**ABSTRACT**

Quantum robotics is an emerging engineering and scientiﬁc research discipline that explores the application of quantum mechanics, quantum computing, quantum algorithms, and related ﬁelds to robotics. is work broadly surveys advances in our scientiﬁc understanding and engineering of quantum mechanisms and how these developments are expected to impact the technical capability for robots to sense, plan, learn, and act in a dynamic environment. It also discusses the new technological potential that quantum approaches may unlock for sensing and control, especially for exploring and manipulating quantum-scale environments. Finally, the work surveys the state of the art in current implementations, along with their beneﬁts and limitations, and provides a roadmap for the future

**2 1. INTRODUCTION**

of large amounts of data by robotic systems. While there are key limitations with storing and extracting data from a quantum memory, there are expected beneﬁts even with the fundamen- tal limitations. Whether the beneﬁts are mostly for model building in oﬄine mode or extend to real-time operation remains to be seen, but the potential for impact is surely there. In addition, the potential energy eﬃciency of quantum-scale circuitry and qubit hardware may bring down the power consumed by robotic systems.

Aside from providing potential computational software and hardware advantages for robots operating in classical environments, quantum approaches unlock new possibilities for robot sens- ing and control in environments governed by quantum dynamics. Quantum mechanical principles may be useful in engineering new quantum sensors and creating new quantum robot controllers that can operate on matter at a quantum scale. Many of the classical ﬁltering algorithms (such as Kalman Filters or Hidden Markov Models) have quantum analogues and expected improve- ments in dealing with uncertainty, representational power, and with operating in quantum envi- ronments.

Quantum robotics is as much about science as it is engineering, and the emphasis of our ﬁeld is on plausible science. Most quantum algorithms have highly speciﬁc conditions under which they work. Recognizing the rigorous scientiﬁc limitations of quantum methods is important for appropriate application in robotics.

## AIM AND OVERVIEW OF OUR WORK

Our book serves as a roadmap for the emerging ﬁeld of quantum robotics, summarizing key recent advances in quantum science and engineering and discussing how these may be beneﬁcial to robotics. We provide both a survey of the underlying theory (of quantum computing and quantum algorithms) as well as an overview of current experimental implementations being developed by academic and commercial research groups. Our aim is to provide a starting point for readers entering the world of quantum robotics and a guide for further exploration in sub-ﬁelds of interest. From reading our exposition, we hope that a better collective understanding of quantum robotics will emerge.

In general, our work is written for an audience familiar with robotic algorithms. While our book provides brief introductions to classical methods commonly used in robotic planning, learning, sensing, and control, the reader may wish to brush up on the prerequisites from other readily available robotic textbooks. Our work does not, however, presume any prior knowledge of quantum mechanics or quantum computing.

In Chapter [2](#_bookmark10), we provide background on relevant concepts in quantum mechanics and quantum computing that may be useful for quantum robotics. From there, the survey delves into key concepts in quantum search algorithms (Chapter [3](#_bookmark56)) that are built on top of the quantum computing primitives. Speedups (and other algorithmic advantages) resulting from the quantum world are also investigated in the context of robot planning (Chapter [4](#_bookmark70)), machine learning (Chap- ter [5](#_bookmark98)), and robot controls and perception (Chapter [6](#_bookmark173)). Our survey explores how algorithms com-

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monly used for robots are expected to change when implemented with quantum mechanisms. We survey the literature for time and space complexity diﬀerences, key changes in underlying prop- erties, and possible tradeoﬀs in scaling commonly used robotic techniques in quantum media. Our book also highlights some of the current implementations of quantum engineering mecha- nisms (Chapter [7](#_bookmark215)) as well as current limitations. Finally, we conclude with a holistic summary of potential beneﬁts to robotics from quantum mechanisms (Chapter [8](#_bookmark231)).

## QUANTUM OPERATING PRINCIPLES

Quantum approaches can be diﬃcult to understand. eir mathematics can be quite nuanced and esoteric to the uninitiated reader. Even someone who is a talented robotics engineer and master of traditional mathematically intense robotic methods may struggle! To make quantum approaches easier to comprehend, our book boils each technique we discuss down to its essential Quantum Operating Principles (QOPs).

QOPs is a presentation style we introduce to make the assumptions of quantum approaches clearer. Many of the more sophisticated algorithms are really just applications of a few fundamen- tal quantum principles.

