National Science Foundation (NSF)
Grant IRES 1829078
IRES TRACK II: US-UK international student research in robust control of quantum networks

Edmond Jonckheere
Dept. of Electrical and Computer Engineering

USC University of Southern California
Los Angeles, CA 90089

jonckhee@usc.edu
http://ee.usc.edu/~jonckhee
US-UK international student research in robust control of quantum networks

- People (students, postdoc, faculty) involved
- Venue: Wales, United Kingdom
- First week program in Cardiff: spintronics control
- Second week program in Swansea: photonics
- Products
  - Classical versus quantum fundamental limitations
  - Structurally uncertain quantum network robustness
- Social (or aerospace?) activity: Wales Air show
NSF Grant IRES 1829078
Principal Investigators

Prof. Sophie Shermer
Prof. Edmond Jonckheere
Dr. Frank Langbein
US Students, postdoc participants

Emily Reed, Ph.D. student, Univ. of South. Calif.

Benjamin Sheller
Postdoc, Rutgers Univ.
Consultant, Iowa State Univ.

Carrie Weidner
Ph.D., U. Col., Boulder, Postdoc, Aarhus Univ., Denmark

Jonathan Monroe
microelectronics physicist at BOEING

Eliav Maas
System engineer, startup

“Carrie [Weidner] comes to Bristol with the ultimate goal of developing a quantum gas microscope with two orthogonal axes of high-resolution imaging for use in quantum simulation, but she plans to start with an ultracold atom setup that will be used (among other things) to study robust quantum control.”
US Students personal statements

“I enjoyed the experience very much. The environment was very conducive for learning and exploring ideas, and especially the chance to engage with each other outside of the formal lecture environment was very useful. I would highly recommend the experience to others, or take advantage of it again if able. I am still in semi-regular contact with several of the other participants, and hope to work more with them in the future, as a result of the discussions we had at the time.”

Benjamin Sheller, Postdoc, Rutgers University

“I am grateful to have had the opportunity to attend the international robust quantum control workshop in the UK in 2019. Not only did I learn a lot about the foundations of robust quantum control, but I also was able to form relationships with new colleagues in this area of research. Out of this, we were able to write and submit a tutorial paper that outlines robust quantum control for new researchers and overviews the current challenges in this exciting area of study. I look forward to continuing to research in this area and collaborate with my colleagues.”

Emily Reed, Ph.D. student, Univ. of South. California

“The ASI was a phenomenal opportunity to learn from experts I would have otherwise not had the pleasure of meeting. The subjects we covered opened incredible opportunities in my current position, and I have benefitted immensely from the experience of learning alongside my new peers. The fact that we were able to publish a paper based on our discussions is an apt testimony to the depth of learning and productivity that I enjoyed at ASI.”

Jonathan Monroe, Microelectronics physicist at Boeing
“In many ways the ASI was a highlight of my postdoc. It was excellent to connect with students, postdocs, and professors in robust control, a field that I was (and still am) quite new to. I bonded immediately with my peers and truly enjoyed the balance of study and leisure that the program provided, because this facilitated discussion amongst all of us—even resulting in a paper under review. The collaboration that I have built up as a result of the ASI is, without a doubt, one of my most productive in terms of measurable research outputs and sheer enjoyment, and I am very grateful to have taken part.”

Dr. Carrie Weidner
Lecturer, Bristol University
British student participants

Anastasia Ugaste, Software engineer/HP computing

Benedict Uttley, Bioinformatician/Computational Biologist

Chris Davis-Jenkins, Postdoc at Johns Hopkins specializing in Magnetic Resonance spectroscopy

Max Chandler, Site reliability engineer
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Anne Boden
Welch tech entrepreneur

Iain Maxted,
Founder
Guardian Global Technologies
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### Programme

