wormhole attacks, challenges pertaining to avatar authentication, misappropriation of avatars, false data injection, data tampering, and numerous other vulnerabilities [4], [60]. Consequently, implementing extensive security measures within the metaverse is critical.

System architectures have been proposed with the aim of safeguarding the metaverse platform, user identity, authentication process, network, and data from the attacker. Among them broadly, AI-based methods are proposed for securing the metaverse network and blockchain for authentication and traceability. One of the methods for authentication involves employing biometrics-based techniques through the utilization of AR/VR/XR devices. Cheng et al. [61], proposed biometrics authentication integrating privacy-preserving federated learning. In [2], a two-step authentication framework is introduced, wherein biometric information is conjoined with blockchain. The framework incorporates a modified chameleon collision signature to facilitate real-time mutual authentication [62]. It is considered that the metaverse constitutes a diverse ecosystem encompassing multiple platforms tailored for distinct objectives, ensuring connectivity and preserving authenticity across these metaverse platforms emerges as a crucial imperative. In [63], a comprehensive framework is presented to address the authentication requisites of various metaverse platforms, synergistically integrating biometric authentication with blockchain mechanisms. Specifically, the proposed model leverages Elliptic Curve Cryptography (ECC) in conjunction with a bio-hashing blockchain scheme, thereby delineating a novel approach within this study. In the paper a comprehensive survey on authentication methods rooted in blockchain technology is expounded [64]. In addition to signature-based authentication, the metaverse employs other blockchain technologies such as NFTs [65], smart contracts [66], and consensus algorithms [67] for enhancing security. Instead of relying solely on traditional machine learning or AI approaches, the metaverse incorporates cutting-edge AI technologies such as generative AI and explainable AI (xAI) to ensure robust network security. Generative Adversarial Network (GAN) [68], SHapley Additive exPlanations (SHAP) [69] as a part of XAI are used for intrusion detection in metaverse. In addition to detection of network anomalies, AI could also be used to detect hate speech, harassment, or misconduct within the metaverse. Madina et al. [70] propose audio-based hate speech detection inside metaverse.

Quantum computing is being investigated as a prospective avenue for enhancing the security of cyberspace, encompassing cryptography, data transmission, and machine learning [71]. Taking advantage of the concept of teleportation, a fundamental element in the domain of quantum computing, Cui [72] present an innovative blockchain-based cross-chain protocol designed to enhance security within the metaverse. Instead of establishing a direct link between the user and the metaverse server, the authors applied an intermediary router, analogous to the role of Telamon in teleportation, thus serving as an intermediary conduit for information transmission.

### *D. AI*

Quantum machine learning (QML) holds significant potential for various applications within the metaverse. Before diving into the potential applications of QML in the metaverse, it is worth acquiring fundamental knowledge about QML [73]. The relationship between quantum computing and machine learning can be explored through four distinct approaches, as described in figure 7 [74].

- The *Classical-Classical approach (CC)* also referred to as 'quantum-inspired' machine learning, involves entirely classical algorithms operating on classical data that are influenced by quantum principles and information processing techniques.
- The *Quantum-Classical approach (QC)* often referred to as 'quantum-enhanced machine learning,' encompasses the utilization of classical data processed through quantum circuits on a quantum computer.
- The *Classical-Quantum approach (CQ)* sometimes termed'machine learning for physics' involves the application of classical machine learning techniques to quantum data, enabling the extraction of valuable insights. Examples of this approach include detecting the behavior of quantum computing and studying the effects of noise.
- The *Quantum-Quantum approach (QQ)*, also known as 'purely quantum machine learning,' centers on quantum algorithms that manipulate data encoded as quantum states.

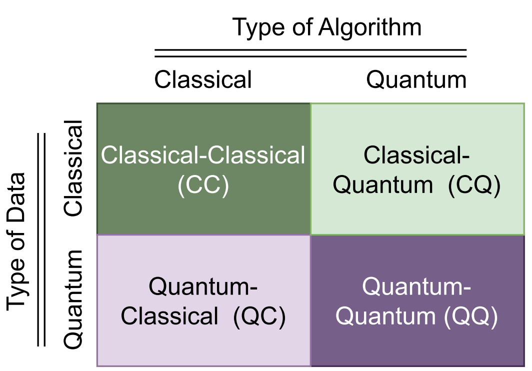


**FIGURE 7. Categorizing QML into four subcategories [74].**

The HHL (Harrow Hassidim and Llyod) algorithm [75] proposed in 2009, is regarded as the foundation of QML. In order to solve linear equations for machine learning, HHL is used. HHL accelerates more quickly than the classical algorithm.

Neural networks (NN) have shown substantial application and social benefits, undergoing rapid development over decades. However, there remains ample room for enhancing NN to achieve superior results and faster performance [76]. [77], [78], [79] use Lyapunov-Krasovskii functional (LKF) for estimating suitable $H_\infty$ state for NN with time-varying delay. Quantum version of NN approaches are quantum neural network (QNN), quantum recurrent neural network (QRNN), quantum convolutional neural network (QCNN), and quantum long short-term memory (QLSTM). These algorithms are similar to classical algorithms. However, they use a quantum circuit or quantum gate to perform operations.

According to [80], the metaverse comprises seven layers: infrastructure, human interface, decentralization, spatial computing, creator economy, discovery, and experience. AI has a significant role within each of these layers and is also essential for facilitating services within the metaverse [1]. Natural Language Processing (NLP) stands as a significant example of an AI application within the metaverse. NLP encompasses a range of tasks, including language detection, translation, human language comprehension, speech-to-text conversion, text-to-speech conversion, and more. NLP serves as an essential criterion for facilitating metahuman activities. Additionally, NLP can be harnessed to mitigate harassment and violations within the metaverse. For instance, Madina et al. [70] employ Convolutional Neural Networks (CNNs) to identify hate speech within the metaverse through audio analysis. The referenced paper [81] also assesses the effectiveness of translation tools for virtual assistance in the metaverse. In order to comprehend 3D text derived from a book and analyze emotions conveyed through the text within a metaverse platform, a Recurrent Voting Generator (RVG) system is introduced in [82]. The proposed RVG consists of three distinct algorithms: the first for emotion analysis, the second for sentiment decomposition, and the third for voting-based learning and optimization.