Whenever we discuss a quantum improvement for a robot, we do so in relation to the classical techniques used in robotics. For the quantum technique, we attempt to highlight its fun- damental QOPs and the potential advantages of the quantum technique to the classical method. At the end of each chapter, we also include a table of QOPs that diﬀerent quantum methods discussed in the chapter use. We hope that these explanations will make the reader’s journey into quantum robotics smoother.

Quantum robotics (and quantum computing at large) are ﬁelds whose fundamentals are still in ﬂux. ey are exciting ﬁelds with daily new insights and discoveries. However, the best ways to engineer quantum systems are still being debated. Because of the rapid movement of the ﬁeld, we believe that the best student of quantum robotics is one that understands the fundamental assumptions of diﬀerent methods. If tomorrow a particular quantum theory were to accumulate more evidence, the algorithms and techniques based on it would be more likely to be used in the future for robots. Conversely, if a particular quantum theory is proven false, it is good to know which techniques in the literature will not pan out. Our goal with the QOPs breakdown is to help readers understand the spectra of possible truth in the quantum world, since there is not yet certainty.

In the next section, we introduce the basics of the current theory of quantum mechanics. Later sections will apply these QOP concepts to robotic search and planning, machine learning, sensing, and controls.

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| C H A P T E R 2 |  |
| **Relevant Background on Quantum Mechanics** | |
| In this section, we provide a concise survey of key concepts from quantum mechanics that are essential for quantum robotics. In general, our work is written for an audience familiar with typical robotic algorithms and technologies and presumes no prior knowledge of quantum mechanics.  **2.1 QUBITS AND SUPERPOSITION**  e fundamental unit of quantum computation is the qubit. e qubit can be thought of as the “transistor” of a quantum computer. A classical transistor controls a single binary bit that repre- sents just a single discrete value, 0 or 1. A quantum bit, or qubit, assumes a complex combination of the two states, 0 and 1. is leads to some special properties unique to qubits. For instance, classical bits are independent of each other. Changing the value of a classical bit generally does not aﬀect the value of other classical bits. is is not the case with qubits. As we will see, qubits can represent exponentially more data via special properties of quantum mechanics: superposition and entanglement.  As a simple illustration of the qubit, consider an electron orbiting a nucleus in an atom. e electron can be in one of two orbital states: the “ground” state or the “excited” state. Figure [2.1](#_bookmark12) shows an example depiction of this simple case. e electron functions as a qubit, and the qubit’s computational data is encoded by the electron’s orbital states.  nucleus nucleus    |0 |1  **Figure 2.1:** Illustration of simple qubit. |  |

Bra-ket notation, originally invented by Paul Dirac in 1939, is a standard notation for rep- resenting states of quantum systems. A ket j*A*i represents the numeric state vector of a quantum system and is typically an element of a Hilbert space.[¹](#_bookmark15) With ket notation, the ground state of our

*T*simple qubit can be represented as the ket j*0*i (an abbreviation for the state vector ), and*1 0*

the excited state can be represented as the ket j*1*i (an abbreviation for the state vector *0 1 T* ).

e bra h*A*j is deﬁned mathematically as the conjugate transpose[²](#_bookmark16) of a ket (e.g., h*A*j D j*A*i*†*).

Before measurement, the electron is said to be in a superposition of the two states, denoted as a weighted sum:

j i D *˛* j*0*i C *ˇ* j*1*i (2.1)

where *˛* and *ˇ* are complex numbers. e *˛* and *ˇ* coeﬃcients encode the probability distribution of states the electron can be found in when measured by a lab instrument. Until measurement, the true underlying state of the electron is not known. In fact, technically speaking, the true state of the electron is a linear superposition of both the ground and excited state. e superposition notation indicates that the electron is simultaneously in *both* the ground and excited state.

When the qubit is measured, its superposition collapses to exactly one state (either the

ground or excited state), and the probability of measuring a particular state is given by its ampli- tude weights. e electron is measured to be in the ground state j*0*i with probability j*˛*j*2* and in the excited state j*1*i with probability j*ˇ*j*2* such that j*˛*j*2* C j*ˇ*j*2* D *1*.

e notation can be generalized for describing *k*-level quantum systems. In a *k*-level quan- tum system, the electron can be in one of *k* orbitals as opposed to just one of two states. e state of the *k*-level quantum system j i (when in superposition) can be expressed as:

## QUANTUM STATES AND ENTANGLEMENT

Previously, we illustrated how a simple electron-orbital system could be represented with bra-ket notation. e ket is a mathematical abstraction, a notation representing a physical state that exists

¹Often, for us, just C*N* , the space of complex numbered vectors.