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<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Activity</th>
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<tbody>
<tr>
<td>Mo 06/24</td>
<td>09:30-10:00</td>
<td><strong>Admin and Visa Checks</strong></td>
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<tr>
<td></td>
<td>10:00-13:00</td>
<td>Session 1 (SMS) — Classical vs Quantum Control</td>
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<td>13:00-14:00</td>
<td><strong>Lunch</strong></td>
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<td>14:00-17:00</td>
<td>Session 2 (SMS) — New Ideas for Quantum Control</td>
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<td></td>
<td>19:00-21:00</td>
<td><strong>Welcome Dinner in Cardiff</strong></td>
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<td>Tu 06/25</td>
<td>09:30-12:30</td>
<td>Session 3 (FCL) — Bayesian Learning and Parameter Estimation</td>
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<td><strong>Lunch</strong></td>
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<td>14:00-17:00</td>
<td>Session 4 (FCL) — Machine learning</td>
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<td>17:00</td>
<td>Free to explore on your own</td>
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<td>We 06/26</td>
<td>09:30-12:30</td>
<td>Session 5 — Guest lectures &amp; discussion (Chris, Carrie, Anastasia)</td>
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<td>12:30-14:00</td>
<td><strong>Lunch</strong></td>
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<td>14:00-19:00</td>
<td><strong>Cardiff Castle (£13, 09:00-18:00) and walking tour of city</strong></td>
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<tr>
<td>Th 06/27</td>
<td>09:30-12:30</td>
<td>Session 6 (EJ) — Robust control fundamental limitations</td>
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<td>12:30-14:00</td>
<td><strong>Lunch</strong></td>
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<td>14:00-17:00</td>
<td>Session 7 (EJ) — Structured uncertainties in spin networks</td>
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<td>19:00-21:00</td>
<td><strong>Dinner in Cardiff</strong></td>
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<td>Fr 06/28</td>
<td>09:30-12:30</td>
<td>Session 8 — Participant presentation session</td>
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<td>12:30-13:30</td>
<td><strong>Lunch</strong></td>
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<td>13:30-17:00</td>
<td><strong>Welsh Heritage Centre, St Fagans (free, 10:00-17:00)</strong></td>
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<td>17:00-18:00</td>
<td>Transfer to Marriott-St Pierre (from St Fagans or Cardiff)</td>
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<td>19:00-21:00</td>
<td><strong>Dinner at Marriott-St Pierre</strong></td>
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<td>Sa 06/29</td>
<td>09:30-12:30</td>
<td>Session 9 — Practical work and discussion session</td>
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<td>14:00-17:00</td>
<td>Session 10 — Practical work and discussion session</td>
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<td>18:00</td>
<td><strong>Dinner at Marriott-St Pierre</strong></td>
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<td>Su 06/30</td>
<td>09:30-12:30</td>
<td>Session 11 — Discussions and planning for week 2</td>
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<td>12:30-13:00</td>
<td><strong>Lunch at Marriott St Pierre</strong></td>
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<td>13:30-16:30</td>
<td><strong>Visit to Tintern Abbey (£7.30, 9:30-17:00)</strong></td>
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<td>16:30</td>
<td>Transfer to Swansea</td>
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Spin coupling uncertainty: Mostly anti-classical behavior, especially Anderson localization

The hint for this apparently aberrant behavior is a discrepancy between the classical and the quantum concept of error:

\[ \left\| e_{\text{proj}}(t) \right\| := \min_{\varphi(t)} \left\| \text{OUT} - e^{\varphi(t)} \left\| \Psi(t) \right\| \right\| \ll \left\| \text{OUT} - \Psi(t) \right\| \]

British and American students interacting during a coffee break in Cardiff University

Professor Schirmer lecturing
Quantum dynamics is ergodic (there is Poincare recurrence of the minimum fidelity error.)
Is it (exponentially?) mixing?? What is the distribution of the return time? Erlang?
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# Second Week Program in Swansea

