Advancements and Applications of Quantum Computing in Robotics

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Article Info
Journal of Computing and Natural Science (http://anapub.co.ke/journals/jcns/jcns.html)
Doi: https://doi.org/10.53759/181X/JCNS202404006
Received 10 March 2023; Revised from 18 July 2023; Accepted 22 September 2023.

Abstract – Quantum computing is an advanced computing area that utilizes the principles of quantum mechanics to do certain operations at much faster rates compared to traditional computers. Quantum bits, or qubits, have the ability to exist in multiple states simultaneously, unlike traditional bits, which have a state of 0 or 1. This unique property was created by a process known as superposition. This article reviews the various quantum computing applications within the field of robotics. It further discusses the principles of quantum computing such as superposition and qubits, and puts more focus on exponential processing capacity of it. Various quantum algorithms are reviewed in comparison to traditional methods used on completing machine learning tasks and handling robotics. In addition, this paper reviews potential applications of quantum computing within the field of artificial intelligence, data mining, and image process. Lastly, the paper highlights the necessity of effectively integrating robotics with quantum computing, considering application-based protocols, scale-up capacity, and hardware-free algorithms.

Keywords – Quantum Computing, Advanced Computing, Quantum Algorithm, Multi Quantum Computing Units, Quantum Processing Units.

I. INTRODUCTION

Quantum computers have the potential for using quantum mechanical phenomena like superposition and entanglement to achieve powerful computational abilities required for simulating intricate quantum systems [1]. The advancement in quantum computer hardware development was initially hindered by the slow pace, as the desired mechanical properties of quantum can only be observed at the fundamental scale of nature, like photon polarization or electron spins. Manipulating these properties proved to be highly challenging due to technological limitations.

Nevertheless, the science of quantum computing has seen significant advancements and has become a prominent focus of study in recent years. The potential of quantum computing to exceed the processing capabilities of present supercomputers has generated significant interest from both business and academics in constructing the world's first machine of quantum. Currently, several prominent corporations including IBM, Google, Microsoft, and Intel, together with several ambitious start-ups like IonQ, and Rigetti are aggressively competing in the pursuit of developing the universal quantum computer of first large-scale. Concurrently with the advancement of quantum hardware, significant strides have been made in the field of quantum algorithm and quantum software advancement in recent years.

Quantum computing has been a subject of extensive discussion for many decades. Subsequent findings have progressively advanced the implementation of this theory, building upon the basic assumptions. The European FET Initiative on Quantum Technology and the National Lab for Quantum Science and Technology in China are just two examples of the massive worldwide investments and recent successes that have positioned us on the cusp of a new computer age [2]. This revolution will also have a significant influence on the area of robotics and its applications. Various domains within the field of robotics present complex problems that need extensive computational power. Currently, the preferred approach is to use general-purpose GPUs (GPGPUs) to delegate resource-intensive operations. The advent of quantum computing methods brings out not only novel solutions to existing difficulties, but also opens up new avenues of inquiry. Although quantum computers have the potential to execute various computations, it should not be assumed that there will be fully quantum-powered computers or robots, despite the existence of suggested quantum robots in [3].

A quantum robot is a portable physical device that utilizes the quantum properties of a quantum system to perceive its surroundings and internal state. Additionally, it can manipulate quantum information and perform certain functions. The quantum robot system has three interactive components (see **Fig1):**Units of data acquisition, quantum actuator and controller, and MQCU (multi quantum computing units). Instead, quantum computing cloud services will be available at first, along with the possibility of quantum processing units (QPUs) that collaborate with conventional CPUs.

The purpose of this article is to investigate the possible uses and benefits of computing of quantum in the realm of robotics. Quantum computing has distinct features, such as superposition and entanglement, that may greatly augment processing capacity and effectively address intricate issues compared to traditional computing techniques. Researchers may tackle optimization issues, machine learning tasks, image processing, artificial intelligence, and data mining in robotics by using quantum algorithms such as Grover's approach, Harrow-Hassidim-Lloyd (HHL), and qBLAS. Integrating quantum computing with robotics may result in progress in trajectory planning, robot vision, task allocation, kinematics, perception, localization, control systems, and data analysis.

