

Quantum Robotics

A Primer on Current Science and Future Perspectives

Synthesis Lectures on Quantum Computing

Editors

Marco Lanzagorta, *U.S. Naval Research Labs*

Jeffrey Uhlmann, *University of Missouri-Columbia*

Quantum Robotics: A Primer on Current Science and Future Perspectives

Prateek Tandon, Stanley Lam, Ben Shih, Tanay Mehta, Alex Mitev, and Zhiyang Ong
2017

Approximability of Optimization Problems through Adiabatic Quantum Computation

William Cruz-Santos and Guillermo Morales-Luna
2014

Adiabatic Quantum Computation and Quantum Annealing: Theory and Practice

Catherine C. McGeoch
2014

Negative Quantum Channels: An Introduction to Quantum Maps that are Not Completely Positive

James M. McCracken
2014

High-level Structures for Quantum Computing

Jaroslav Adam Mischak
2012

Quantum Radar

Marco Lanzagorta
2011

The Complexity of Noise: A Philosophical Outlook on Quantum Error Correction

Amit Hagar
2010

Broadband Quantum Cryptography

Daniel J. Rogers
2010

Quantum Computer Science

Marco Lanzagorta and Jeffrey Uhlmann
2008

Quantum Walks for Computer Scientists

Salvador Elías Venegas-Andraca
2008

© Springer Nature Switzerland AG 2022

Reprint of original edition © Morgan & Claypool 2017

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means—electronic, mechanical, photocopy, recording, or any other except for brief quotations in printed reviews, without the prior permission of the publisher.

Quantum Robotics: A Primer on Current Science and Future Perspectives

Prateek Tandon, Stanley Lam, Ben Shih, Tanay Mehta, Alex Mitev, and Zhiyang Ong

ISBN: 978-3-031-01392-8 paperback

ISBN: 978-3-031-02520-4 ebook

ISBN: 978-3-031-03648-4 epub

DOI 10.1007/978-3-031-02520-4

A Publication in the Springer series

SYNTHESIS LECTURES ON QUANTUM COMPUTING

Lecture #10

Series Editors: Marco Lanzagorta, *U.S. Naval Research Labs*

Jeffrey Uhlmann, *University of Missouri-Columbia*

Series ISSN

Print 1945-9726 Electronic 1945-9734

Quantum Robotics

A Primer on Current Science and Future Perspectives

Prateek Tandon

Stanley Lam

Ben Shih

Tanay Mehta

Alex Mitev

Zhiyang Ong

Quantum Robotics Group

SYNTHESIS LECTURES ON QUANTUM COMPUTING #10

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	xi
Acknowledgments	xiii
Notation	xv
1 Introduction	1
1.1 What does Quantum Robotics Study?	1
1.2 Aim and Overview of our Work	2
1.3 Quantum Operating Principles	3
2 Relevant Background on Quantum Mechanics	5
2.1 Qubits and Superposition	5
2.2 Quantum States and Entanglement	6
2.3 Schrödinger Equation and Quantum State Evolution	8
2.4 Quantum Logic Gates and Circuits	9
2.4.1 Reversible Computing and Landauer's Principle	9
2.4.2 Notable Quantum Gates	11
2.4.3 Quantum Circuit for Fast Fourier Transform	12
2.5 Quantum Computing Mechanisms	13
2.5.1 Quantum Parallelism	13
2.5.2 Challenges with Quantum Parallelism	14
2.5.3 Grover's Search Algorithm	15
2.5.4 Adiabatic Quantum Optimization	17
2.5.5 Adiabatic Hardware and Speedups	18
2.5.6 Shor's Quantum Factorization Algorithm	19
2.5.7 Quantum Teleportation	20
2.6 Quantum Operating Principles (QOPs) Summary	21
2.7 Chapter Summary	21