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<td>07/01</td>
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<td>18:00</td>
<td>Swansea Marina and Dinner (Meridian Tower)</td>
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<td>Tu</td>
<td>07/02</td>
<td>09:30-12:30</td>
<td>Session 14 — Guest lectures, Lab Tours, Discussion</td>
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<td>Brecon Beacons or Pembrokeshire Trip</td>
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<td>14:00-17:00</td>
<td>Session 16</td>
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<td>19:00-21:00</td>
<td>Dinner at Mumbles</td>
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<td>Th</td>
<td>07/04</td>
<td>09:30-12:30</td>
<td>Session 17 — Guest lectures, Lab Tours, Discussion</td>
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<td>Session 19 — Participant final presentations</td>
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<td>Free time</td>
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<td>Welsh National Airshow (Swansea)</td>
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## Quantum Light Sources using InAs quantum dots

David Ritchie¹,⁴

Mark Stevenson², Robert Young¹,², Andy Hudson¹,², Cameron Salter¹,², Raj Patel¹,², Antoine Boyer de la Giroday¹,², Matt Pooley¹,², David Ellis¹,², Andre Schwagemann¹,², Christiana Varnava¹,², Anthony Bennett², Martin Ward², Joanna Skiba-Szymanska², Paola Atkinson¹, Ken Cooper¹, Ayesha Jamil¹, Christine Nici¹, Ian Farrer¹,³, Peter Spencer¹, Andrey Krysa³, Jon Heffernan³, Andrew Shields²

¹ Cavendish Laboratory, University of Cambridge
² Quantum Information Group, Toshiba Research Europe
³ University of Sheffield
⁴ Swansea University
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#### Applications of Entangled Photons
- **Quantum Cryptography**: verifiably secure way to distribute digital keys
  - Quantum repeater allows key distribution over long distances
    - Briegel et al., PRL 81, 5932 (1998)
  - Single photon
  - Optical fibre

#### Quantum Imaging
- Using entangled photons to beat the Rayleigh limit
  - Boto et al., PRL 85 (2000)
  - Two entangled beams

#### Quantum Computing
- Logic gates
  - Comprising linear optical elements conditioned by auxiliary measurements
    - Knill, Laflamme & Milburn, Nature 409, 46 (2001)
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Robust Quantum Control in Closed and Open Systems: Theory and Practice


Abstract—Robust control of quantum systems is an increasingly relevant field of study amidst the ascendancy of quantum control, but there remains a gap between quantum physics and robust control. To develop general theories of robust quantum control, this gap must be minimized, as general quantum systems are not amenable to analysis via classical robust control techniques, e.g., the formulation as linear, time-invariant problems. This tutorial is written for the control theorist and presents an introduction to quantum systems, issues that arise when applying classical robust control theory to quantum systems, typical methods used by quantum physicists to explore such systems, and a discussion of open problems to be addressed in the field. This tutorial’s focus is on general, practical applications allowing the control researcher to understand and begin applying their knowledge to advance this burgeoning field.

Index Terms—Quantum Systems, Quantum information, Quantum Control, Robust Control

I. INTRODUCTION

As quantum technologies continue to mature, their development will transition from proof-of-principle to well-engineered systems with numerous commercial applications in computing, sensing, and networking. However, the transformation of quantum technologies into the real-world application space requires the development of robust means to control and manipulate these quantum systems. Quantum control theory has been developed to the point where a number of textbooks [1, 2] and comprehensive review papers [3–8] have been written on the subject. While classical robust control is extensively studied and well-understood [9], rigorous development of robust control protocols for quantum mechanical systems remains an open field of research as classical methods cannot be readily applied to quantum systems in general.