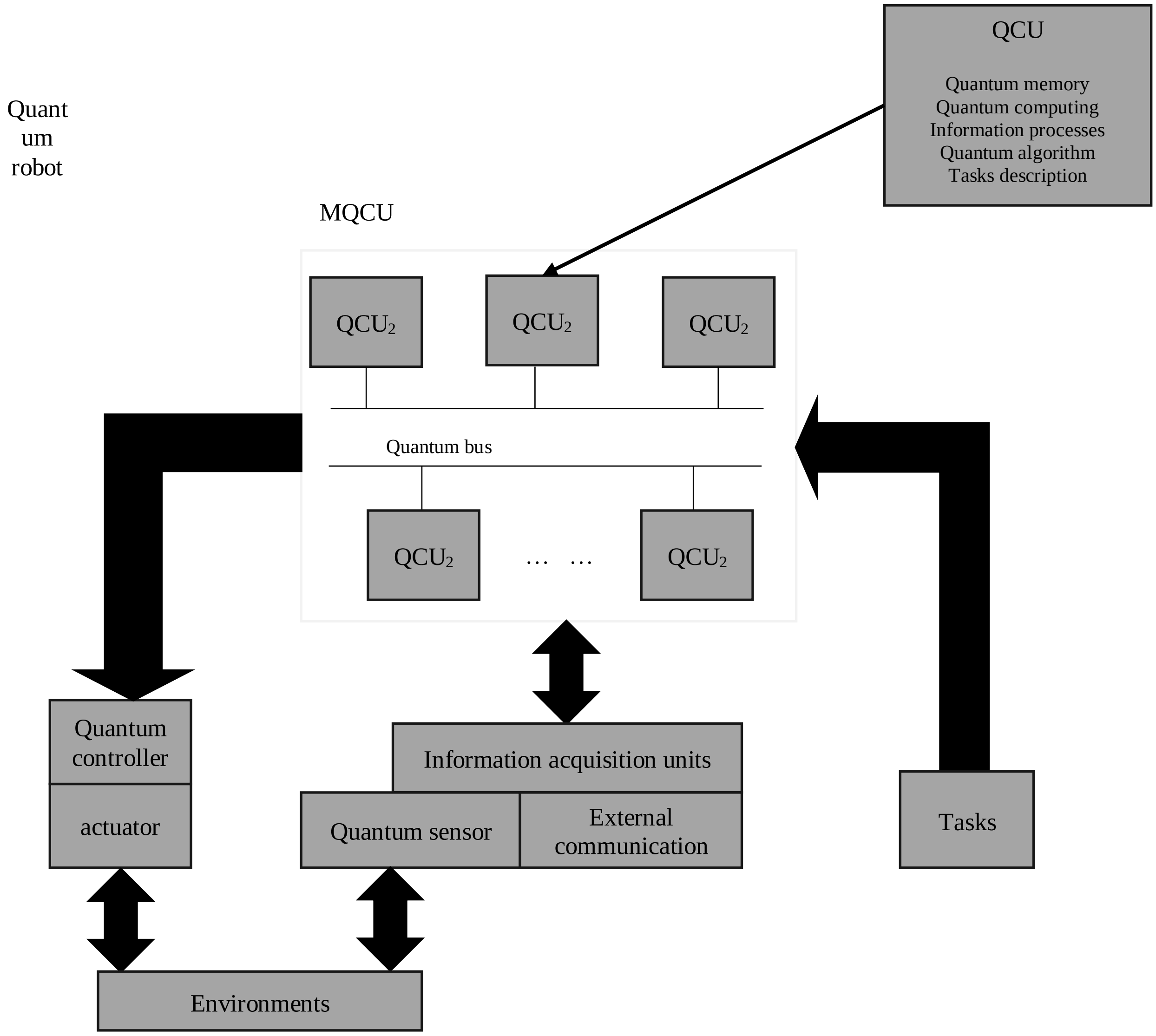

Fig 1. Quantum Robot System Structure.

This paper establishes the superiority of quantum computing over conventional approaches and provide hardware and toolkits to facilitate the implementation of quantum-based robotic applications. In addition, the article aims to create sophisticated algorithms for distributing workloads between local quantum processing units (QPUs) and cloud-based quantum computing services, taking into account variables such as robot mobility and access delays. This paper aims to investigate the capacity of quantum computing to transform the area of robotics and enhance the efficiency and capacities of robotic systems. The rest of the paper is organized as followed: Section II presents a background analysis of quantum computing, quantum acceleration and algorithms, optimization problems and machine learning. Section III focusses on the different robotic possible applications when it comes to sensing, thinking, acting, and observing. Section IV reviews the architecture for quantum computing integration with robotic systems. The last Section V provides a summary of the research on the advancements and applications of quantum computing in robotics.

II. BACKGROUND ANALYSIS

A quantum computer utilizes quantum bits, often referred to as qubits, which has several intriguing properties. Qubits has the unique capability of concurrently existing in several states, such as |0 and |1, before being seen. This phenomenon is known as superposition. The state of superposition may be represented as a combination of linear of the states of the ground. In addition, the phenomenon of entanglement allows two qubits to affect one other's states without the need for a physical link. These particles are formed in a manner that necessitates a complete description of one particle in relation to the other. A scheme consisting of entangled spin may be accurately characterized as a placement. A solitary superposition state has the ability to concurrently represent several classical states, and the computational capacity increases exponentially as a result of entanglement, in relation to the number of qubits.

Hence, the act of incorporating more qubits into a quantum computer may result in a significant and rapid growth in its computational capabilities [4]. Quantum computers possess a significant benefit in their capacity to tackle computationally demanding mathematical problems more efficiently or accurately than conventional computers. Nevertheless, the intricacy of formulating algorithms suitable for execution on a probabilistic computer, together with the required amount of fault-free qubits, remains a significant hurdle. Furthermore, it is important to acknowledge the fragility of qubits, in addition to the aforementioned properties. Any kind of contact, such as measuring, viewing, or disrupting, with a qubit, which is a representation of a system of two-state, results in a state that can be reliably distinguished. Nevertheless, this perceived drawback might be strategically used for certain purposes.

Basics of Quantum Computing

Quantum Computing (QC) utilizes principles and phenomena from Quantum Mechanics (QM), like entanglement and superposition, to carry out computational tasks. Quantum computers are computers specifically designed to do quantum computing. It is important to understand that the concept of superposition is a basic premise in quantum physics. The principle of Quantum Superposition (QS) states that, similar to waves in Classical Physics (CP), or Classical Mechanics (CM)it is possible to combine ("superpose") any two or more quantum states, resulting in another valid quantum state. Conversely, it is also true that every state of quantum can be expressed as a combination of two or more distinct states. Mathematically, it pertains to a property of solutions to both the Time-Independent Wave Equations and Schrödinger Time-Dependent.