Applying NLP to the metaverse, QML has potential applicability. In the domain of NLP, QML demonstrates superiority over classical machine learning approaches. In [83], a comparison is made between the performance of LSTM and QLSTM models for speech tagging on social media code mixed language. The study incorporates data from three distinct languages: Hindi, Bengali, and Telugu. Data is extracted from social media platforms, namely Facebook, WhatsApp, and Twitter. The experimental results indicate that QLSTM exhibits superior performance in contrast to the classical LSTM model. Paper [84] applies LSTM for translation purposes, which speeds up the task with better accuracy. Instead of using the quantum gate, they use a unified quantum circuit based on the DisCoCat diagram(express the meaning of each individual word as well as the combined nature of the sentence stated by grammar). Wright et al. [85] use the DisCoCat model to design a quantum-backend kernel for NLP utilizing the support vector machine (SVM) algorithm. The quantum kernel measures the similarity of two sentences based on transition amplitude and the SWAP test. Furthermore, Quantum SVM (QSVM) is employed across various NLP tasks, encompassing sentiment classification [86], rule-based question-answering systems [74], generating code comments to safeguard malware source code [87], and text classification [88].

Computer vision for the metaverse is required for multiple purposes. AI-driven computer vision plays a pivotal role in discerning 3D objects, recognizing object colors, adapting colors to user preferences, and enhancing images within the metaverse context. A comprehensive survey on quantum image processing is available in [89]. Another noteworthy application within the AI-driven metaverse pertains to avatar creation. Various techniques are employed for avatar generation, including vision-based and sensor-based approaches. In either paradigm, the involvement of AI is indispensable. In vision-based avatar formation, human images or videos captured by Extended Reality (XR) devices necessitate processing for extracting pertinent information, activity recognition, culminating in the fabrication of virtual avatars within the metaverse. In both scenarios, a quantum approach can be employed. In particular, in [90], Mediapipe, an open AI platform developed by Google, utilized to map real-time vision-based humans to avatars in the metaverse. By integrating human-computer interaction with the metaverse, it becomes possible to employ AI for real-time monitoring of an individual's current situation. Padha and Sahoo [91] employed an LSTM model within a quantum circuit for analyzing time series data related to worker health condition monitoring. This time series dataset encompasses variables like body postures, heart rate, and other relevant information collected from workers across different working conditions, with the aim of determining stress levels. QML possesses the capacity to span diverse applications within quantum-enabled metaverses, encompassing sectors of considerable importance such as finance, medicine, energy, education and more. For example, in the financial metaverse sector, QML can be applied in tasks like risk assessment, financial forecasting, fraud detection, and many more [92]. Gurung et al. [93] introduce a quantum federated learning framework empowered by blockchain technology, intended for implementation within the decentralized metaverse. This framework is especially applied for securely-oriented systems, as exemplified by financial systems.

### E. MIDDLEWARE

While the rapid advancement of quantum technology is undeniable, it is important to recognize that its growth trajectory does not necessarily predicate the imminent or inevitable replacement of classical technology. Furthermore, the prospect of a symbiotic coexistence between quantum and classical systems remains viable. Hence, establishing effective communication between quantum and classical systems requires the deployment of middleware solutions. NVIDIA developed the CUDA quantum platform for hybrid computation between classical and quantum computing devices, utilizing a standard programming model [94]. It offers an open platform that allows users to connect any type of QPU. XACC is another system-level software for interacting between heterogeneous quantum and classical systems [95]. XACC offers a low-level software interface for the development of quantum-empowered programs running in a cross-platform operation. In [96], a conceptual architecture for middleware is presented, aimed at facilitating the integration of multiple quantum processing units (QPUs) and classical computing nodes (HPC) within a quantum-classical framework. This outlined architecture advances quantum-classical integration through the provision of unified resource access and management. It empowers applications to allocate resources and oversee quantum and classical tasks with adaptability and coherence. The integration of quantum-classical tasks can be classified into three types: HPC-for-quantum, quantum-in-HPC,and quantum-about-HPC as illustrated in figure 8.

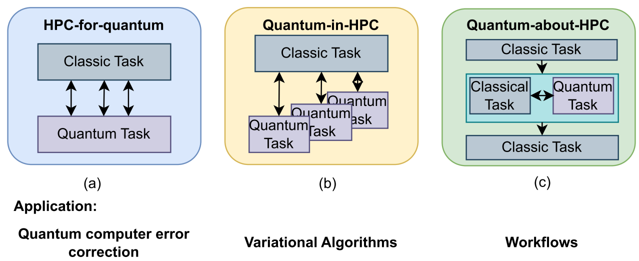


**FIGURE 8. Quantum and classical system integration patterns [96].**

### F. BLOCKCHAIN

In short, blockchain is a distributed digital ledger that contains records cryptographically linked in a chain. Generally, a blockchain consists of four fundamental elements: 1) Hash of the previous block, 2) data of the current block, 3) nonce to generate a specific shape of the hash, and 4) hash of the current block [97]. The concept of blockchain was first introduced in a white paper authored by Nakamoto Satoshi in 2028 [98], [99]. As time passes, the potential power and usability of the blockchain are being explored beyond just the financial sector, although it was initially introduced for the digital currency known as bitcoin.

The significance of blockchain as the foundational infrastructure of the metaverse stems from its provision of essential attributes, including privacy, security, data storage, virtual asset transactions, and data interpretability. Several survey works have been carried out related to the integration of blockchain with the metaverse [98], [100], [101], [102], [103], [104].