Coherent quantum control is naturally formulated in terms of bilinear control systems with time-dependent controls that do not map easily to the framework of robust linear control, and coherent quantum systems are only marginally stable. Progress in decoherence-based state preparation [10, 11] and bath engineering [12] has not strongly leveraged robust control theory. Therefore, more research is needed into the theoretical underpinnings of robust quantum control as well as practical applications and eventual implementation into real systems. The overarching questions still remain to be answered: Can a quantum system ever be inherently robust, especially in the absence of stability? What are the fundamental device limitations established by quantum robust control protocols? Will we ever be able to move past the current noisy, intermediate-scale quantum (NISQ) era and build useful, scalable, and robust devices that are promised by the second quantum revolution? This remains to be seen, but some hope can be offered by the success of related applications that rely on quantum phenomena and control such as nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) (see, e.g., [13–17], among many others. If we can see a coherent signal from the many protons contained in the water that makes up (most of) the noisy, squishy, and chaotic human body, there may yet be hope for large-scale quantum computers.

As a result of the relative immaturity of robust quantum control, the barrier to entry into the field is quite high. As there are few good references for students and researchers in related fields to gain an overview of the state-of-the-art and the open questions in the area. This tutorial attempts to fill this gap. It is written for beginning graduate students and researchers from a variety of backgrounds, including quantum chemistry, optical engineering, mathematics, or quantum information, but we focus especially on the classical robust control researcher. Our goal is to introduce quantum theory and explain why classical robust control theory cannot be directly mapped onto quantum systems. We further introduce the Lie algebraic theory of geometric quantum control and discuss how quantum control is currently applied in practical settings. Where applicable, we include basic examples as well as relevant references. We do not cover measurement-based control, coherent feedback control, or Lyapunov control, as these are covered by existing tutorial papers and texts [18–20], with an introduction to robust control for linear quantum systems found in [21]. In particular, for a special class of quantum optical systems, the quantum system is separable on a linear, time-invariant (LTI) system; see [7, 22] for excellent reviews of these systems. All references listed previously are excellent resources for the interested student looking to supplement what they can learn in this tutorial. Our approach is to be as general as possible through a discussion of closed and open quantum systems, robust control challenges framed in the context of classical control, and current methods for finding optimal controls with notions of robustness in practice.

The tutorial is organized as follows: Section II introduces quantum systems, starting from fully coherent Hamiltonian systems and moving into dissipative Lindbladian systems and the Bloch representation of such systems. We also introduce the example problems that will be revisited throughout the tutorial. Section III discusses the issues that arise when applying classical robust control methods to quantum systems, particularly those stemming from the differences between classical linear systems to the bilinear systems described by quantum mechanics. We discuss the notions of controllability and observability.
Robustness of quantum controllers—and its relation to the global phase—has been one of the primary foci of the Advanced Study Institute.

Robust Control Formulation

1) Closed Quantum Systems: Minimizing the tracking error so that the desired final state matches the actual state is similar to maximizing the fidelity between two states in quantum systems. Here, the fidelity is represented in the following equation

$$F = |\langle \psi_d | U(H, t_f) | \psi_0 \rangle|^2.$$  \hfill (58)

It would be prudent to design a control that manipulates a system to ensure that the actual final state of the system is close to the desired final state. This would translate to maximizing the fidelity and minimizing the control effort subject to the dynamics in Eq. (40). We can represent this mathematically as

$$J^* = \max_u \left( |\langle \psi_d | \psi_{t_f} \rangle|^2 - \int_{t_0}^{t_f} u(t)^2 dt \right),$$ \hfill (59)

where $u(t)$ is the control and $U(H + H_{eu}(t), t_f) | \psi_0 \rangle = | \psi_f \rangle$.

One important remark is that the fidelity will never overshoot past 1 as it is defined to only take on values between 0 and 1. Hence, designing a system that ensures a fast rise time is achieved by maximizing the fidelity for all time. Therefore, in seeking a minimum steady-state error and fast rise time without any overshoot, the objective would take the following form

$$J^* = \max_u \left( |\langle \psi_d | U(H + H_{eu}(t), t_f) | \psi_0 \rangle|^2 \right.$$

$$\left. + \int_{t_0}^{t_f} |\langle \psi_d | U(H + H_{eu}(t), t) | \psi_0 \rangle|^2 dt - \int_{t_0}^{t_f} u(t)^2 dt \right).$$ \hfill (60)