Due to the linearity of the equation of Schrödinger, any solutions combination that is likewise linear will be a solution. A concrete illustration of the wave-like behavior of quantum systems may be seen in the form of interference peaks produced by an electron beam in an experiment that is double-slit, as shown in **Fig 2**. The pattern seen in **Fig 2** closely resembles the one acquired from the classical wavesdiffraction. Computers of Quantum are thought to possess the capability to perform particular computational issues like factorization of integers, which forms the basis of RSA encryption, at a much-accelerated rate compared to conventional computers. Quantum computing is a specialized area within the broader subject of quantum information science.

The basic element of classical computing is a bit, which may be in one of two binary states: '0' or '1'. In contrast, quantum computing employs a quantum bit, also known as a qubit, as the basic element of information. Qubits, according to the principles of quantum physics, may possess a state of '0', '1', or a juxtaposition of both '0' and '1' contemporary. Analytically, a qubit may be expressed as $a|0\rangle + b|1\rangle$, where a and b are quantities that enable the combination or juxtaposition of the '0' and '1' states. **Fig 3** illustrates the distinction between a qubit and a bit in a state of juxtaposition in a graphic manner. The qubits superposition gives access to an extensive computing space capable of solving problems with significant complexity that is computational. For instance, a 3-bit number may only have one value at a time, which can be any of the eight possible values in the set $\{000, 001, 010, 011, 100, 101, 110, 111\}$.

Nevertheless, a 3-qubit state has the capability to exist in a juxtaposition of all eight possible values: $a|000\rangle + b|001\rangle + c|010\rangle + d|011\rangle + e|100\rangle + f|101\rangle + g|110\rangle + h|111\rangle$. This indicates that increasing the bits number in a conventional machine computing by two would result in a twofold increase in processing capacity. In contrast, achieving the same increase in computational capacity in a quantum computing machine may be accomplished by only adding one more qubit, moving from 3 to 4 qubits. The exponential growth of computational space, based on the number of qubits, is the foundation of the immense computational power of quantum computing. This allows quantum computers to efficiently solve complex problems involving massive datasets, even with a limited qubits number. Nevertheless, the process of transferring large sets of information into states of quantum remains unresolved.

The utilization of quantum random access memory was suggested by Giovannetti, Lloyd, and Maccone [5], but, its implementation on existing devices of quantum has not been empirically illustrated. Additional potential methods includeutilizing technologies of machine learning and using constructions of coreset to generate quantum states using trained data sets. Entanglement, a crucial characteristic of quantum computing, is seen in **Fig 3**. Unlike classical bits, which may have their values set separately, qubits possess the capability to be placed in states of entanglement. When qubits are in a state that is entangled, their characteristics are interconnected, even if they are physically separated. Thus, by measuring one qubit, it is possible to modify the characteristics of the other qubits that are in the same state that is entangled. Einstein used the term 'spooky action at a distance' to describe this phenomenon. Entanglement is a valuable asset that may be used for quantum modeling and dense coding of coupled systems.

Fig 3 (Left) illustrates a binary digit that may assume either a value of '0' or '1' with absolute certainty. The middle. A qubit may exist in a state represented by the quantum states $|0\rangle$ or $|1\rangle$, or it can be in a superposition state where it simultaneously exists in both states $|0\rangle$ and $|1\rangle$. Here, a qubit is indicated in a superposition state, containing of an equal probability of being in the state $|0\rangle$ and the state $|1\rangle$. (Correct) Depiction of a pair of qubits existing in a state of entanglement. The characteristics of the two entangled qubits are interconnected in such a way that seeing (i.e., weighing) one of them will disclose information about the other qubit, even if they are substantially far apart.

Quantum Acceleration and Quantum Algorithms

Algorithms of quantum exhibit significant superiority over classical algorithms for many situations, such as searching in a list unsorted. This phenomenon is referred to as quantum acceleration. Nevertheless, the primary advantage of quantum computers does not lie in finding solutions for problems that have already been effectively resolved.

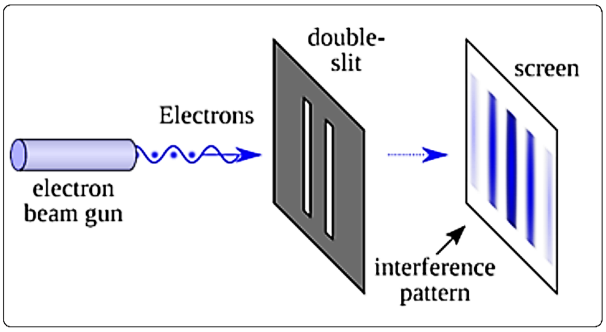

Fig 2. Double-Slit Experiment Setup.

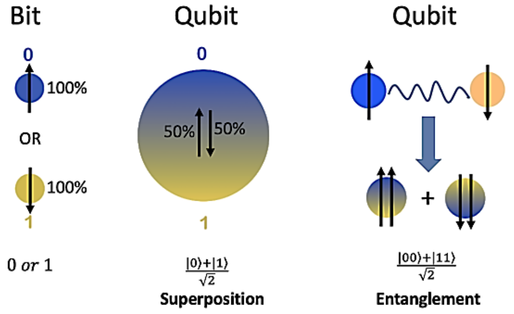

Fig 3. Qubit and Bit Illustration.

