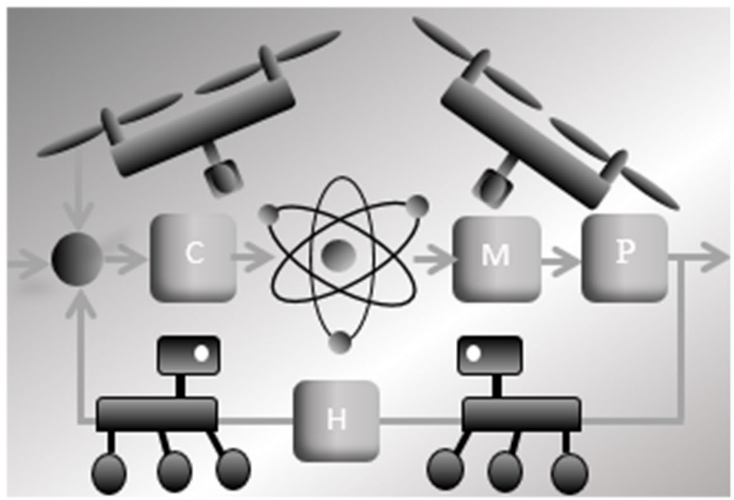
Quantum Cryptography and Quantum Entanglement for Engineering Applications

Quantum Robotics and Autonomy



Mechatronics ETM 4931 - Lecture 9

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"***Quantum Engineering*** *should be established as a new discipline or a sub-discipline in engineering schools which requires developing curricula and textbooks both at undergraduate and graduate levels*." –
THE WHITE HOUSE, NATIONAL QUANTUM COORDINATION OFFICE

"The National Science Foundation shall:
award grants for the ***establishment of Multidisciplinary Centers for Quantum Research and Education****." National Quantum Initiative Act.*

Introduction

- Rapid advances in quantum technologies such as quantum communications, sensing, computers, and algorithms demand for:
  - Training engineers in quantum technologies, and prepare them for their future careers
  - The integration of quantum technologies with classical mechanical systems will be inevitable

- Our research proposes to extend the mechatronics course beyond traditional engineering topics

Some light quantum mechanics (with minutephysics)
https://www.youtube.com/watch?v=MzRCDLre1b4

Quantum Technologies

(Complementary to quantum computing/computers/devices)

- Research (Quantum/Classical Integration is inevitable)

Integration of the quantum technologies such as quantum communication with mechatronics/robotics/autonomous systems.

- Education

- Photon Quantum Mechanics (Experimental quantum entanglement, cryptography, teleportation, etc.)

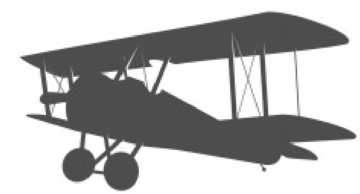
- Integration of Quantum Communication and Autonomous Systems for control

Quantum Engineering

- Experimental Quantum Entanglement
- Experimental Quantum Cryptography
- Quantum Teleportation (for communication)
- Quantum technologies for robotics and autonomy applications

Mechanical Systems + Classical Computers

Mechanical Systems



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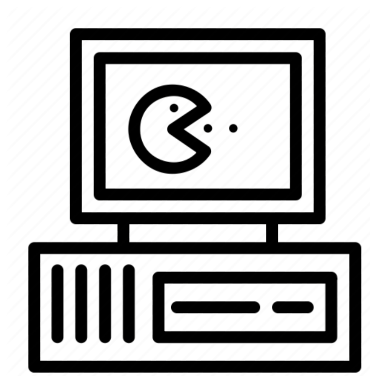
Classical Computers/Technologies



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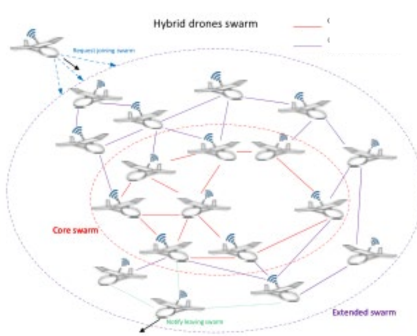
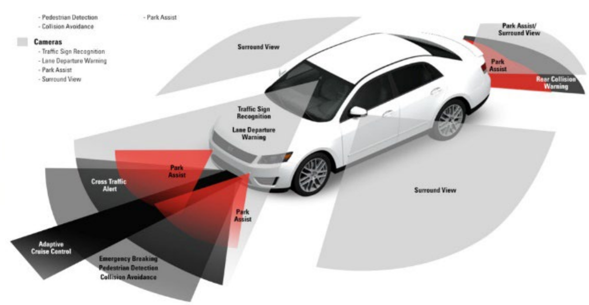
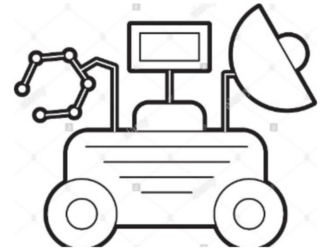
The State of the art





