Quantum Robotics

A Primer on Current Science and Future Perspectives

Synthesis Lectures on Quantum Computing

Editors

Quantum Robotics: A Primer on Current Science and Future Perspectives
Prateek Tandon, Stanley Lam, Ben Shih, Tanay Mehta, Alex Mitev, and Zhiyang Ong
2017

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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. This 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.

KEYWORDS

Quantum Robotics, Quantum Computing, Quantum Algorithms

Contents

Preface

The Quantum Robotics Group was founded in March 2015. The group met every weekend over the course of a year to discuss different emerging topics related to quantum robotics. This book is the product of our lecture series.

Computational speedups in planning for complex environments, faster learning algorithms, memory and power efficiency using qubit representation of data, and capability to manipulate quantum phenomena are only some of the many exciting possibilities in the emerging world of quantum robotics. Robotic systems are likely to benefit from quantum approaches in many ways.

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.

Chapter 1 introduces our work and framework. 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 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).

We hope you enjoy this work and, from it, are inspired to delve more into the exciting emerging world of quantum robotics.

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Notation

In this section, we detail some of the notation and conventions used throughout the book. In writing our work, we have attempted to use the same notation as the original cited publications to maintain a high fidelity to the original literature. However, in some cases, we have modified the notation to make equations easier to read.

STANDARD NOTATION

- $\mathbb{N}$ denotes the set of nonnegative integers.
- $\mathbb{R}$ denotes the set of real numbers.
- $\mathbb{C}$ denotes the space of complex numbers.
- $\mathbb{C}^N$ denotes the N-dimensional space of complex numbered vectors.

COMPUTER SCIENCE

We make extensive use of asymptotic notation. For two functions $f, g : \mathbb{N} \to \mathbb{N}$, we write:

- $f(x) = O(g(x))$ if and only if there exists a positive constant C and an integer x_0 such that $|f(x)| \leq C|g(x)|$ for all $x \geq x_0$.
- $f(x) = \Omega(g(x))$ if and only if $g(x) = O(f(x))$.
- $f(x) = \Theta(g(x))$ if and only if $f(x) = O(g(x))$ and $f(x) = \Omega(g(x))$.
- $a \oplus b$ refers to the XOR operation between two binary bits, a and b.

CALCULUS

- $\dot{f}(x)$ generally refers to the first derivative of the differentiable function $f(x)$.
- $\ddot{f}(x)$ generally refers to the second derivative of the differentiable function $f(x)$.

LINEAR ALGEBRA

- I generally refers to the identity matrix of appropriate size (unless otherwise stated).
- $\det(A)$ refers to the determinant of the matrix A.
- $A^\dagger$ refers to the conjugate transpose of A.
- F^+ denotes the Moore-Penrose pseudoinverse of F.

QUANTUM MECHANICS

- $\hbar$ refers to Planck's constant.
- $|\psi\rangle$ refers to a ket, which is generally a state vector for a quantum state.
- $\langle\psi|$ refers to a bra, the conjugate transpose of the vector $|\psi\rangle$.
- ρ generally refers to the density matrix of a quantum system (unless otherwise stated).
- U generally refers to a unitary matrix where $U^\dagger U = UU^\dagger = I$ (unless otherwise stated).
- $\langle\phi|\psi\rangle$ refers to the inner product between the vectors $|\phi\rangle$ and $|\psi\rangle$.
- $\langle\phi|A|\psi\rangle$ refers to the inner product between ϕ and $A\psi$.
- $|\phi\rangle \otimes |\psi\rangle$ refers to a tensor product between $|\phi\rangle$ and $|\psi\rangle$.
- $|\phi\rangle\,|\psi\rangle$ also refers to the tensor product between $|\phi\rangle$ and $|\psi\rangle$.
- $|\psi\rangle^{\otimes N}$ refers to the quantum state (in superposition) of the composite system with N interacting quantum systems, each having quantum state $|\psi\rangle$.
- σ_x often refers to the Pauli-X matrix $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$.
- σ_y often refers to the Pauli-Y matrix $\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$ where $i = \sqrt{-1}$.
- σ_z often refers to the Pauli-Z matrix $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$.
- $[A, B]$ often refers to a commutation operator $[A, B] = AB - BA$.
- A set of matrices $\{K_i\}$ is a set of Kraus matrices if it satisfies $\sum_{i=1}^{\kappa} K_i^\dagger K_i = I_d$