3	Quantum Search	25
3.1	Uninformed Grover Tree Search	25
3.2	Informed Quantum Tree Search	27
3.3	Application of Quantum Annealing to STRIPS Classical Planning	28
3.3.1	Classical STRIPS Planning	28
3.3.2	Application of Quantum Annealing to STRIPS Planning	28
3.4	Chapter Summary	31
4	Quantum Agent Models	33
4.1	Classical Markov Decision Processes	34
4.2	Classical Partially Observable Markov Decision Processes	35
4.3	Quantum Superoperators	36
4.4	Quantum MDPs	36
4.5	QOMDPs	38
4.6	Classical Reinforcement Learning Models	39
4.6.1	Projection Simulation Agents	40
4.6.2	Reflective Projection Simulation Agents	41
4.7	Quantum Agent Learning	42
4.8	Multi-armed Bandit Problem and Single Photon Decision Maker	44
4.9	Chapter Summary	45
5	Machine Learning Mechanisms for Quantum Robotics	47
5.1	Quantum Operating Principles in Quantum Machine Learning	48
5.1.1	Quantum Memory	48
5.1.2	Quantum Inner Products and Distances	48
5.1.3	Hamiltonian Simulation	50
5.1.4	QOPs Summary for Quantum Machine Learning	50
5.2	Quantum Principal Component Analysis (PCA)	50
5.2.1	Classical PCA Analysis	51
5.2.2	Quantum PCA Analysis	51
5.2.3	Potential Impact of Quantum PCA on Robotics	51
5.3	Quantum Regression	52
5.3.1	Least Squares Fitting	52
5.3.2	Quantum Approaches to Curve Fitting	52
5.3.3	Potential Impact of Quantum Regression on Robotics	53
5.4	Quantum Clustering	53

5.4.1	Classical Cluster Analysis	54
5.4.2	Quantum Cluster Analysis	55
5.4.3	Potential Impact of Quantum Clustering on Robotics	56
5.5	Quantum Support Vector Machines	56
5.5.1	Classical SVM Analysis	56
5.5.2	Quantum SVM Analysis	58
5.5.3	Potential Impact of Quantum SVMs on Robotics	59
5.6	Quantum Bayesian Networks	59
5.6.1	Classical Bayesian Network Structure Learning	60
5.6.2	Bayesian Network Structure Learning using Adiabatic Optimization	60
5.6.3	Potential Impact of Quantum Bayesian Networks on Robotics	62
5.7	Quantum Artificial Neural Networks	62
5.7.1	Classical Artificial Neural Networks	62
5.7.2	Quantum Approaches to Artificial Neural Networks	64
5.7.3	Potential Impact of Quantum Artificial Neural Networks to Robotics	67
5.8	Manifold Learning and Quantum Speedups	67
5.8.1	Classical Manifold Learning	68
5.8.2	Quantum Speedups for Manifold Learning	69
5.8.3	Potential Impact of Quantum Manifold Learning on Robotics	70
5.9	Quantum Boosting	70
5.9.1	Classical Boosting Analysis	70
5.9.2	QBoost	71
5.9.3	Potential Impact of Quantum Boosting on Robotics	72
5.10	Chapter Summary	72
6	Quantum Filtering and Control	75
6.1	Quantum Measurements	75
6.1.1	Projective Measurements	75
6.1.2	Continuous Measurements	76
6.2	Hidden Markov Models and Quantum Extension	76
6.2.1	Classical Hidden Markov Models	76
6.2.2	Hidden Quantum Markov Models	78
6.3	Kalman Filtering and Quantum Extension	80
6.3.1	Classic Kalman Filtering	80
6.3.2	Quantum Kalman Filtering	82
6.4	Classical and Quantum Control	83
6.4.1	Overview of Classical Control	83

6.4.2	Overview of Quantum Control Models	84
6.4.3	Bilinear Models (BLM)	85
6.4.4	Markovian Master Equation (MME)	85
6.4.5	Stochastic Master Equation (SME)	86
6.4.6	Linear Quantum Stochastic Differential Equation (LQSDE)	87
6.4.7	Verification of Quantum Control Algorithms	87
6.5	Chapter Summary	88
7	Current Strategies for Quantum Implementation	89
7.1	DiVincenzo Definition	89
7.2	Mosca Classification	91
7.3	Comparison of DiVincenzo and Mosca Approaches	92
7.4	Quantum Computing Physical Implementations	92
7.5	Case Study Evaluation of D-Wave Machine	94
7.6	Toward General Purpose Quantum Computing and Robotics	96
7.7	Chapter Summary	97
8	Conclusion	99
A	Cheatsheet of Quantum Concepts Discussed	103
	Bibliography	107
	Authors' Biographies	129
	Index	131

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.

Prateek Tandon, Stanley Lam, Ben Shih, Tanay Mehta, Alex Mitev, and Zhiyang Ong
January 2017

Acknowledgments

We would like to acknowledge Dr. Steven Adachi, Professor Marco Lanzagorta, Professor Jeffrey Uhlmann, and Dr. Henry Yuen, among others, for their helpful comments in the development of this work.

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 $f, g : \mathbb{N} \rightarrow \mathbb{N}$, 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 $U^\dagger U = U U^\dagger = I$ (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 $\sum_{i=1}^{\kappa} K_i^\dagger K_i = I_d$