Authentication plays a significant role in the metaverse, as a substantial portion of research endeavors seeks to incorporate blockchain technology through various approaches. The paper [105] presents a novel proposition concerning a smart contracts-based secure authentication mechanism, targeting the interaction between the Metaverse Service Provider (MSP) and the Metaverse users (MU). To incentivize desired user behavior within the metaverse, the authors incorporate a Stackelberg game theory-based incentive scheme, rewarding MUs for their engagement and activities within the metaverse platform. Since there is multiple service and facilities, and institutes in the metaverse. The service providers also will be multiple. To address this complexity, paper [106] presents a cross-chain transaction and verification scheme. The scheme incorporates a notary mechanism to effectively supervise and facilitate cross-chain operations among multiple metaverse platforms. In [107], the authors employ secure proxy signatures within smart contracts to ensure privacy during mutual communication within the metaverse. In the metaverse, the interaction between two participants is typically considered as signature-based authentication. In [63] a mutual authentication scheme is introduced that uses elliptic curve cryptography (ECC) and biometric data to establish secure communication between users and platform servers within the metaverse. The study takes into account interactions involving multiple metaverse platform servers and avatars. Pseudo-identities, public keys, and personal information are stored in the blockchain, enabling the metaverse platform servers to verify users by utilizing these values. The article [62], uses biometric information from the iris scan along with a chameleon signature. The modified chameleon collision signature guarantees real-time user authentication with the physical user and the avatar. To establish a secure environment within the metaverse, where only authorized users can access the virtual institute, a blockchain-based multisignature lock is proposed in [108]. Another case of blockchain implementation is the management of digital asset stores and services. Ersoy et al. [109] propose a complete metaverse structure for 3D virtual asset transactions and security for the metaverse to prevent assets from being stolen, lost or transformed into another metaverse. Lin et al. [110] propose a blockchain-aided semantic communication framework for AI-generated automatic content sharing systems in the metaverse. Semantic zero-knowledge proof defense is employed to identify the image of the attacker. Instead of submitting data from the user directly, the edge server process data using bilinear interpolation before transmitting.

In blockchain networks, security is maintained through the implementation of public/asymmetric key cryptography or hash functions. However, both these schemes are susceptible to compromise by powerful quantum computers employing Shor's and Grover's algorithms. The public-key algorithms commonly employed in blockchain, for example, DSA (Digital Signature Algorithm), RSA (Rivest, Shamir, Adleman), and ECDH (Elliptic Curve Diffie-Hellman), are susceptible to being broken by Shor's algorithm. Additionally, Grover's algorithm poses a threat to hash functions, potentially enabling swift generation of hashes and detection of hash collisions. This compelling scenario necessitates the transition of blockchain into the post-quantum era by adopting post-quantum cryptographic schemes [111]. The fast improvement in quantum technology has prompted the development post-quantum blockchain into two distinct categories: quantum-resistant blockchain and quantum-enabled blockchain. Numerous survey works have been carried out in the field of postquantum cryptographic systems, indicating their importance and active exploration in academic research [97], [111], [112], [113], [114], [115], [116]. Quantum-resistant blockchain aims to counteract quantum attacks, such as those based on Grover's and Shor's algorithms, through the utilization of mathematical algorithms and protocols that are currently effective against quantum computers. Lattice cryptosystems [117], [118], [119], multivariate cryptosystems [120], [121], code-based cryptosystems [122], [123], and some others cryptographic schemes are recognized as quantum-resistant post-quantum cryptosystems.

However, it should be noted that these defenses may not be sufficient against more powerful quantum computers with larger qubits. In contrast, a quantum-enabled blockchain seeks to harness the advantages of quantum computing to enhance security and efficiency. This survey aim is to find the scope of quantum-enabled blockchain that can integrate with metaverse for security and robustness against the classical attack and quantum attack [111], [112]. After significant years of advancement, traditional cryptography has achieved a high level of maturity in contrast to quantum cryptography, which remains relatively nascent in its development. Currently, most of the research on quantum-enabled blockchain is focused on ideas and theoretical analysis. There are very few works that have actually implemented quantum-enabled blockchain in practice. Quantum cryptography comprises essential components, including quantum key distribution, quantum authentication, quantum communication, quantum signatures, and other fundamental quantum applications.

In the case of a quantum-enabled signature for authentication, one of the candidates is a quantum-blind signature. There are multiple mechanisms for carrying out the signature, such as entanglement [124], without employing entanglement [125], correlation of EPR (Einstein–Padolsky–Rosen) pairs [126], [127], and teleportation [128]. Quantum-blind signature contains additional quantum information based on the system. Quantum blind signature has diverse potential application fields including in the metaverse. In [129], a multiparty quantum blind signature is applied for industrial blockchain networks. In this system, QKD is employed to execute a signature in a secure way. The implementation of quantum signatures necessitates the utilization of quantum systems. However, to achieve quantum advantages in classical systems, a hybrid quantum/classical cryptographic