Even more intriguing are issues that develop exponentially and cannot be solved by conventional computers. These problems may be specifically articulated using gates of quantum combination. Notable and extensively used algorithms of quantum include quantum basic linear algebra subroutines (qBLAS), which are employed for computing Fourier analysis, determining eigenvalues and their associated eigenvectors, and solving linear equation systems.

The Grover's method is a well-known quantum algorithm that efficiently item searches in a database unsorted of size n in O(√n) steps. This algorithm has been shown to be quicker than any conventional technique. Prior to delving into the technical details of implementing AES as a quantum circuit, it is necessary to quickly review the requirements for conducting a key search using Grover's method. The Grover process requires a quantum circuit that represents a Boolean function $f: \{0,1\}^k \to \{0,1\}$. This circuit, denoted as U_f, transforms the input state $|xi|yi\, 7 \to |xi|y \oplus f(x)i$, where $x \in \{0,1\}^n$ and $y \in \{0,1\}$. The fundamental Grover method identifies an element, denoted as x_0, for which the function $f(x_0) = 1$ equals 1. Let H represent the 2 × 2 Hadamard transform. The Grover algorithm involves iteratively applying the operation G to the starting state $|\psi i \otimes |\phi i$, where $||\psi i = \frac{1}{\sqrt{2^k}} \Sigma_{\in\{0,1\}\,k} |x\,, |\phi = \frac{1}{\sqrt{2}} (|0i - |1i)$, G is defined as:

$$G = U_f\big((H^{\otimes k} 2|0\rangle 0| - 1_{2^k})H^{\otimes k}\big) \otimes 1_2\big) \tag{1}$$

The notation $|0$ represents the base state consisting of all zeros, with the size being suitable for the context. The algorithm G has to be executed $O(\sqrt{N/M})$ times to accurately measure an element $x_0$such that $f(x_0) = 1$ with a consistent probability. Here, N represents the entire number of candidates, specifically $N = 2^k$, and M represents the exact number of solutions, i.e., $M = |\{x: f(x) = 1\}|$. If it is known that there is only one solution, denoted as $M = 1$, it implies that a solution can be obtained by applying $H^{\otimes k+1}$ to the initial state $|0i\ \otimes^k \otimes |1$ and subsequently applying G^ℓ, where ℓ is determined as $\left[\frac{\pi}{4}\sqrt{N}\right]$. This should be followed by a measurement of the entire quantum register, which will likely result in the identification of a solution x_0.

Quantum algorithms can determine the eigenvectors and eigenvalues of a n × n matrix in O(log(n)) iterations. The Harrow-Hassidim-Lloyd (HHL) method of quantum is employed to tackle linear equation models and exhibits exponential speedup compared to conventional algorithms addressing the same issue [6]. **Table 1**, partially derived from [7], illustrates the acceleration attained by algorithms of quantum compared to their classical equivalents. The item of O(√N) represents a quadratic increase in speed. Similarly, the notation O(log(n)) denotes a logarithmic time complexity, indicating a much faster growth rate compared to algorithms of convention.The column labeled "HHL" indicates if the HHL algorithm is used. QRAM, an abbreviation for Quantum Random Access Memory, is employed in certain techniques to transform vectors of information into states of the quantum. The column given highlights the indispensability of QRAM for executing the suitable algorithm. The swift advancement of these methodologies' hinges on many algorithms of quantum, including HHL, algorithm of Grover's, and qBLAS.

Optimization problems

Optimization challenges are ubiquitous in robotics research. The application domains include kinematics, trajectory planning, and robot vision. The objective of ID optimization is to identify the optimal element based onissue specification and a specified cost function. The space solution of an optimization issue often has several plausible clarifications for the underlying issue. However, the objective is to identify a single optimal clarification, which is distinct in the case of convexity. The level of work required to find a solution varies based on the problem's characteristics and the technique used to solve it, either increasing in a linear, polynomial, or exponential manner. However, the traditional method of solving problems with exponentially growing complexity rapidly encounters its constraints. Optimization issues may be rephrased as search problems. Various quantum techniques, such as the Shor algorithm, quantum annealing, and Grover's algorithm, are available to address both general and particular search issues.

Table1. Various Algorithms from Quantum Acceleration

Literature	Method	Acceleration	QRAM	HHL
Kadane, Box, and Tiao [8]	Bayesian Inference	$o(\sqrt{n})$	no	yes
Lee [9]	Online Perception	$o(\sqrt{n})$	optional	no
Marquardt [10]	Least Squares Estimation	$o(\log(n))$	yes	yes
Lloyd, Mohseni, and Rebentrost [11]	Quantum principal component analysis	$o(\log(n))$	optional	yes
Bishwas, Mani, and Palade [12]	Quantum SVM	$o(\log(n))$	yes	yes
Dong, Chen, Li, and Tarn [13]	Quantum Reinforcement Learning	$o(\sqrt{n})$	no	no

Quantum annealing is a method used to identify the lowest possible value of amain purpose or the most stable system`s state. It is often used to issues with diverse areas of search that have a large number of possible minimum values. In the sector of computing of quantum, the quantum random walk serves as an analogy to conventional random walks. This tool is used for the creation of randomized quantum algorithms and for enhancing the efficiency of various problem categories. The Shor method enhances the process of factoring numbers by effectively identifying discrete logarithms, a challenging issue for classical computers that forms the foundation of several cryptosystems. Multi-objective optimization is a branch of optimization of mathematicthat focuses on optimizing many objective functions simultaneously. Pareto optimality is the prevailing method for multi-objective optimization. Like one-dimensional optimization issues, it is feasible to formulate it as a search problem. Hence, there is significant promise in exploring quantum algorithms for addressing multi-objective optimization problems.