Mechanical Systems + Quantum Technologies

Mechanical Systems



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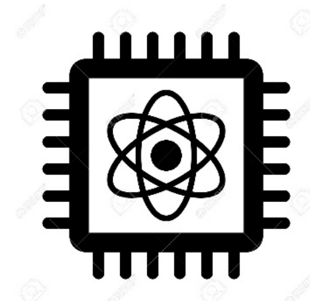
Quantum Computers/Technologies



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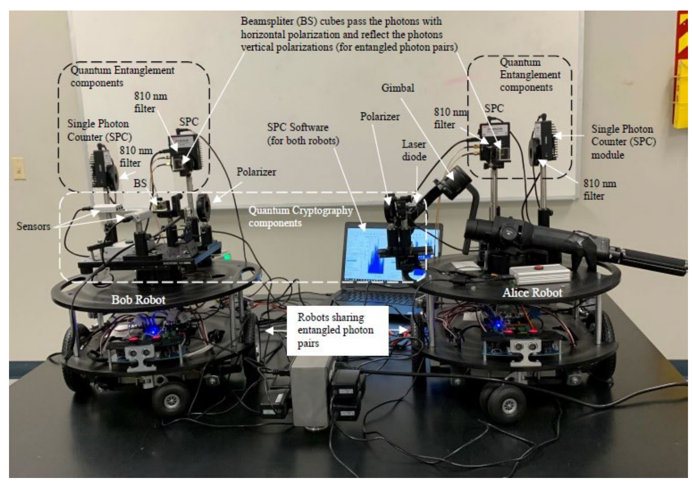
Quantum Robotics and Autonomy (e.g., The Alice and Bob Robots)



We coined the term "Quantum Robotics"

Wikipedia
The Free Encyclopedia

Search Wikipedia | Search

Create account Log in •••

Quantum robotics

Add languages

Contents hide

Article Talk

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From Wikipedia, the free encyclopedia

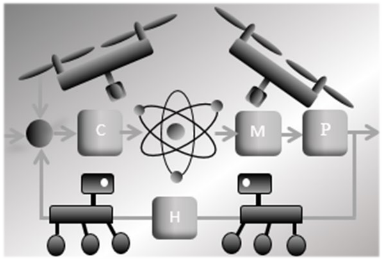
Quantum robotics is an interdisciplinary field that investigates the intersection of robotics and quantum mechanics. This field, in particular, explores the applications of quantum phenomena such as quantum entanglement within the realm of robotics. Examples of its applications include quantum communication in multi-agent cooperative robotic scenarios, the use of quantum algorithms in performing robotics tasks, and the integration of quantum devices (e.g., quantum detectors) in robotic systems.[1][2][3][4][5][6][7]

Alice and Bob Robots [edit]

In the realm of quantum mechanics, the names Alice and Bob are frequently employed to illustrate various phenomena, protocols, and applications. These include their roles in quantum cryptography, quantum key distribution, quantum entanglement, and quantum teleportation. The terms "Alice Robot" and "Bob Robot"[1][2][3][4][5][7] serve as analogous expressions that merge the concepts of Alice and Bob from quantum mechanics with mechatronic mobile platforms (such as robots, drones, and autonomous vehicles). For example, the Alice Robot functions as a transmitter platform that communicates with the Bob Robot, housing the receiving detectors.

References [edit]

1. ^ a b Farbod Khoshnoud, Lucas Lamata, Clarence W. De Silva, Marco B. Quadrelli, Quantum Teleportation for Control of Dynamic Systems and Autonomy, Journal of Mechatronic Systems and Control, Volume 49, Issue 3, pp. 124-131, 2021.
2. ^ a b Lamata, Lucas; Quadrelli, Marco B.; de Silva, Clarence W.; Kumar, Prem; Kanter, Gregory S.; Ghazinejad, Maziar; Khoshnoud, Farbod (12



Quantum Technologies in mechanical systems domain

– Drone-to-Drone Quantum Key distribution (Kwiat, P., et al., 2017).

The aim is to enhance quantum capability (not mechanical systems).