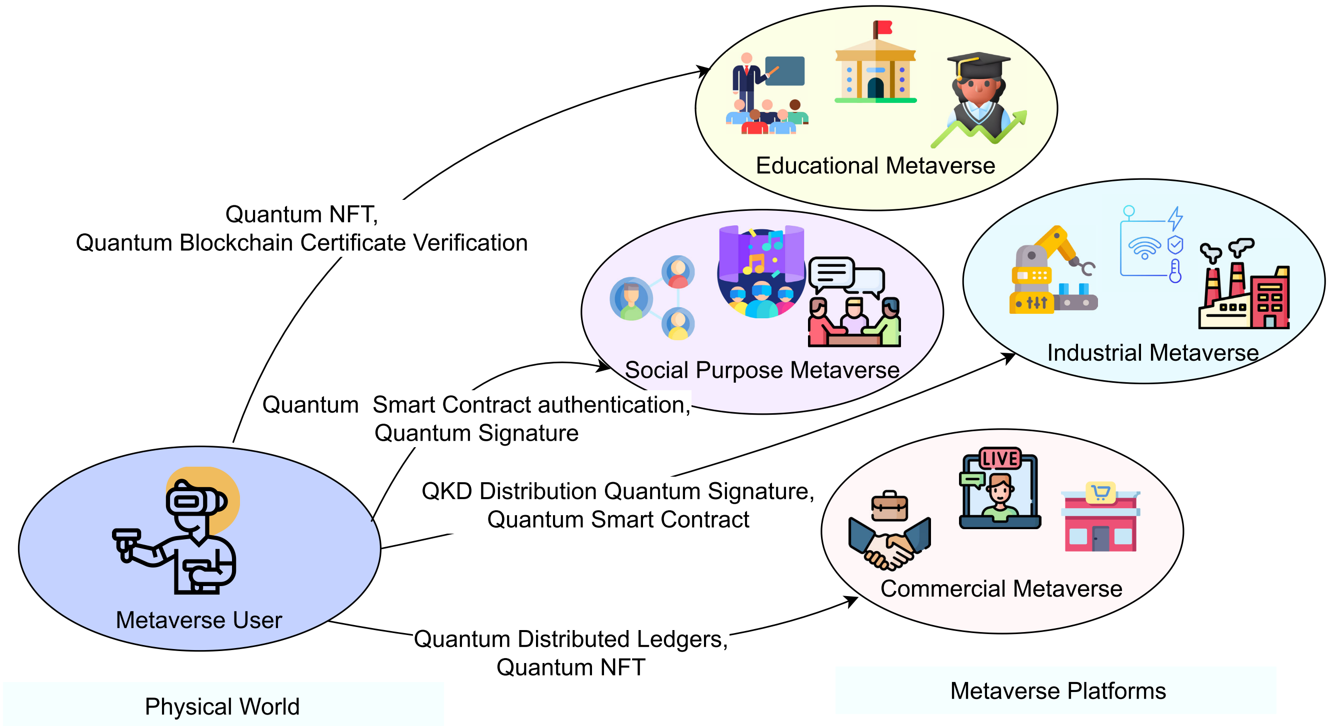


**FIGURE 9. The role of quantum blockchain: Bridging between the real world and metaverse.**

approach using one-shot signatures can be adopted [130]. One potential straightforward approach for implementing a quantum-enabled blockchain involves the utilization of Grover's quantum search algorithm for data mining purposes [131]. The core concept behind this proposition resembles the process of identifying the hash function used to attack the cryptographic system. Ronczka [132], proposed an idea to generate a secure key by shuffling a qubit. Instead of using traditional cryptographic schemes, generate keys using the quantum properties of living and non-living entities in a qubit. To address the challenges posed by quantum computing, it is imperative to redesign existing cryptosystems. Jogenfors [133], proposes "quantum bitcoin," a blockchain-based distributed quantum money system that draws upon a fundamental property of quantum mechanics known as "no cloning." In this system, quantum states serve as currency units and carry classical information embedded within them for verification purposes. Another cryptocurrency called "quantum coin" is established on the principles of quantum entanglement and Delegated Proof of Stake (DPoS) to construct a quantum blockchain framework [134]. Quantum entanglement is utilized to establish connections between quantum blocks, and furthermore, an information authentication mechanism based on Bell states is implemented. Li et al. [135] introduce a quantum blockchain framework featuring a consensus algorithm known as quantum delegated proof of stake (QDPoS). This algorithm is based on quantum voting mechanisms executed by the participant nodes. The proposed quantum blockchain system is implemented on an IBM real quantum computer, and its efficacy is evaluated through fidelity testing. Another dimensional lifting employing quantum blockchain approach is based generalized Gram-Schmidt procedure [136]. In Gram-Schmidt orthogonalization, the initial states is extended by dimention of the original Hilbert Space. In this process, transaction information is encoded using the generalized Gram-Schmidt process and stored in a multi-qubit state. As shown in figure 9, the role of quantum blockchain is bridging between real world and metaverse applying verious methods such as quantum NFT for virtual assets, quantum private blockchain for industrial applications, and many more. Table 4 lists the current quantum computing works that exhibit potential for the metaverse.

## IV. QUANTUM-METAVERSE ENABLED APPLICATION FIELD

### A. HEALTHCARE

Applications of quantum computing and metaverse in the healthcare sector both have their own set of benefits. Quantum computing offers the required backend capabilities, encompassing areas such as genomics and clinical research, diagnostics, treatments, and interventions [137]. On the contrary, the metaverse serves as a front-end facilitator, providing immersive 3D visualizations for applications such as virtual assistance, telemedicine, and virtual training [138]. The integration of quantum technology with the metaverse will bring about evolutionary improvements in the healthcare system.

**TABLE 4.** Summary of the application of quantum-enabled technology for the metaverse across various technical aspects.

| Technical Aspect | Ref. | Purpose | Technique |
|---|---|---|---|
| QI | [46] | Generate random key for one-time pad (OTP) encryption | QKD |
| | [47] | Simultaneous communication classical and quantum | Wavelength allocation for fiber optic cable |
| | [48] | Cover long distance 1200 km in case of QKD sharing | DV-QKD |
| | [49] | Apply the mm wave THz band in both SISO and MIMO system | CVQKD |
| | [50] | Apply MCM over gaussian channel | ODFT is used for demultiplexing of the CVQKD scheme |
| | [51] | wireless QKD for indoor communication | CVQKD is utilized |
| Security | [72] | blockchain-based cross-chain protocol | Quantum teleportation |
| Blockchain | [106] | Authentication for metaverse | Smart contracts used for access control |
| | [107] | Authentication in multiple metaverse platform | cross-chain scheme with improved hash timelock |
| | [63] | Signature Based Mutual authentication for metaverse | Elliptic Curve Cryptography (ECC) and biometric data |
| | [62] | Signature Based Mutual authentication | Chameleon signature and biometric data |
| | [110] | Asset transactions inside metaverse | Propose blockchain framework |
| | [111] | Asset transactions inside metaverse | Zero-knowledge proof semantic system |
| | [125]- [129] | Quantum based authentication | Quantum-blind signature |
| | [134], [135] | Quantum cryptocurrency | QDPoS consensus algorithm |
| AI | [83] | NLP (speech tagging on social media) | QLSTM |
| | [84] | NLP (translation) | QLSTM and DisCoCat diagram |
| | [85]- [89] | NLP for various purposes | QSVM |
| | [92] | Worker health condition monitoring | QLSTM |
| | [94] | Secure Data Gathering utilizing blockchain | Quantum federated learning |
| Middleware | [95] | hybrid computation between classical and quantum | CUDA Quantum platform |
| | [96] | System-level software for quantum classical interaction | XACC |
| | [97] | Interaction between quantum classical computation | Conceptual model |