Machine Learning

Contemporary robots heavily rely on machine learning techniques to perform a range of activities, such as analyzing and extracting information from sensor inputs for perception, localizing the robot, developing controllers and planners, and improving human-robot interaction. Application algorithms include a wide variety of techniques, including quantum artificial neural networks, quantum regression, and quantum principal component analysis (PCA). Reduction of dimensionality is often used to build models for applications of machine learning. Quantum PCA is used in the quantum realm to achieve this objective and offers exponential acceleration in comparison to the conventional technique.

In general, tasks of learning may be classified into three primary categories: reinforcement, unsupervised, and supervisedlearning. Quantum computing methods may accelerate many supervised learning methodologies. The HHL method may significantly expedite the process of regression or curve fitting, both of which are supervised learning techniques. This approach is particularly effective in solving linear systems of equations, resulting in exponential acceleration. Various iterations of Quantum SVM have been proposed, with some versions demonstrating exponential superiority over conventional approaches. Quantum cluster analysis, an unsupervised learning approach, may be performed using algorithm of Grover's together with a specialized function of oracle.

Quantum reinforcement learning may be implemented by using the characteristics of the quantum parallelism and state the principle of superposition [14]. The capable influence of quantum ML on robots is extensive. The aforementioned techniques are extensively used in robotics and may be further expedited by the utilization of quantum concepts. PCA is used in several applications of roboticslike simultaneous localization and mapping (SLAM) and habitat modeling. SVMs are often used for tasks such as fusion of information and object recognition. Algorithms of Clustering, among other applications, are used to comprehend picture information.

III. ROBOTICS POSSIBLE APPLICATIONS

Within this part, we want to go further into the specific study domains within robotics that we anticipate will be most profoundly influenced by quantum computing. Our comments will be organized based on the conventional sense-think-act cycle, with the addition of an overarching observe action that serves as a system diagnostic (refer to **Fig 4)**.

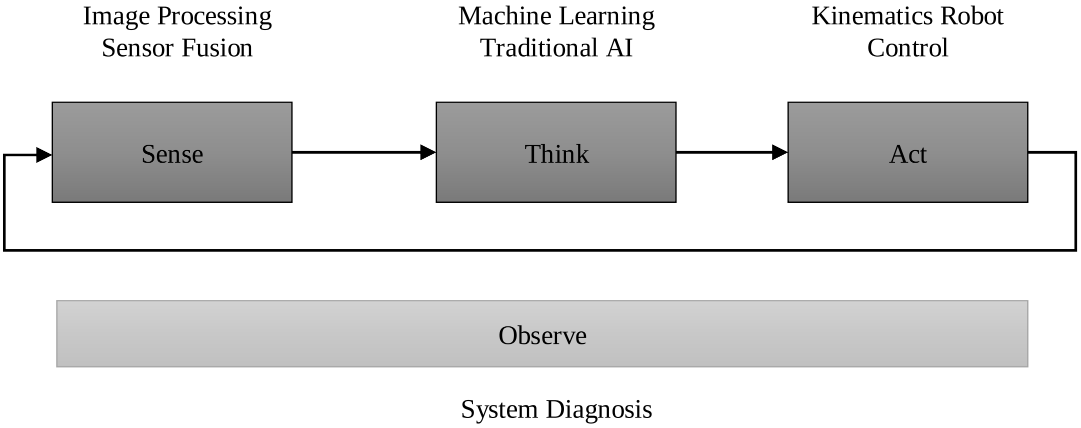

Fig 4. Utilization of Emerging Technology in The Process of Seeing, Analyzing, and Responding to Stimuli.

Sense: Sensor Data Processing, Vision, and Perception

Contemporary robots that are autonomous require rapid visual skills to see and evaluate their surroundings. Computer vision and image processing methods are computationally demanding due to the need to process results on many pixels. The need to get a deeper understanding of visual information and effectively use quantum features such as entanglement and parallelism, along with quantum computing methods, is naturally rather significant. Further efforts in this field led to the development of a specialized branch known as quantum image processing (QIP) [15]. The fundamental concept is that characteristics of images like location-oriented colors, may be represented as qubit-lattices [16]. This notion has been extensively acknowledged and further developed in many representations and potential applications, including films. The emergence of quantum computers has sparked significant interest among academics in the sector of image editing quantum, leading to an increasing number of scholars dedicating their efforts to this area of study. The study of QIP is primarily categorized into two areas: quantum image processing and quantum image representations methods [17]. The image representation by the quantum is fundamental for image processing and determines the manner in which visuals are encoded in a quantum computer. The representation paradigm of portion of image is crucial for the foundation of quantum processing of image. Various research studies have been published on models for representing quantum images, one of which is the Qubit Lattice.

