Introduction to Quantum Robotics: Concepts, Applications, and Future Directions

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***Abstract*—Quantum robotics arises at the intersection of advanced robotic systems and rapidly evolving quantum technologies. This paper introduces the concept of quantum robotics on how quantum computing augments perception, planning, and control in robotic systems. This paper clarifies the structure of a quantum robot as a classical robotic stack enhanced by quantum resources. Furthermore, this paper introduces and analyzes representative applications of quantum computing in robotics, which include kinematic optimization, navigation, and control based on quantum reinforcement learning (QRL). Furthermore, the paper suggests various future directions for developing quantum robotics. In conclusion, the paper provides a compact entry point for understanding current approaches and future directions in quantum robotics.**

***Index Terms*—Quantum Computing, Quantum Robotics, Quantum Sensing, Quantum Reinforcement Learning (QRL)**

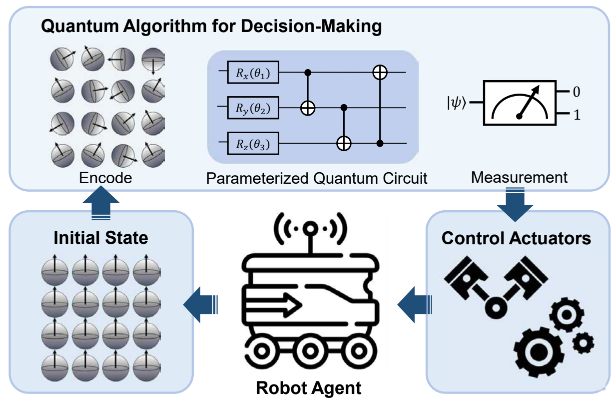

Fig. 1: Overall architecture of the quantum algorithm for robots.

I. Introduction

Robotic systems are rapidly shifting from ideal industrial environments to dynamic, uncertain real-world settings. As robots are deployed in autonomous navigation, healthcare, and human–robot interaction, the computational cost of perception, planning, and control continues to grow. However, high-dimensional sensor data for long-horizon decision-making and real-time constraints expose fundamental limitations in classical algorithms. Additionally, quantum technologies, such as quantum computing, quantum sensing, and quantum communication, have progressed from theoretical constructs to experimentally accessible platforms. Furthermore, it motivates a re-examination of how robots can sense, train, and make decisions with quantum resources [1]. Early works have studied how quantum algorithms, quantum machine learning models, and quantum-enhanced sensing could be embedded into robotic architectures to improve performance. Recently, quantum robotics has highlighted that novel algorithmic frameworks are beginning to appear across navigation, manipulation, and human–robot interaction [2]. These developments suggest that quantum robotics is transitioning from a speculative concept to a research area with identifiable trends and benchmarks [3]. Quantum sensors can provide precise measurements of inertial, gravitational, or electromagnetic fields, such as atom-based interferometric gravimeters and spin-based magnetometers. When embedded into robotic systems, such devices can improve localization and mapping accuracy. In principle, quantum-enhanced inertial measurement units and gravimetric sensors can support long-term drift reduction and robust simultaneous localization and mapping (SLAM). More practically, quantum sensing can provide robots to perceive weak signals, such as subtle vibrations or minute changes in gravity that are difficult to detect with classical hardware. Therefore, it enables new classes of inspection, exploration, and medical-assistance tasks. Moreover, quantum computing and quantum machine learning are used in robotic decision-making. Quantum-enhanced learning frameworks employ parameterized quantum circuits (PQCs) and hybrid quantum–classical models as function approximators for policies or value functions. In many cases, the quantum part serves as a compact, expressive feature map, while the classical part performs gradient-based optimization [4]. Such hybrid systems have been investigated for robot navigation, manipulation, and continuous control tasks. Therefore, the systems can achieve competitive performance with fewer trainable parameters or faster convergence than purely classical baselines. In addition, quantum algorithms for search and optimization, such as Grover-type search and quantum approximate optimization algorithms, are being explored to accelerate path planning, task allocation, and motion planning in high-dimensional spaces [5]. In conclusion, this paper analyzes quantum computing methods for robotics and quantum machine learning algorithms which used in robot systems.

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II. The Concept of Quantum Robotics

Quantum computing for robotics is currently realized mostly through hybrid quantum-classical pipelines, where PQCs or quantum optimization routines are embedded into learning and planning modules. Rather than replacing the entire robotic stack, recent works use quantum processors to handle subproblems that are combinatorial or representation-heavy, such as policy approximation, motion planning, or multi-robot coordination. Quantum robotics is an emerging interdisciplinary field at the intersection of robotics and quantum technologies. It studies how quantum mechanics, quantum computing, and related quantum information processing methods can be incorporated into robotic systems to enhance capabilities. In contrast to classical robotics, which relies solely on conventional sensors and digital processors, quantum robotics assumes that robots can access quantum resources, such as quantum processors or quantum sensors [6]. From a high-level perspective, quantum robotics can be viewed as a robotic system stack augmented by quantum technologies. At the physical layer, a robot is still composed of sensors, actuators, communication modules, and embedded controllers [7]. On top of this, perception, planning, and control algorithms define the robot's behavior. Quantum sensing can replace or complement classical sensors, offering higher precision or access to new physical signals. Furthermore, quantum computing can provide new algorithms for perception, learning, and decision-making. Quantum robotics is described through the structure of a quantum robot system. A typical model includes three interacting components: 1) a set of multi-quantum computing units, 2) a quantum controller, and 3) classical actuators. The quantum computing units execute quantum algorithms or PQCs to process information about the environment or the robot's internal state. The quantum controller converts measurement outcomes into control signals or higher-level decisions. Finally, the actuators implement these decisions in the physical world. This structure highlights that a quantum robot is not only a classical robot with a faster processor, but a system where quantum and classical information are tightly coupled in the perception–action loop.