### 1) SECURE HEALTHCARE

In the healthcare metaverse, secrecy and privacy are essential components. The metaverse platform has the potential to require sensitive medical data. Therefore, data must be protected by current or upcoming privacy laws, such as the Health Insurance Portability and Accountability Act (HIPAA) in the United States. In a zero-trust environment, secure computation techniques, such as blockchain technology, are indispensable tools [139]. In [140], blockchain and SHAP (SHapley Additive exPlanations) explainable AI (XAI) are utilized to enable remote real-time execution of telesurgery operations with the help of the metaverse. Notably, the doctor and patient are not co-located within the system architecture. The surgical procedure is performed remotely by the doctor through the metaverse, facilitated by a robotic arm. To process the patient data and ensure secure data sharing from the doctor to the patient via the metaverse, XAI is employed in combination with a blockchain network. Kaushik and Kumar [141] provide a thorough and detailed survey of the current state of research on quantum blockchain within the healthcare sector.

#### 2) DRUG DISCOVERY AND COMPLEX SIMULATION

Conducting research and simulations to understand the origins of diverse diseases and employing quantum-enabled metaverses for disease detection could mark a significant milestone for humanity. In [142], a hybrid Quantum Machine Learning (QML) approach was implemented to achieve early detection of skin cancer through the classification of pigmentation within cancerous and non-cancerous skin lesions.

### B. INDUSTRIAL APPLICATION

Industry 4.0 is characterized by IoT-driven connectivity within the smart manufacturing sector. In contrast, Industry 5.0 represents a paradigm in which human-robot collaboration amplifies productivity in manufacturing, considering not only economic aspects but also environmental and social challenges [143]. Quantum computing and the metaverse assume pivotal roles within Industry 5.0. Quantum-enabled metaverse can be used for enhancing security, optimization, authentication, maintenance, management, and secure data storage. Paper [144] offers a comprehensive survey focusing on the extensive industrial real-life applications of quantum computers. Moreover, the survey paper [145], extensively explores the future prospects of the industrial metaverse, offering an in-depth analysis and discussion. Ensuring security in industrial data communication is of paramount importance. Quantum Key Distribution (QKD) can be effectively employed within the industrial metaverse to facilitate secure real-time data analysis and visualization. Additionally, the integration of quantum-enabled blockchain within the metaverse environment presents an opportunity for data authentication, verification, and traceability. Research community and companies are also interested in metaverse and quantum computing. For example, IBM has pioneered the establishment of IBM Q, a groundbreaking commercial quantum system for business and research domains. In a notable partnership, IBM Q collaborates with an extensive network of over 500 commercial enterprises and esteemed research organizations, counting ExxonMobil and CERN among its prominent partners [146]. Table 5 provides some commercial applications of quantum computing and metaverse at the industry level.

### C. AUTONOMOUS VEHICLE

The development of autonomous vehicles is due to outstanding research achievements in embedded systems, Vehicular Ad hoc Networks (VANET), wireless sensor networks, real-time navigation, deep learning-based data collection and dissemination, and analytics. All of the major automobile industries focus on autonomous cars and have already taken significant steps throughout the manufacturing phases with the help of top technology companies like Samsung, Unity, Microsoft, etc [163]. Millions of test miles already have been logged by prototype autonomous vehicle models [164]. Nevertheless, mass-scale adoption is still impossible due to safety concerns. Autonomous driving prototypes frequently experience accidents. Around 400 car crashes are reported in USA within 11 months in the year between 2021 and 2022 [165]. It propels the widespread use of simulation-based autonomous vehicle system development and design. The integration of autonomous vehicles into quantum-enabled metaverses holds potential as a futuristic avenue. Quantum enabled metaverse applications could extend to the domain of autonomous vehicles, encompassing functions such as algorithm testing, battery monitoring, routing optimization, traffic monitoring, and real-time traffic data integration for control purposes. The first commercial quantum application initiative for autonomous vehicles was undertaken by the automotive company Volkswagen in 2019. They implemented quantum computing-based real-time traffic optimization using live data from the streets of Lisbon. This process involved two steps: firstly, the acquisition of the bus pathway of the city, and secondly, installing an Android app on the bus to obtain the optimized route powered by a quantum processor [166]. Another automobile company, BMW, utilizes Honeywell's quantum computer to enhance its supply chain efficiency. The Recursive Quantum Approximate Optimization Algorithm (R-QAOA) is employed on Honeywell H1 hardware to address number partitioning challenges within the context of industrial supply chains [147].

### D. ENERGY SYSTEM

Since the 1st Industrial Revolution, fossil fuels have been the main source of energy for industrial production, development, domestic applications, and the generation of electricity. The term "fossil fuel" is a complete context to indicate nonrenewable energy sources, including coal, coal-derived products, natural gas, derived gases, crude oil, petroleum products, and nonrenewable waste materials.[1] The extensive use of fossil fuels has resulted in environmental damage, global warming, greenhouse effects, and other crucial side effects, prompting researchers, policymakers, and global politicians to seek sustainable, environmentally friendly energy production. Furthermore, the integration of advanced information and communications technology into energy systems, encompassing production, distribution, storage, consumption, and billing, has led to a new proposed system called the "Energy Internet" [167], [168], [169]. The research community and industries are actively exploring the potential of both metaverse and quantum computers for energy system design, optimization, visualization, and simulation. Quantum computing is employed for handling complex computations and optimization tasks, while the metaverse finds application in design, simulations, and visualizations. However, the possibility of integrating quantum computing with the metaverse has not yet been explored. This section presents an overview of the