Here are some such quantum picture representations: The following are various models and representations used in quantum image processing: new quantum representation model of color digital images (QRCI) [18], entangled Image [19], bitplane representation of quantum images (BRQI) [20], flexible representation for quantum images (FRQI) [21], novel quantum representation of color digital images (NCQI) [22], enhanced quantum representation (NEQR) [23], generalized model of NEQR (GNEQR) [24], normal arbitrary quantum superposition state (NASS) [25], Improved NEQR (INEQR) [26], multi-channel representation of quantum image (MCRQI) [27], multi-channel quantum images (MCQI) [28], Caraiman’s quantum Image representation (CQIR) [29], simple quantum representation of infrared images (SQR) [30], and quantum log-polar images (QUALPI) [31].Various models exist for representing images based on quantum principles, including the Double Quantum Color Images Representation Model (DRQCI) [32], Quantum Representation of Multi Wavelength Images (QRMW) [33], Quantum Representation Model for Multiple Images (QRMMI)[34], Optimized Quantum Representation for Color Digital Images (OCQR) [35], Improved FRQI Model (FRQCI) [36], Order-Encoded Quantum Image Model (OQIM) [37], Quantum Block Image Representation (QBIR) [38], Improved FRQI, and Digital RGB Multi-Channel Representation for Quantum Colored Images (QMCR) [39], among others. Quantum imagestore color pixel’s locations and representations in distinct manners, resulting in variations in algorithmic complexity and applications of image processing.

However, the aforementioned methods just address two-dimensional pictures, which is inadequate for robotic perception. In this field, several sensor inputs are often combined to form a three-dimensional point cloud, enabling the identification and localization of objects and surroundings. Currently, there are only a limited number of ways available to depict a three-dimensional picture using quantum point cloud, as described in [40]. Similar to other quantum technologies, it is widely anticipated that QIMP would far exceed the capabilities and performance of its conventional counterparts. In order to demonstrate the superiority of QIMP over traditional image processing, it is necessary to showcase applications of great impact and provide associated toolkits and hardware. Although some techniques have previously shown potential advantages, more evidence is needed.

Think: Traditional AI in Robotics

Traditional AI, often known as Weak or Narrow AI, is mainly concerned with efficiently executing a certain cognitive activity. It pertains to systems that are specifically built to react to a certain set of inputs. These systems possess the capacity to acquire knowledge from data and then generate judgments or predictions based on that data. Envision yourself engaging in a game of computer chess. The computer has comprehensive knowledge of all the regulations and is capable of anticipating your actions while also formulating its own decisions using a predetermined plan. The AI does not create novel chess-playing techniques, but rather chooses from pre-programmed methods. Traditional AI may be likened to a proficient strategist capable of making intelligent choices based on a predefined set of principles.Additional instances of conventional artificial intelligences include voice-based virtual assistants such as Siri or Alexa, personalized recommendation systems seen on platforms like Netflix or Amazon, and Google's search algorithm [41]. These artificial intelligences have undergone training to adhere to predefined guidelines, do a designated task, and execute it proficiently, although they do not generate any novel content.

Traditional AI, as opposed to contemporary machine learning methods, relies on representations of formal knowledge (such as facts and rules) and algorithms to maximize robot behavior, or imitate (human) behavior. Applications of AI are often used in robotics for jobs like deducing new knowledge, route planning, reasoning, and coordinating many agents, diagnosing system issues, and generating goal-oriented action plans. Many of these applications employ various versions of informed (heuristic) or uninformed (blind) search algorithms. These algorithms are rooted in the process of navigating through graphs or trees, where potential state is represented by each node within the search area and is linked to further exploration subsequent states. Vikas and Parhi [42] presents a comparison of the complexity of fundamental search algorithms used in applications of AI and robots. The variables used in the comparison are as follows: d represents a solution depth inside the tree of search, b represents the factor of branching of the tree of search, and n represents a subdivision of b that the numeric will examine.

Queralta et al. [43] reviews the robotics publications that primarily use these search algorithms for the purposes of trajectory planning and multi-robot coordination. Combinatorial search algorithms may be transformed into quantum algorithmic problems by using Grover's method, resulting in a significant reduction in complexity. Graph search techniques may be replaced by a quantum version that relies on random walks of quantum. Another category of algorithms of AI focuses on making decisions in situations with unknown outcomes using processes that are stochastic. Typically, this is achieved by using chains of Markov or networks of Bayesian which are essentially graphs that represent transitions between states using stochastic features. Quantum algorithms have been developed for various applications, such as processes of quantum Markov and chain of quantum Markov. Various algorithms supersede the conventional concepts of probability with probability of the quantum.

Monte Carlo techniques, evolutionary algorithms, and simulated annealing may be seen as stochastic processes with a limited number of possible states. As a result, they can benefit from a quantum formulation, which typically leads to a twofold increase in speed in the majority of situations. Both simulated annealing and genetic algorithms are used in several methods to address the task of robot trajectory planning, which might also benefit from the utilization of quantum representation. Quantum random travels exhibit distinct characteristics when compared to conventional random walks.

Act: Dynamics and Kinematics

Efforts have been undertaken for a considerable period of time to address conventional robotic jobs by using artificial intelligence techniques as a viable option. Therefore, it is unsurprising that there is similar research that aim to address kinematic difficulties using quantum neural networks. Examples include solving the inverse issue of kinematics and using an algorithmof quantum evolutionary for planning of trajectory. **Fig 5** depicts acategorization of fundamental optimization choices that may be used in the development of a manipulator and its control of kinematics. The opportunities may be seen as a planner partial specification, where select and place poses are specified, but the path between them is not. Furthermore, all of these choices result in a continuous or discrete optimization issue, which increases exponentially as the number of excess actuators increases. Arranging the order of sub jobs in an issue is a difficult matter that may be represented as the traveling salesman issue, which falls under the NP-complete complexity class. There is a possibility that this problem can be effectively addressed using a quantum computer.

