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 quantumscale 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

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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 fundamental limitations. Whether the benefits are mostly for model building in offline mode or extend to realtime operation remains to be seen, but the potential for impact is surely there. In addition, the potential energy eciency of quantumscale 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 sensing 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 improvements in dealing with uncertainty, representational power, and with operating in quantum environments.

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.

1.2 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 subfields 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, 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) 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), machine learning (Chapter 5), and robot controls and perception (Chapter 6). 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 properties, and possible tradeoffs in scaling commonly used robotic techniques in quantum media. Our book also highlights some of the current implementations of quantum engineering mechanisms (Chapter 7) as well as current limitations. Finally, we conclude with a holistic summary of potential benefits to robotics from quantum mechanisms (Chapter 8).

1.3 QUANTUM OPERATING PRINCIPLES

Quantum approaches can be dicult 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 fundamental 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 fundamental 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 readers 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 represents 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 shows an example depiction of this simple case. e electron functions as a qubit, and the qubits computational data is encoded by the electrons orbital states.

nucleus nucleus

Figure 2.1: Illustration of simple qubit.

Braket notation, originally invented by Paul Dirac in 1939, is a standard notation for representing states of quantum systems. A ket jAi represents the numeric state vector of a quantum system and is typically an element of a Hilbert space. With ket notation, the ground state of our

the excited state can be represented as the ket j1i (an abbreviation for the state vector 0 1 T ).

e bra hAj is defined mathematically as the conjugate transpose of a ket

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

where and are complex numbers. e and coecients 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 amplitude weights. e electron is measured to be in the ground state j0i with probability jj2 and in the excited state j1i with probability jj2 such that jj2 C jj2 D 1.

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

2.2 QUANTUM STATES AND ENTANGLEMENT

Previously, we illustrated how a simple electronorbital system could be represented with braket notation. e ket is a mathematical abstraction, a notation representing a physical state that exists

Often, for us, just CN , the space of complex numbered vectors.

e conjugate transpose of a matrix AH 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).

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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 braket notation will specify some of the systems 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 si 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 particles 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 2qubit system. j iA and j iB are two qubits that have probability distributions for being measured in states j0i and j1i respectively. e tensor product () of their distinct probability distributions can sometimes represent the joint probability distribution of the composite systems measurement outcome probabilities.