[1] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Fossil_fuel

**TABLE 5. Summary of the commercial application of QC and metaverse by the companies.**

| Organization | Ref. | Sector | Objective | Platform |
|---|---|---|---|---|
| BMW | [148] | Automotive | Supply chain Management efficiently handles myriad components which used in BMW vehicles | Honeywell (quantum computer) |
| | [149] | Automotive | Virtual product testing (iX1 vehicle), explore virtual world, and get in-vehicle environment | JOYTOPIA (metaverse) |
| | [150] | Manufacturing | Simulate automotive manufacturing lifecycle in to digital twins | BMW and NVIDIA (metaverse) |
| Accenture | [151] | Pharmaceutical | Discover new drug by using molecular comparison was as good or better than existing methods | 1QBit (quantum computer) |
| | [152] | Consumer Discretionary | As a case study, develop virtual Tuvalu digital nation inspired from Tuvalu pacific island nation | CONTINUUM (metaverse) |
| NVIDIA | [95] | Service | Provide hybrid quantum-classical computing by Quantum processing units (QPUs) | cuQuantum (quantum computer) |
| | [153] | Service | Operation and application creation with the help of Universal Scene Description (OpenUSD) | Omniverse (metaverse) |
| Microsoft | [154] | Service | Help scientists and industries to work with climate change, chemistry, materials science, and space | Azure Quantum (quantum computer) |
| | [155] | Consumer Discretionary | 3D virtual version of Microsoft Teams software | Mesh (metaverse) |
| SK Telecom | [156] | Telecommunication | Security against cyber-attacks by utilizing QKD based VPN | Quantum random number generator (QRNG) chipset with AXGate's VPN (quantum cryptography) |
| | [157] | Consumer Discretionary | A metaverse for Social networking for small to large scale, e-commerce | ifland (metaverse) |
| Hitachi | [158] | Transportation | Automate and optimize train operations by adapting quantum system to schedule crews based on a single train line, considering other conditions | Metal-oxide semiconductor annealing, or CMOS annealing (quantum computer) |
| | [159] | Industry | Provide software and operating system for the industrial metaverse | Lumada (metaverse) |
| NASA | [160] | Aerospace | To arrange energy-intensive tasks by planetary explorers, utilizing high battery power, to meet mission objectives | Google (quantum computer) |
| | [161] | Education | Training, visualization, and mission engineering | MRET (metaverse) |
| Samsung | [162] | Electronics | simulation of the dynamics of an interacting spin model to improve phone batteries | Honeywell (quantum computer) |
| | [163] | Consumer Discretionary | Blockchain based Decentraland platform | 837X (metaverse) |

ongoing research directions toward quantum computing and metaverse-aided energy systems. Subsequently, it proposes a pathway for the integration of a quantum-enabled metaverse.

Energy system design and optimization pose challenges for classical algorithms. Quantum computers offer potential solutions in such intricate scenarios. The applications of quantum technologies in the energy internet are classified into two types implementing quantum mechanics (superposition, entanglement, and error correction and detection) in classical devices. Another is executing complex algorithms in real quantum hardware [170]. There are some significant application areas in the energy industry where quantum computing is applied. Electric power flow analysis using QC techniques for efficient management of load settings. The QAOA [171], the Harrow-Hassidim-Lloyd (HHL) algorithm [172], and other quantum algorithms are used to analyze power flow. A crucial optimization challenge within a smart grid is the unit commitment (UC) problem, which involves scheduling electricity production to minimize production costs based on energy demand and maximize profits. UC problem formulates large-scale mixed integer nonlinear problem which is difficult to solve. Various quantum optimization algorithms, including QAOA, Quadratic Unconstrained Binary Optimization (QUBO), and Quantum Annealing Algorithm (QAA), are employed for solving the UC problem [173], [174], [175], [176]. Others use of quantum technology in energy internet are QML-based forecasting [177], heat exchanger network synthesis [176], smart grid security [178], facility location allocation [179], power system control [180], etc.

The metaverse and its associated technologies can play an important role in the coming energy revolution. Metaverse and its complementary technologies offer a foundation for intelligent energy oversight, intelligent administration, and sophisticated transactions, intelligent energy simulation, forming the fundamental bedrock for the energy internet envisaged [181], [182]. Deng et al. [183] presented a metaverse-centric approach for an intelligent energy storage station. The objective of this metaverse lies in constructing a virtual representation of power system storage, facilitating management, control, and disentanglement of intricate coupling interdependencies within the system. Furthermore, it facilitates the exploration and optimization of processes that elude precise modeling. Houda and Brik [184] propose a blockchain-based metaverse framework for a secure and sustainable energy trading system. In this context, smart contracts on Ethereum with cooperative game theory are used for energy pricing. Communication between the energy customer and the provider is established using a mutual authentication token. In [185] propose a metaverse-based ecosystem for a total solution of battery management for electric vehicles connected with the smart grid. The convergence of quantum technology and the metaverse has the potential to propel us toward a carbon-neutral world. A notable instance lies in the realm of green energy, particularly within the context of wind farm design and optimization, where the collaborative utilization of metaverse and quantum computing is conceivable. Qubit Engineering, for example, provides wind farm developers with meticulously optimized turbine layout designs that effectively mitigate interturbine wake effects [186]. Conversely, in collaboration with Siemens, NVIDIA has pioneered the development of a metaverse platform designed to simulate wind turbine behavior [187].

### E. MILITARY AND DEFENCE

One of the greatest possibilities involves the utilization of quantum-enabled metaverse platforms for military applications. While the integration of quantum technology into a metaverse framework has yet to receive significant academic attention, it is noteworthy that quantum technology has the potential to satisfy the rigorous demands of a military metaverse. In the military metaverse, a substantial volume of profoundly sensitive data necessitates transmission from an edge server to a metaverse server. The potential for a data breach or compromise raises significant national security apprehensions. Some intelligence agencies are amassing encrypted information that may eventually be decrypted through the utilization of advanced quantum computing capabilities [188]. Hence, stringent information security measures are imperative to avert vulnerabilities. In this regard, quantum cryptography emerges as a compelling prospective remedy that offers unparalleled security. Furthermore, the integration of a quantum internet could provide the military metaverse with the means to ensure exceedingly secure communication channels. Quantum cryptography, quantum Internet, and quantum clocks, QML for detecting drones, could be harnessed within a military metaverse setting [9]. Moreover, quantum-enabled metaverses have the potential to serve in simulating battlefield environments, devising strategic plans, advancing weaponry, and researching new materials for military objectives [189], [190], [191].