In practice, most quantum robotics approaches follow a hybrid quantum–classical design. For example, quantum machine learning models can be trained or evaluated on cloud-based quantum devices or simulators, and their outputs are then used by classical controllers. This hybrid design reflects the reality of current noisy intermediate-scale quantum (NISQ) hardware and the strict timing constraints of real-world robotic systems. It also shows that quantum robotics is not only about designing new algorithms, but also about integrating quantum components into robot architectures in a way that respects latency, reliability, and resource limitations. In summary, the concept of quantum robotics can be understood as a classical robotic system augmented by quantum computing. Therefore, quantum computing mainly affects how robots learn, plan, and make decisions.

III. Quantum Computing for Robotics

Quantum computing provides new computational models for robotic systems. Instead of classical bits, quantum computers use qubits, which can exist in superposition and become entangled. Quantum algorithms apply unitary operations to these qubits and measure them to obtain classical outputs. In current NISQ devices, the number of qubits and the allowable circuit depth are limited, but small and medium-scale quantum circuits are already available through cloud platforms and simulators. In this context, quantum computing for robotics focuses on how to map robotic problems, such as perception, planning, and control, into quantum or hybrid quantum–classical models that can be executed on NISQ hardware [8].

Quantum computing has been used to accelerate kinematic and motion optimization for robotic manipulators. A recent quantum-native framework combines quantum machine learning with Grover's algorithm to solve high-degree-of-freedom (DoF) kinematic optimization problems [9]. A PQC is trained to approximate the forward kinematics of a manipulator, and its output is embedded into an oracle that marks configurations satisfying task constraints. Grover's search is then applied over a discretized configuration space to amplify feasible solutions. Demonstrations on 1-DoF, 2-DoF, and dual-arm setups indicate that the quantum approach can reduce search complexity and runtime compared to classical gradient-free optimizers. Moreover, quantum reinforcement learning (QRL) has also been explored in more complex robotic scenarios. A representative example is a hybrid double deep Q-network (DDQN) framework in which a PQC acts as the Q-network for a mobile robot [10]. Classical robot states are encoded into quantum states, processed by a shallow circuit, and then measured to obtain Q-values. Reported experiments show that such quantum deep RL agents can learn collision-free navigation policies with notably fewer trainable parameters than classical neural network baselines. Furthermore, the quantum agent can achieve comparable performance when models are matched by capacity [11].

In addition to value-based QRL for navigation, policy-gradient and actor–critic formulations have been considered for robotic control. In these approaches, the policy network, the critic network, or both are implemented as PQCs and trained using variants of policy-gradient or actor–critic algorithms. Continuous state and action spaces are handled by mapping classical state vectors into quantum feature spaces, and some works also investigate using quantum modules for representation learning from high-dimensional sensor inputs [12]. Furthermore, QRL has been integrated into robotic systems in a modular way. One method is to rely on quantum models during training and then distill the learned policy into a purely classical network for deployment so that real-time control does not depend on quantum hardware. Another method is to use quantum components only in specific parts of the pipeline; for example, a quantum critic network can be used to shape the reward, or a quantum exploration module can propose candidate actions, while the main controller remains classical.

IV. Discussions and Future Directions

Quantum robotics exhibits significant progress, and various algorithms are now available. However, several open research issues remain as below.

- **NISQ hardware constraints and integration with robotic systems:** Recent studies primarily validate algorithmic feasibility using cloud-based NISQ devices or simulators, rather than executing quantum modules directly on physical robots. Practical deployment on real robots must additionally consider communication latency, measurement noise, decoherence, and the overhead of error mitigation at the system level. As a result, it is necessary to discuss not only raw computational speedup but also how to schedule quantum computations within the robot control cycle. Furthermore, it is essential to discuss how to design safety mechanisms that can tolerate noisy or failed measurements.
- **Scope of performance gains and lack of benchmarks:** Papers on robotic navigation, path planning, and manipulator control report that QRL and quantum optimization can reduce the number of trainable parameters or alleviate search complexity when compared with classical baselines. Nevertheless, most experiments assume small grid-based environments, a limited number of robots, and simplified dynamics. There is no systematic benchmark that clarifies under which conditions and noise levels quantum methods provide practically meaningful advantages. A standardized evaluation framework is therefore required to assess the true contribution of quantum robotics methods.
- **Hybrid architecture design and modularization strategies:** Existing research generally adopts hybrid architectures that introduce quantum modules only for specific subtasks instead of constructing fully quantum robots. Some approaches employ quantum models only during training and then distill the resulting policy into a lightweight classical neural network for deployment. These designs indicate that the key question is where in the perception–planning–control pipeline quantum resources are most effective. Future work needs systematic methodologies to determine the placement and role of quantum modules based on task characteristics, state and action dimensionality, and admissible latency.
- **Expansion of application domains and ethical and societal implications:** Current quantum robotics applications mainly target navigation, path planning, and manipulator optimization. However, recent papers attempt to extend quantum methods to social robots, swarm robots, and logistics robots. At the same time, the combination of AI, robotics, and quantum computing raises ethical and societal concerns, including unclear responsibility for decisions and concentrated energy and hardware resource usage. Therefore, research on quantum robotics needs to consider not only performance improvement but also design principles and guidelines that account for the long-term impact.