The process of resolving redundancy in an over-determined system of a robot is referred to as a nonlinear optimization issue. Global solutions are only computable for simplechains of kinematic. Therefore, the commonly used approach is to evaluate the Jacobian matrix to get a local solution. The existing state of knowledge does not provide a definitive answer as to whether it is possible to find globally optimum solutions for generic redundant manipulators. The modification in trajectory immediately alters the end-effector pose function, resulting in the minimization or maximization of a cost function between the initial and final locations. The study of robotics science will once again focus on the manipulation of non-rigid and malleable objects, as shown by extensive research in this area. The computational intricacy of determining an ideal motion execution escalates considerably when dynamic models are included, as opposed to only examining kinematics.

Furthermore, we anticipate that the two tiers of regulation in robotics, namely precise movement-planning, and abstract task-planning, which are now often addressed independently owing to their combined intricacy, may be resolved in a more cohesive manner via the utilization of quantum computing. Quantum optimization has the potential to provide intriguing possibilities for control systems that use on-line optimization, like traditional approaches of dynamic programming to control problems or model-predictive control. The difficulty of placing the manipulator and optimizing its design is particularly intricate due to the large size of the search area. Furthermore, traditional methods are entirely inadequate in identifying the most optimum resolution to the overarching issue, which considers all possible optimization choices simultaneously. Similarly, if we expand the accuracy of mathematical modeling to include dynamic scenarios, we would include factors such as the inertia moments of the manipulator components and joint friction. Some members of the robotics field believe that the only way to address this issue is via the use of quantum reinforcement learning, which involves models that are capable of self-improvement.

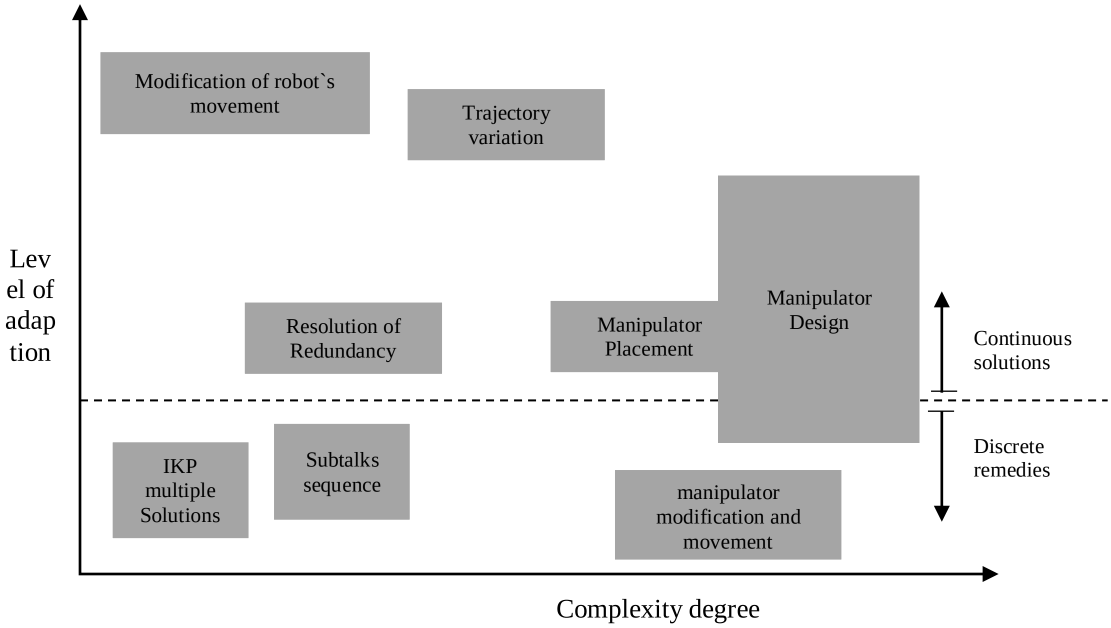

Fig 5. Taxonomy of Optimization Techniques forRobotic Manipulators.

Hybrid quantum-classical algorithms provide another effective approach to tackle such combinatorial issues. Moreover, the usage of computers that are quantum in an operation of multi-state seems to be advantageous in discovering the overall solution to intricate optimization issues. To achieve this objective, two quantum computing resources are employed: one for generating initial solutions and another for identifying optimum solutions.

Observe: Data Mining and Diagnosis

At a macroscopic level, robotics revolves on data. Basically, every robot agent must handle data in some manner to carry out its assigned responsibilities, whether that involves gathering data from the surroundings or producing internal data. Therefore, given the wide array of potential uses, effectively collecting, and handling this data is a significant concern within the discipline. Data, in its many forms, is considered a highly important asset of knowledge and insight in any information system. Data mining has been a prominent area of interest for over twenty years, since it involves uncovering concealed information. Data mining is an immensely significant phenomena that impacts several scientific domains, including robotics. In recent years, several research have explored the use of data mining methods in the field of robotics to enhance robot performance in diverse ways. Nevertheless, despite the existing fragmented and disorganized investigations in several fields, there are some prospective areas that have been overlooked.

In the field of contemporary robotics, empirical evidence demonstrates that meticulously designed and produced robots inevitably face malfunctions because of factors such as the gradual deterioration of components or the lack of comprehensive understanding of the robot's operating environment. Hence, it is essential to use techniques that can identify and precisely characterize these defects. The issue of diagnosis may be defined as the task of identifying the elements inside a system that most accurately explain the difference between the actual and anticipated behavior of the system. The collection of techniques is based on either systems theory, AI methodologies, or hybrid approaches. The traditional technique, known as the consistency-based approach, infers diagnoses by solving a minimum hitting-set issue, a frequently encountered optimization issues in the AI field. The hitting-set problem is one of most applied NP-hard challenges identified by Moreno-Centeno and Karp [44]. The issue may be restated as a vertex cover challenge, which has previously been addressed using quantum computing methods.