### F. OTHERS

Beyond the applications listed above, there are numerous additional fields in which quantum-combined metaverse applications could be used. Quantum-enabled metaverse for energy optimization is one of them.

The financial sector constitutes another crucial application field of the quantum-enabled metaverse. The metaverse, in turn, is poised to unveil novel avenues for business and e-commerce. In this context, quantum computers can significantly expedite the processes for derivative pricing and risk analysis. Furthermore, the QAOA holds promise for efficiently addressing optimization challenges within polynomial time constraints [192].

The quantum-enabled metaverse has potential applicability in the prediction of natural disasters. The metaverse can serve as a platform for simulating various phenomena, such as airflow and water dynamics. The computational demands of these simulations can be effectively addressed through the utilization of quantum computing. As an illustration, Mezzacapo et al. [193] have introduced a quantum simulator designed for encoding fluid dynamics and transport phenomena. This innovation introduces a broad spectrum of prospective applications, ranging from the analysis of blood flow within the cardiovascular system to the modeling of flow within industrial heating systems, as well as defending low-lying coastal regions from threats of seawater inundation [194].

Quantum-enabled metaverses have potential applications in the fields of education and research. For instance, metaverse could be utilized in Astrophysics to simulate complex galaxy systems and analyze vast astronomical datasets using Quantum Machine Learning (QML). This would allow for the presentation of dynamic and immersive outcomes within the metaverse, enhancing the analysis process [195].

## V. CHALLENGES OF INTEGRATION QUANTUM TECHNOLOGIES IN THE METAVERSE

Many obstacles exist when integrating quantum computing with the current classical systems in the metaverse [196]. Quantum technology is not a new concept theoretically, but its practical implementation is still at the beginning stage. There are lots of practical implementation limitations for quantum technologies. However, despite those implementation limitations, quantum computing shows extensive power in each field. Therefore, this survey tries to connect quantum computing with the metaverse for the researchers to show the scopes of integration of these two technologies for improving the metaverse. The primary focus of this survey is the metaverse, not quantum computing. It is not, therefore, concerned with lessening the constraints and challenges associated with quantum computing. Instead, focus on how to improve the metaverse through the application of existing quantum technology. The present constraints on quantum hardware could make it unable to fulfil the complex computational requirements of large-scale metaverse applications. In the metaverse, achieving interoperability between quantum and classical systems is crucial but complex, requiring data transport, communication protocols, and coherence maintenance to be considered. Because quantum computing technologies are expensive, it can be difficult for many developers and organizations to acquire quantum resources. It takes many resources to build the infrastructure required for quantum-powered metaverse applications. Moreover, the lack of qualified quantum programmers highlights the necessity for tools and languages that make quantum programming accessible to anyone. Developing customized quantum algorithms requires knowledge of both metaverse development and quantum computing. Further discussion on the challenges is discussed in the following subsections:

### A. HARDWARE LIMITATIONS

Hardware is one of the main barriers for both the metaverse and quantum systems. Furthermore, the research and commercial attention toward quantum-enabled user hardware for accessing metaverses remains limited. For Web 2, the smartphone is considered a representative device. On the other hand, for the metaverse or Web 3.0, the ultimate primary hardware is still questionable. Some devices are being considered, such as smart glasses and devices that are head-mounted (HMD). However, each of them has pros and cons and is not strong enough to meet the challenges of metaverse demands. Furthermore, the metaverse is considered to have to have a similarity to the real world, where a multitude of sensations occur, encompassing not only sight and hearing, but also elements such as smell, wind, and slipperiness. To enhance the metaverse's fidelity to real-world experiences, the incorporation of sensor hardware becomes imperative [197]. However, in the future, quantum sensors could find application in improving precision within metaverse experiences [198].

The primary constraint of quantum technology lies in hardware improvement. Presently, fundamental quantum mechanical attributes are attained through foundational principles derived from nature, such as electron spins or photon polarization, which function as qubits [199]. One of the primary challenges confronting contemporary quantum systems revolves around the enhancement of qubit quality, thereby ensuring its stability and concurrently augmenting the qubit count. A qubit necessitates coherence error resistance (a temporal duration during which the qubit preserves its quantum information without undergoing deterioration) while maintaining high gate fidelity. Significant further research is imperative for qubit error correction. Due to the inherent quantum principle of "no cloning," the process of error correction for qubits presents intricate complexities as opposed to error correction for classical bits [9].

### B. SYSTEM REDESIGN

The existing metaverse standards, namely IEEE P7016 [200], IEEE P2048 [201], IEEE P1589 [202], IEEE 2888 [203], and ISO/IEC 23005 [204] do not encompass quantum computing and its related applications within their scope. To embrace quantum computing within the metaverse, a substantial system redesign becomes imperative. This redesign should encompass the incorporation of quantum-enabled user devices, such as quantum Head-Mounted Displays (HMDs), alongside the existing smartphones employed in web2. Additionally, network infrastructure, edge computing, and cloud computing must undergo upgrades to accommodate and integrate quantum technologies effectively. Metaverse development tools, application software, and future operating systems for the metaverse need the capability to work with the quantum environment and adhere to quantum principles. While it may raise financial concerns in the short term, it is expected to be cost-effective in the long run, resulting in significant benefits.

### C. SECURITY CHALLENGES

Although we are considering quantum computer with metaverse for enhancing security. However there is possibility of attack in quantum system also. While quantum systems are commonly regarded as secure and resistant to attacks, it is essential to acknowledge the existence of potential vulnerabilities within these systems. Various types of attacks may be possible in quantum systems, such as eavesdropping on channels, the injection of faults to disrupt qubits, and the introduction of malicious entanglement. In paper [205], a comprehensive and thorough analysis is presented, delving into the possible attacks that could compromise the integrity of quantum systems. Therefore, it is necessary to consider and research the impact of attacks, along with various types of attack scenario within the quantum-enabled metaverse platform.