²e conjugate transpose of a matrix *A*h D *AT* . To form the conjugate transpose of *A*, one takes the transpose of *A* and then computes the complex conjugate of each entry. e complex conjugate is simply the negation of the imaginary part (but not the real part).

**2.2. QUANTUM STATES AND ENTANGLEMENT 7**

in the real world. e beauty of this abstraction is that a variety of quantum systems, although implemented diﬀerently, can be described by the same underlying theory.

For a particular quantum system being studied, a physicist using the bra-ket notation will specify some of the system’s elementary physical states as “pure states.” Pure states are deﬁned as fundamental states of a quantum system that cannot be created from other quantum states.

where j *s*i are the individual pure states participating in the mixture, and the *Ps* are mixing weights.

Composite systems are quantum systems that consist of two or more distinct physical par- ticles or systems. e state of a composite system may sometimes be described as a tensor product (˝) of its components.

Here is an example of a 2-qubit system. j i*A* and j i*B* are two qubits that have probability distributions for being measured in states j*0*i and j*1*i respectively. e tensor product (˝) of their distinct probability distributions can sometimes represent the joint probability distribution of the composite system’s measurement outcome probabilities.

When the composite system can be represented using the tensor product decomposition, the qubit measurement events are eﬀectively statistically independent probability events. e joint measurement outcome probabilities equal the numeric multiplication of individual measurement probabilities. In Equation ([2.6](#_bookmark19)), the composite system consists of entangled qubits, and the sta- tistical independence assumption no longer holds. In an entangled system, the qubits exhibit state correlations. If one knows the state of one qubit in an entangled pair, he or she necessarily obtains information about the state of the other entangled qubit.

e overall quantum state (in superposition) of a composite system with *N* qubits hav- ing state j i (or more generally as *N* quantum subsystems each with quantum state j i) can be denoted as ji˝*N* . Entanglement of qubits provides a potentially powerful data representation mechanism. Classically, *N* binary bits can represent only one *N* -bit number. *N* qubits, however,

can probabilistically represent *2N* states in a superposition. *N* qubits can thus represent all pos- sible *2N N* -bit numbers in that superposition. is advantage is partially oﬀset by the additional processing overhead necessary to maintain quantum memory (since a qubit can only take on one state when measured and thus maintains the data only probabilistically). However, even with the additional overhead, quantum storage is expected to produce data representation advantages over classical implementations.

## SCHRÖDINGER EQUATION AND QUANTUM STATE EVOLUTION

Quantum states change according to particular dynamics. e Schrödinger Equation can be used to describe a quantum system’s time-evolution:

*ı*

*i* G *ıt* j i D *H* j i (2.7)

where ji is the state of the quantum system, *H* is a pHamiltonian operator representing the total

energy of the system, G is Planck’s constant, and *i* D —*1*. Schrödinger’s Equation expresses that

the time-evolution of a quantum system can be expressed in terms of Hamiltonian operators. is description of quantum systems is key to Adiabatic Optimization (see Section [2.5.4](#_bookmark41)).

Hamiltonian operators that govern the evolution of quantum systems have special structure. In general, the evolution of a closed quantum system must be unitary, and the time-evolution of a closed quantum system can be described by application of a sequence of matrices that are unitary.

Formally, a complex square matrix *U* is unitary if its conjugate transpose *U †* is also its inverse. is means:

*U †U* D *UU†* D *I* (2.8)

where *I* is the identity matrix. Unitary matrices have several useful properties including being norm-preserving (i.e., h*Ux; Uy*i D h*x; y*i for two complex vectors *x* and *y*), being diagonalizable (i.e., writable as *U* D *VDV* \*), having j det *U* j D *1*, and being invertible.

Unitary matrices help formalize the evolution of a quantum system. e state vector j i of a quantum system can be pre-multiplied by a unitary matrix *U* . When a state vector containing a probability distribution over measurement outcomes is pre-multiplied by a unitary matrix, the operation always produces a new probability distribution vector whose elements also sum to 1. e resulting probability distribution represents the possible measurement outcomes of the quantum system after the system is evolved by the unitary matrix operator *U* . Unitary matrix operators can also be chain multiplied together (e.g., *U1U2 : : : Un*) to represent a sequence of evolution steps on a quantum system. As we will see next, another view of unitary matrices is as logic gates in a quantum circuit that process input data (i.e., quantum states) and return outputs.