Data mining refers to the systematic extraction of valuable insights and the identification of recurring patterns within extensive collections of data. Data mining is an invaluable tool for uncovering information, such as diagnosing systems, for instance, by using the robot's log files to determine the origins and causes of incorrect robot behavior. The process of data analysis and mining utilizes techniques from database systems(such as index searches, statistics, and machine learning. These methods are best addressed using quantum algorithmic approaches.

IV. ARCHITECTURES FOR QUANTUM COMPUTING INTEGRATION WITH ROBOTIC SYSTEMS

Evidently, the primary computing component of a robot will not only rely on quantum technology. Instead, we anticipate the prevalence of two hybrid architectures. Firstly, the only architecture available will likely consist of services of quantum computing hosted in the cloud, which may be accessed remotely as needed. Presently, there are comparable methodologies accessible for processing centered on GPU. However, this is now only applicable to jobs that need extended durations and non-real-time tasks that permit deferred solutions. Secondly, as miniaturization advances, QPUs will be included into robots specifically for tasks in which they excel.

The first practical implementations of quantum processors are expected to be shown in configurations where quantum co-processors are used as accelerators to execute highly specialized and demanding computational jobs inside a High Performance-Computing (HPC) system. The efficacy of the co-processor will be assessed by comparing the performance of a calculation that incorporates it, maybe in combination with classical methods, to the performance of a computation that only relies on classical methods. Considering this, Effective QCVV methods should meet the following three criteria (see **Table 2**):

Table 2. A High-Performance Computing-Driven Criteria

QCVV protocols	Description
Application-centric	The protocol should provide a single integer (or a small number) that clearly represents the capability of a certain QPU for addressing a practical HPC application. Optimally, the QPU's score for this specific application should serve as an indicator of the processor's overall performance, including its performance in other applications.
Hardware-agnostic	The protocol should provide fair treatment of all current and future hardware innovations. Specifically, it should refrain from showing excessive preference for any single technology over the others. By prioritizing applications, the benchmark guarantees that hardware manufacturers are motivated to make substantial improvements across the board, rather than making specific adjustments intended at deceiving the benchmark, which is more likely to occur at the gate or circuit level.
Scalable	The protocol must provide scalability to accommodate a substantial quantity of qubits. Specifically, the computing complexity of processing the quantum output and generating the metric should be sufficiently modest. This limitation eliminates protocols that need classical calculations with an exponential cost in relation to the number of qubits.

Naturally, the local QPUs will not possess the same level of computational capacity (in terms of the qubits number accessible) as the counterparts that are cloud-based. Hence, intelligent analytics for distributing the tasks at hand will be a key determinant of achievement in using computing of quantum. In order to effectively use both local QPUs and high-power cloud services, it is essential to provide intelligent scheduling between the QPU and CPU for all scenarios.

Similar strategies for CPU-GPU scheduling may be used, either via a domain-specific language (DSL) or by using program profiling [45]. These approaches can serve as first steps in the process. However, it is fundamental to consider specific attributes such as the robots' mobility or the significant delay in services of cloud accessing. Furthermore, GPU-scheduling often operates under the assumption of fixed program flows to enhance optimization, including profiling tasks. Due to the strong interdependence between robots' activities and their operating surroundings, there is no set program flow. Alternatively, the sizes of the challenge for algorithms change dynamically based on the habitat. Hence, there is a need for techniques that can do context-sensitive scheduling as and when required. Two conditions must be met for this: firstly, the robot program must be executable on both CPU and QPU, and secondly, there must be a real-time competent decision engine that acts on incomplete information. The aforementioned variables contribute to the increased complexity of CPU-QPU scheduling. Alternatively, the scheduling method itself might potentially be enhanced using quantum power.

V. CONCLUSION

Quantum computing provides substantial benefits in resolving optimization issues, tackling machine learning tasks, upgrading conventional artificial intelligence algorithms, and increasing data mining and analysis in the realm of robotics. Quantum algorithms, such as Grover's technique, Harrow-Hassidim-Lloyd (HHL), and qBLAS, have shown their superiority over conventional algorithms in several scenarios. Quantum computing has the ability to effectively handle intricate issues that include enormous amounts of data, even when the number of qubits is restricted. Quantum approaches have the capability to expedite supervised learning procedures, enhance image processing, and optimize control systems. In order to efficiently employ both local quantum processing units (QPUs) and high-power cloud services, the integration of quantum computing with robotics necessitates the use of application-centric, hardware-agnostic, and scalable protocols. Quantum computing has the capacity to completely transform the skills and efficiency of robots across several fields. Future research might prioritize the development of highly effective quantum algorithms for targeted robotic tasks, investigating the possibilities of quantum reinforcement learning, and enhancing quantum image processing approaches. Furthermore, it is possible to make endeavors to demonstrate the significant and influential uses of quantum image processing and provide the corresponding hardware and toolkits. Scalable protocols and clever scheduling algorithms are essential for efficiently using quantum computing in robotics.

Data Availability

No data was used to support this study.

Conflicts of Interests

The author(s) declare(s) that they have no conflicts of interest.

Funding

No funding agency is associated with this research.

Competing Interests

There are no competing interests.

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