V. Concluding Remarks

Quantum robotics emerges as a promising research direction that augments conventional robotic systems with quantum computing to address the complexity of perception, planning, and control in real-world environments. Existing studies demonstrate that quantum computing can be embedded into robotic pipelines through hybrid quantum–classical architectures. At the same time, current results mostly rely on NISQ-era hardware, small-scale simulations, and heterogeneous experimental setups. The discussions on hardware constraints, benchmark design, architectural modularization, and ethical implications indicate that quantum robotics is still in an exploratory stage that requires careful system-level and societal considerations. As quantum hardware and evaluation frameworks develop, quantum robotics has the potential to evolve from demonstrations into a systematic methodology for designing robotic systems that leverage quantum resources.

References

[1] M. Nie, G. Yang, and R. Wei, "Quantum self-organizing network and routing protocol for cooperative communication of intelligent robot soccer game," in *Prco. International Conference on Control and Robotics Engineering (ICCRE)*, Osaka, Japan, April 2020, pp. 48–52.

[2] C. Huang, Y. Guo, Z. Zhu, M. Si, D. Blankenberg, and R. Liu, "Quantum exploration-based reinforcement learning for efficient robot path planning in sparse-reward environment," in *Prco. IEEE International Conference on Robot and Human Interactive Communication*, Pasadena, CA, USA, August 2024, pp. 516–521.

[3] M. Fazilat, N. Zioui, and J. St-Arnaud, "A novel quantum model of forward kinematics based on quaternion/Pauli gate equivalence: Application to a six-jointed industrial robotic arm," *Results in Engineering*, vol. 14, pp. 1–9, June 2022.

[4] M. Sarkar, J. Pradhan, A. Kumar Singh, and H. Nenavath, "A novel hybrid quantum architecture for path planning in quantum-enabled autonomous mobile robots," *IEEE Transactions on Consumer Electronics*, vol. 70, no. 3, pp. 5597–5606, August 2024.

[5] L. Gao, R. Liu, F. Wang, W. Wu, B. Bai, S. Yang, and L. Yao, "An advanced quantum optimization algorithm for robot path planning," *Journal of Circuits, Systems and Computers*, vol. 29, no. 08, pp. 1–9, June 2020.

[6] D. O. Santos, F. M. De Assis, E. A. N. Carvalho, and L. Molina, "A Grover-operator-based quantum variant of particle swarm optimization for robot manipulators' inverse kinematics: Theory and simulation," *IEEE Access*, vol. 13, pp. 188 420–188 431, November 2025.

[7] Y. Cao, W. Wang, L. Ma, and X. Wang, "Inverse kinematics solution of redundant degree of freedom robot based on improved quantum particle swarm optimization," in *Proc. International Conference on Control Science and Systems Engineering (ICCSSE)*, Qingdao, China, July 2021, pp. 68–72.

[8] J. Clark, T. West, J. Zammit, X. Guo, L. Mason, and D. Russell, "Towards real time multi-robot routing using quantum computing technologies," in *Proc. International Conference on High Performance Computing in Asia-Pacific Region (HPCAsia)*, Guangzhou, China, January 2019, p. 111–119.

[9] H. Nigatu, G. Shi, J. Li, J. Wang, G. Lu, and H. Li, "Quantum machine learning and Grover's algorithm for quantum optimization of robotic manipulators," *IEEE Robotics and Automation Letters*, vol. 10, no. 12, pp. 13 090–13 097, December 2025.

[10] H. Hohenfeld, D. Heimann, F. Wiebe, and F. Kirchner, "Quantum deep reinforcement learning for robot navigation tasks," *IEEE Access*, vol. 12, pp. 87 217–87 236, June 2024.

[11] A. Alomari and S. A. P. Kumar, "ReLAQA: Reinforcement learning-based autonomous quantum agent for quantum applications," *IEEE Transactions on Artificial Intelligence*, vol. 6, no. 3, pp. 549–558, March 2025.

[12] R. Deng, Y. Huang, and M. Perkowski, "Quantum motions and emotions for a humanoid robot actor," in *Proc. International Symposium on Multiple-Valued Logic (ISMVL)*, Nur-sultan, Kazakhstan, May 2021, pp. 207–214.