### D. QUANTUM-METAVERSE WORKING GROUP

To effectively incorporate quantum computers into the metaverse, it is essential to devise systems that can effectively embrace quantum principles. This undertaking necessitates the presence of a workforce, which may not exclusively comprise quantum researchers, however, should ideally encompass quantum engineers possessing a comprehensive understanding of quantum mechanics, quantum systems, and the methodologies associated with the development of systems and software employing quantum frameworks.

## VI. PROJECTS AND DEVELOPMENT TOOLS

The establishment of the Quantum in Consumer Technology Technical Committee (QCT TC) is attributed to CTSoc, the technical sponsor of IEEE Quantum Week. This committee serves as a platform that facilitates the exchange of insights, challenges, and opportunities among a diverse community of quantum researchers, entrepreneurs, educators, programmers, and newcomers [198].

For simulating quantum information on a classical computer, there is a Python-based simulator named SimulaQron [206]. This software allows qubit transmission, entanglement generation, QKD generation, quantum network build and measurement of the results within local computer which is remotely connected with the quantum processor. Several platforms are available for quantum machine learning, including:

- *Qiskit* [207], is an open-source software development kit, is developed by IBM for working with quantum computers. It is a Python-based tool that provides facilities for researchers and engineers to work with quantum circuits, hardware, and software simulation, and machine learning, running on cloud-based actual quantum computers.
- *TensorFlow quantum* [208] is developed by Google for QML. It provides hybrid quantum-classical computation for machine learning combining Google quantum computer with TensorFlow.
- *Azure Quantum* [209] is a cloud-based quantum computing solution provided by Microsoft. Quantum-based software development entails the utilization of a Quantum Development Kit (QDK), the Q# programming language (integrated with Python or the.NET framework), as well as compatibility with Visual Studio.
- *Amazon-braket* [210] constitutes a web-based quantum computing service offered by Amazon Web Services (AWS). It supports multiple programming languages and access multiple supercomputers including D-Wave, IonQ, and Rigetti.

Several platforms are available to create 3D environments for the metaverse, which also integrate various technologies such as AI, blockchain, and more.

- *Unity:* Unity[2] is a 3D development engine utilized for games, virtual reality, augmented reality, digital twin applications, as well as industrial and automotive simulations.
- *Unreal Engine:*The Unreal Engine[3]
- *Omniverse:* Omniverse[4] is an Universal Scene Description (OpenUSD)-based 3D platform for metaverse applications developed by NVIDIA. It provides the capability to integrate other platforms into its workflows.
- *Blender* Blender[5] is an open source platform-independent 3D content development tool for the metaverse.

Plugins are needed to facilitate the interconnection between quantum computing and metaverse development platforms. For example, Quantum Computing Unity (QCU)[6] stands out as an open-source platform that links Qiskit with Unity3D. QCU enables the establishment of a connection with real quantum computers through an Authentication Token, which can be integrated with Unity game objects.

## VII. RESEARCH DIRECTIONS

The integration of quantum computing within the metaverse offers a promising highway for extensive research and application. The inherent possibility for quantum computing to contribute to various elements of the metaverse opens up numerous possibilities for investigation and invention in this field.

The metaverse is considered a 3D environment; therefore, the data traffic and resource demands are significantly heavier compared to today's 2D internet. As a result, resource optimization, scheduling, and network traffic routeing pose challenges to the metaverse. In this case, a quantum optimization algorithm can be considered. Furthermore, a research opportunity exists to explore and assess the feasibility of various quantum algorithms for implementing network traffic optimization, resource allocation optimizations, and routing path optimization within the context of the metaverse.

AI constitutes an essential element of the metaverse platform. Quantum machine learning [211], quantum neural networks (QNN) ( [212]), and quantum reinforcement learning [213], [214] have already been explored in the existing literature as potential applications for AI model optimization within the metaverse.

To ensure secure authentication and data storage in the metaverse, blockchain is considered a fundamental component. However, as mentioned earlier, the security of blockchain relies on hash functions or asymmetric encryption, both of which could be vulnerable to compromise by a quantum computer with sufficient computational power. Consequently, post-quantum cryptography has emerged as a prominent subject of research. There exists substantial research potential of quantum-enabled blockchain applications for metaverse platforms. In contrast, there are research opportunities to identify potential security vulnerabilities within quantum-enabled blockchain systems operating in the metaverse. Moreover, there is the possibility of exploring the application of QI or QKD techniques to enhance security measures within the metaverse. For example, the use of QKD for OTP implementation could be considered to ensure secure metaverse authentication. Moreover, numerous research prospects exist within the application domain of the quantum-enabled metaverse. Intricate system design and

[2]https://unity.com/

[3]https://www.unrealengine.com/en-US/, developed by Epic Games, is an open-source 3D development tool that offers digital twin and metahuman creation capabilities.

[4]https://www.nvidia.com/en-us/omniverse/

[5]https://www.blender.org/

[6]https://github.com/TigrisCallidus/QCU

simulation could be undertaken in diverse sectors, including energy, industry, defense, medicine, autonomous vehicles, climate change mitigation, and many others.

## VIII. CONCLUSION

Metaverse and quantum technologies are both currently undergoing development. Despite this, their potential impact on various sectors, such as industry, politics, environment, lifestyle, and others, is substantial. Given that the metaverse standards are yet to be finalized, it becomes relatively more feasible to consider the infrastructure and applications of a quantum-enabled metaverse. The rapid progress in quantum hardware instills hope for the imminent commercial availability of quantum computing.

This paper begins by introducing the metaverse and quantum computing. To facilitate a comprehensive comprehension, the background of quantum computing and related quantum mechanics terminologies are also elucidated. Subsequently, the discussion delves into quantum-enabled technologies for constructing the metaverse, alongside the exploration of prominent application fields for a quantum-enabled metaverse. Furthermore, research gaps are identified for future researchers, along with the challenges that must be overcome to achieve a successful quantum-enabled metaverse.

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