## QUANTUM LOGIC GATES AND CIRCUITS

Quantum logic gates are the analogue to classical computational logic gates. Computational gates can be viewed as mathematical operators that transform an initial data state to a ﬁnal data state. Since quantum state evolution must be unitary, quantum gates must be unitary operators.

### REVERSIBLE COMPUTING AND LANDAUER’S PRINCIPLE

An interesting departure from classical computation is that quantum computer gates are always reversible. One can always, given the output and the operators, recover the initial state before the computation. is follows because a unitary matrix used to evolve a quantum system is also invertible.

Logic reversibility is the ability to determine the logic inputs by the gate outputs. For ex- ample, the classical NOT gate is reversible, but the classical OR gate is not. By deﬁnition, a reversible logic circuit has the additional following properties [[Vos](#_bookmark446), [2010](#_bookmark446)]:

* + - 1. e number of inputs and outputs are the same in the circuit.
      2. For any pair of input signal assignments, there are two distinct pairs of output signal as- signments.

Conveniently, the truth table of a reversible circuit with width *n* is represented as a square matrix of size *2n*. While there are *.2n/Š* diﬀerent Boolean logic circuits of width *n* that can be realized, only a handful are valid reversible computing mechanisms.

Reversible quantum computing has a remarkable thermodynamic interpretation. In a phys- ical sense, a reversible circuit will preserve information entropy, i.e., lead to no information content lost. Landauer’s principle [[Landauer](#_bookmark343), [1961](#_bookmark343)] states that any logically irreversible manipulation of information (such as the erasure of a classical digital bit) must lead to entropy increase in the sys- tem. e principle suggests the “Landauer Limit” that the minimum possible amount of energy required to erase one bit of information is *kT* ln *.2/* where *k* is Boltzmann’s constant and *T* is the temperature of the circuit. At room temperature, the Landauer Limit suggests that erasing a bit requires a mere *2:80* zettajoules!

e energy expenditure of current computers is nowhere near this theoretical limit. e most energy-eﬃcient machines today still use millions of times this forecasted energy amount. In fact, in many realms of computer science and engineering, there is an expectation of intelli- gent computation being a highly power-intensive activity. Even neuroscientiﬁc predictions es- timate human brain activities account for more than 20% of the body energy needs, with more than two-thirds of power consumption associated with problem solving activities [[Swaminathan](#_bookmark432), [2008](#_bookmark432)]. It seems natural to expect intelligence to be power-intensive. At the same time, the brain only uses about 20W of electricity, which is less than the energy required to run a dim light bulb [[Swaminathan](#_bookmark432), [2008](#_bookmark432)]. Clearly, more can still be done to optimize power consumption of digital circuits, even if generating intelligent behavior requires more energy consumption than other useful functions.

Excitingly, many studies appear to conﬁrm the Landauer predictions for small-scale cir- cuitry (though, convincing empirical proof is not without counterargument). [Bennett](#_bookmark259) [[1973](#_bookmark259)] showed the theoretical validity of implementing an energy eﬃcient reversible digital circuit in terms of a three-tape Turing machine. In 2012, an experimental measurement of Landauer’s bound for the generic model of one-bit memory was demonstrated empirically [[Bérut et al.](#_bookmark261), [2012](#_bookmark261)]. Recently, [Hong et al.](#_bookmark317) [[2016](#_bookmark317)] used high precision magnetometry to measure the energy loss of ﬂipping the value of a single nanomagnetic bit and found the result to be within tolerance of the Landauer limit (about 3 zettajoules).

Since bulky battery technology is one of the key limiting factors of many current robotic systems, Landauer’s Principle provides hope for increasing the computational power of robots while simultaneously making robots more power-eﬃcient. If true, Landauer’s Principle suggests a world with highly energy-eﬃcient robots operating with quantum-scale circuits that allow mas- sive reduction in power consumed.