Finally, it is desirable that the settling time is minimized. This translates to minimizing the final time. Hence, we can add this to the objective in the following manner

$$J^* = \max_{u, t_f} \left( |\langle \psi_d | U(H + H_{eu}(t), t_f) | \psi_0 \rangle|^2 \right.$$

$$\left. + \int_{t_0}^{t_f} |\langle \psi_d | U(H + H_{eu}(t), t) | \psi_0 \rangle|^2 dt - \int_{t_0}^{t_f} u(t)^2 dt - t_f \right).$$ \hfill (61)

The formulation in Eq. (61) was explored for Bose-Einstein condensates in optical lattices in [60].

To make these controllers robust, we can maximize the worst-case scenario fidelity to ensure that it is as large as possible under all possible perturbations and control schemes. Hence, we obtain the following formulation

$$J^* = \max_{u, t_f} \min \left( |\langle \psi_d | U(H + H_{eu}(t) + H_\Delta, t_f) | \psi_f \rangle|^2 \right.$$

$$\left. + \int_{t_0}^{t_f} |\langle \psi_d | U(H + H_{eu}(t) + H_\Delta, t) | \psi_0 \rangle|^2 dt - \int_{t_0}^{t_f} u(t)^2 dt - t_f \right).$$ \hfill (62)

This problem formulation is the crux of quantum robust control and has been examined for quantum molecular systems [34]. Furthermore, imposing upper and lower bound constraints on the control $u$ requires complex optimization methods for more general objectives as we overview in the next subsection.
For such nonlinear measure as the concurrence (or entanglement) error, some form of the classical $S+T=I$ limitation reappears!
The key-point of this article is a new—physically inspired—measure that captures both the fidelity and its robustness. It is the $p$-Wasserstein distance between the ideal fidelity distribution, a Dirac $\delta_1$ at 1, and the probability density $p_F$ of the fidelity $F$ subject to uncertainties:

$$W_p\left(p_F, \delta_1\right)$$
Conclusion?
Confront models and reality
Cold atoms in optical lattice

Bose-Hubbard

Digital Micro-mirror Device

Control of Cold atoms

HF

If not, what did we miss?

+ Hamiltonian uncertainty

∆H

Compare Consistent with ∆H, ∆F?

- Field uncertainty including Fresnel diffraction

ΔD

Classical microwave port

Addressing qubits on the pulse level

|Ψ⟩

IBM 4-qubit platform

Control of IBM qubits

|Ψ⟩

Models (rings, chains)

Heisenberg

Control of models

|Ψ⟩

Bias field D

Field uncertainty including Fresnel diffraction

ΔD

Classical optical port

Need to revise actuation device, model?

|Ψ⟩

IBM

|Ψ⟩

Cold atoms in optical lattice

|Ψ⟩

Compare

|Ψ⟩

Classical microwave port

Classical optical port

Need to revise actuation device, model?
US-UK international student research in robust control of quantum networks

- People (students, postdoc, faculty) involved
- Venue: Wales, United Kingdom
- First week program in Cardiff: spintronics control
- Second week program in Swansea: photonics
- Products
  - Classical versus quantum fundamental limitations
  - Structurally uncertain quantum network robustness
- Social (or aerospace?) activity: Wales Air show
End Second Week Program in Swansea and end of Advanced Study Institute

Red Arrows pilot reveals one key secret to not crashing into other jet planes.

In control jargon, “formation control”
The “canards” of the Eurofighter Typhoon making it supermaneuverable, but statistically unstable.
Thank you for your attention!

Questions?
Video clip of Prof. Schirmer’s statement

https://urldefense.com/v3/__https://www.youtube.com/watch?v=Mc62IEgg-mg__;!!LIr3w8kk_Xxm!oWbJWQN4N4ZP7Ufm0DQ1b-5ktcgXIMl60_ozMwknnd9hi09ejOl3PmZqELosRELBAoxGEFl-aWv2-Q$