## QUANTUM COMPUTING MECHANISMS

In general, quantum gates placed in a circuit can create interesting computational behavior not possible in classical circuits. Quantum computing methods oﬀer potential speedups and improved properties for many classical algorithms. Some introductory background can be found in [Kaye](#_bookmark334) [et al.](#_bookmark334) [[2006](#_bookmark334)], [Rieﬀel and Polak](#_bookmark396) [[2000](#_bookmark396)], [Steane](#_bookmark430) [[1998](#_bookmark430)]. e key general mechanisms of quantum speedup and improvement are discussed in this section.

where *X* is the set of *2n* unique binary bit strings of length *n*. e Hadamard Transform produces a superposition of *2n* states using *n* gates, simultaneously evaluating all values of the function while the system is in superposition. is is a remarkable amount of computation done, compared to classical systems.

### CHALLENGES WITH QUANTUM PARALLELISM

e major limitation of quantum parallelism is that, while the output state contains information about multiple function evaluations of *f.x/* when the system is in superposition, only one of the function evaluations is returned when the quantum system is measured. In the basic Hardamard transform, any of the function values j*f.x/*i can be returned, each with equal probability. Limited data return from measurement is a common theme in quantum computing. For many methods, it is common for a quantum system to perform a signiﬁcant amount of computation while in superposition but to reveal only a small fraction of the result upon measurement.

Much research is dedicated to evolving quantum systems that encode useful information in superposition so that the most useful output information is returned upon measurement. For example, there exist quantum parallel techniques to extract some meaningful information about the global properties of a function as opposed to just raw function values at points. Deutsch’s algorithm [[Deutsch and Jozsa](#_bookmark287), [1992](#_bookmark287)] allows for the evaluation of the parity *f.0/* ˚ *f.1/* using one parallel computation whereas classically two computations would be required.

In general, a convincing empirical demonstration of quantum parallelism is a subject of ongoing research. Some authors ask whether quantum parallelism (in the unitary circuit formu- lation) is even realizable. e construction of the *Uf* gate in practice may require internal logic that scales with the number of unit-cost operations for the precision of *x*. e quantum circuit complexity result may be beneﬁting from gate-level parallelism not realizable in classical circuits. When one looks at the complexity of the complete circuit, there may not always be an advantage of quantum parallelism to classical parallelism [[Lanzagorta and Uhlmann](#_bookmark345), [2008b](#_bookmark345)].

Despite the current challenges with quantum parallelism, it is still regarded as a major hope for the future success of quantum computing. It is also one of the fundamental pillars on which more sophisticated quantum algorithms are built.

If an optimization problem can be cast as a QUBO, it can be represented as an Ising model and optimized by adiabatic hardware. Many computational problems can be cast as QUBOs. Abstractly, the Ising model represents a set of elements and their pair-wise interactions. e Ising model has seen many real-world modeling applications because interacting elements must be modeled in a large number of ﬁelds. e world is full of interacting elements (e.g., electrons in an atom, neurons in a network, birds in a ﬂock, or even interacting social agents in a crowd psychology setting).

Current adiabatic hardware is mostly limited to solving QUBOs. As such, it is, at best, a limited form of universal quantum computing. In addition, current hardware does not allow many qubits, produces many defects such that not all pairs of qubits are entangled, and must use sparse, pre-speciﬁed topologies for qubit interconnections [[Neven et al.](#_bookmark376), [2009](#_bookmark376), [Pudenz et al.](#_bookmark389), [2014](#_bookmark389)].

### SHOR’S QUANTUM FACTORIZATION ALGORITHM

One of the hallmark results in quantum computing is Shor’s algorithm for integer factoriza- tion. When ﬁrst proposed, Shor’s algorithm was one of the key theoretical insights that showed quantum computing could be very diﬀerent from (and has the potential to be signiﬁcantly more powerful than) classical computing.

Integer factorization is a fundamental problem in computer science. While it is relatively easy to ﬁnd large prime numbers, it is particularly hard to resolve a composite number into its prime factors. A decomposition of an arbitrary *N* -bit number, executed on a classical computer,

has an exponential complexity *O.kN /*, for some constant *k*. Prime factorization is among the class of NP problems.

e hardness of factorization has historically served as a boon in ﬁelds such as public- key cryptography and network communication. e widely used RSA encryption scheme [[Rivest](#_bookmark398) [et al.](#_bookmark398), [1978](#_bookmark398)] has been one of the more popular algorithms for secure communication on net- works [[Menezes et al.](#_bookmark364), [1996](#_bookmark364)]. In a robotics context, algorithms such as RSA help keep robot communication and teleoperation secure from possible hackers. Quantum factorization, how- ever, could be used to break RSA and change the nature of internet security.

In 1994, Peter Shor formulated a hallmark quantum factorization algorithm that performs factorization in polynomial time [[Shor](#_bookmark416), [1999](#_bookmark416)]. For an arbitrary odd number *N* , consider a random *x*, *1 < x < N* , for which *xr* D *1* mod *N* , for some *r* . e series *.1; x; x2; x3; : : : /* mod *N* is periodic with a period not greater than *N* . e above relations can be succinctly represented as:

*.xr=2* — *1/.xr=2* C *1/* D *0* mod *N:* (2.24)

From the equation (*ab* D *0* mod *N* ), one can ﬁnd, in polynomial time, the greatest common divisors, *gcd.a; N/* and *gcd.b; N/*. ese divisors, if they are found, will be factors of *N* . If a non-trivial divisor does not exist, the *x* variable can be re-picked and the computation repeated.

e described steps can be performed on a classical computer in polynomial time, with the exception of calculating the exponential function *xr* . Shor’s algorithm uses the Discrete Fourier Transform (DFT) and quantum parallelism to calculate the periodic function simultaneously for many values *x*, so that all operations happen in *O.N/* time.

Shor’s algorithm is a major advancement in the theory of quantum computing, and one of the most interesting predictions posited by the ﬁeld. A practical implementation for large integer factorization instances is still a subject of major research [[Dattani and Bryans](#_bookmark282), [2014](#_bookmark282)].

### QUANTUM TELEPORTATION

Another major engineering possibility posited by quantum mechanics is quantum teleportation. Quantum teleportation is a technique which transmits a quantum state by using a pair of entan- gled qubits and a classical communication channel. In this section, we provide a brief outline of how quantum teleportation works.

Consider two parties, Alice and Bob, who wish to communicate the state j i of a qubit. Alice wants to send the qubit state to Bob. However, Alice does not know what the state of the qubit is and, by the laws of quantum mechanics, observing the state collapses the qubit into a deﬁnite value, j*0*i or j*1*i. Furthermore, even if Alice knows the superposition state j i D *˛* j*0*i C *ˇ* j*1*i, communicating it over a quantum channel would take an inﬁnite amount of time, since the amplitudes *˛* and *ˇ* are complex numbers with inﬁnite precision. However, the quantum teleportation technique allows one to transmit the state j i using an entangled pair of bits and communication of two bits of information over a classical communication channel.

* 1. **QUANTUM OPERATING PRINCIPLES (QOPS) SUMMARY 21**

e protocol for transmitting the state j i begins with forming an entangled pair of qubits *A* and *B*. e qubit *A* is given to Alice and the qubit *B* is given to Bob. Alice now takes the qubit j i that she wishes to communicate and makes a joint measurement of it with the entangled qubit *A*. is results in Alice entangling her two qubits and observing one of four states. is observed state can be encoded in two classical information bits. Alice encodes her observations into two classical bits and transmits them to Bob. As a result of Alice’s observation, *B* is now in one of four possible states, which correspond to the state j i. Using the information Alice sent with two classical bits, Bob can perform operations on *B* so that its state becomes j i. Bob can thus successfully recreate the state j i on his end.

Quantum teleportation has many potential applications in robotics. One could potentially use quantum teleportation to transmit information about qubits between a robot and a server op- erating in diﬀerent locations. Note that information cannot be transmitted faster than the speed of light, since the communication of two classical bits of information is needed in the protocol. One does not expect a better network speed from quantum teleportation. However, quantum telepor- tation might one day allow qubit information to be transported with less eﬀort than is currently required. Some additional applications in robotics include building noise-resistant quantum gates, quantum error correcting codes, and further development of quantum information theory.

## QUANTUM OPERATING PRINCIPLES (QOPS) SUMMARY

We have discussed some key basic principles of quantum mechanics and quantum computation. Many techniques in quantum robotics can be understood as applications of these core principles which we call “Quantum Operating Principles” (or QOPs). In Table [2.1](#_bookmark54), key QOPs are men- tioned as well as some of their potential applications in quantum robotics that will be discussed in upcoming chapters.

## CHAPTER SUMMARY

e material on fundamental quantum mechanics forms the backbone of our discussion of quan- tum robotics. Entanglement of qubits is the basis of quantum parallelism, a key speedup strategy for algorithms. Quantum adiabatic processors allow one to cast certain classical optimization problems in the framework of quantum optimization. In the next section, we will apply these concepts to robotic search and planning.