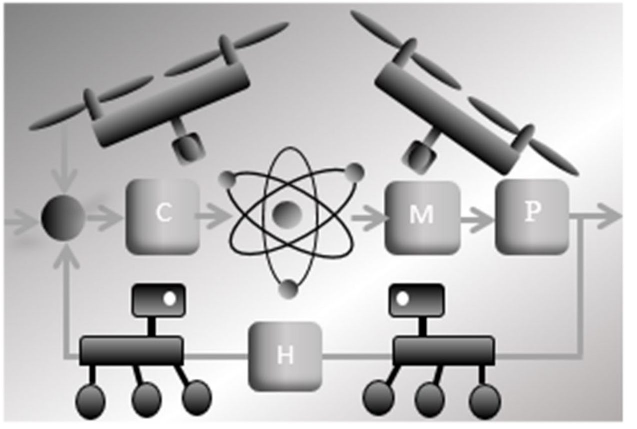
– Space and underwater Quantum Communications (various references)

The aim is enhancing communication not mechanical systems.

– "Quantum Robotics and Autonomy" (Khoshnoud, F., de Silva, C.W., Quadrelli, M.B., Esat, I.I., et al., 2019: https://arxiv.org/search/?query=khoshnoud&searchtype=all&source=header)

– More recently various attempts has been carried out on quantum communications for UAVs.

Introduction
Quantum in Engineering Education



- Preparing for the quantum revolution -- what is the role of higher education? (Michael F. J. Fox, Benjamin M. Zwickl, H. J. Lewandowski, 2020)

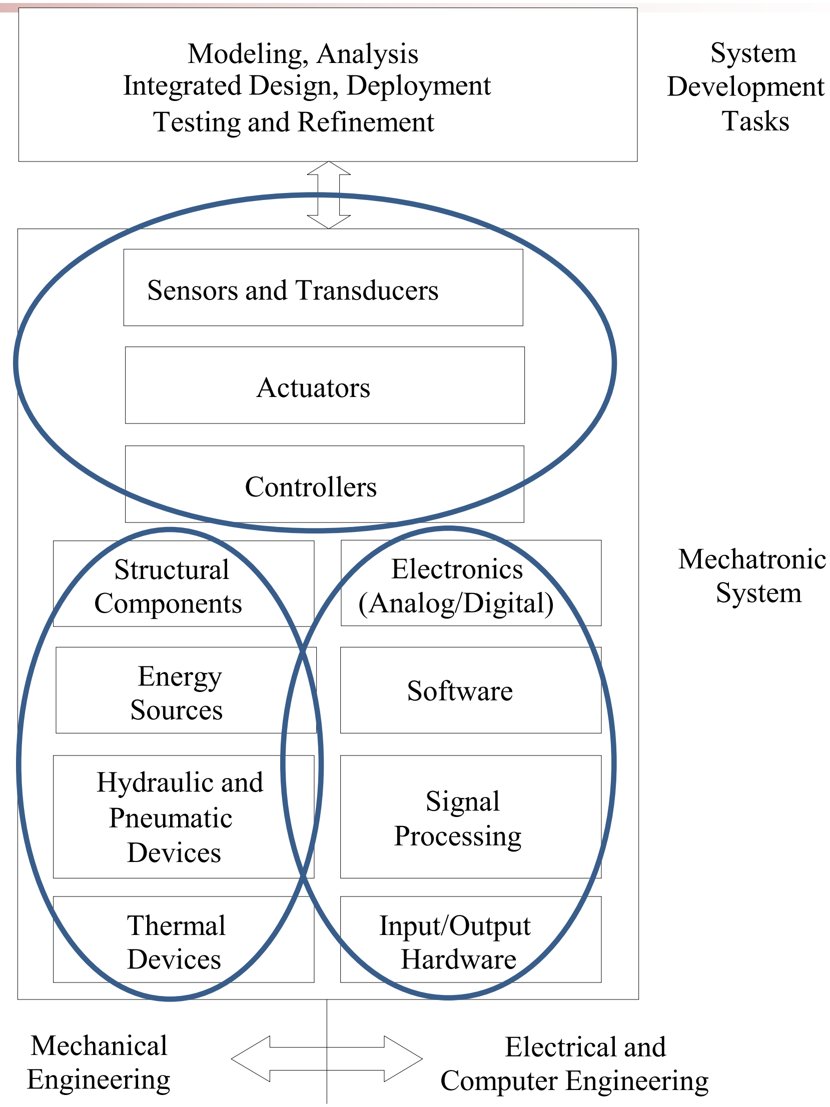
(https://arxiv.org/abs/2006.16444)

- Achieving a quantum smart workforce (Clarice D. Aiello, et. al., 2020)

(https://arxiv.org/abs/2010.13778)

Mechatronics

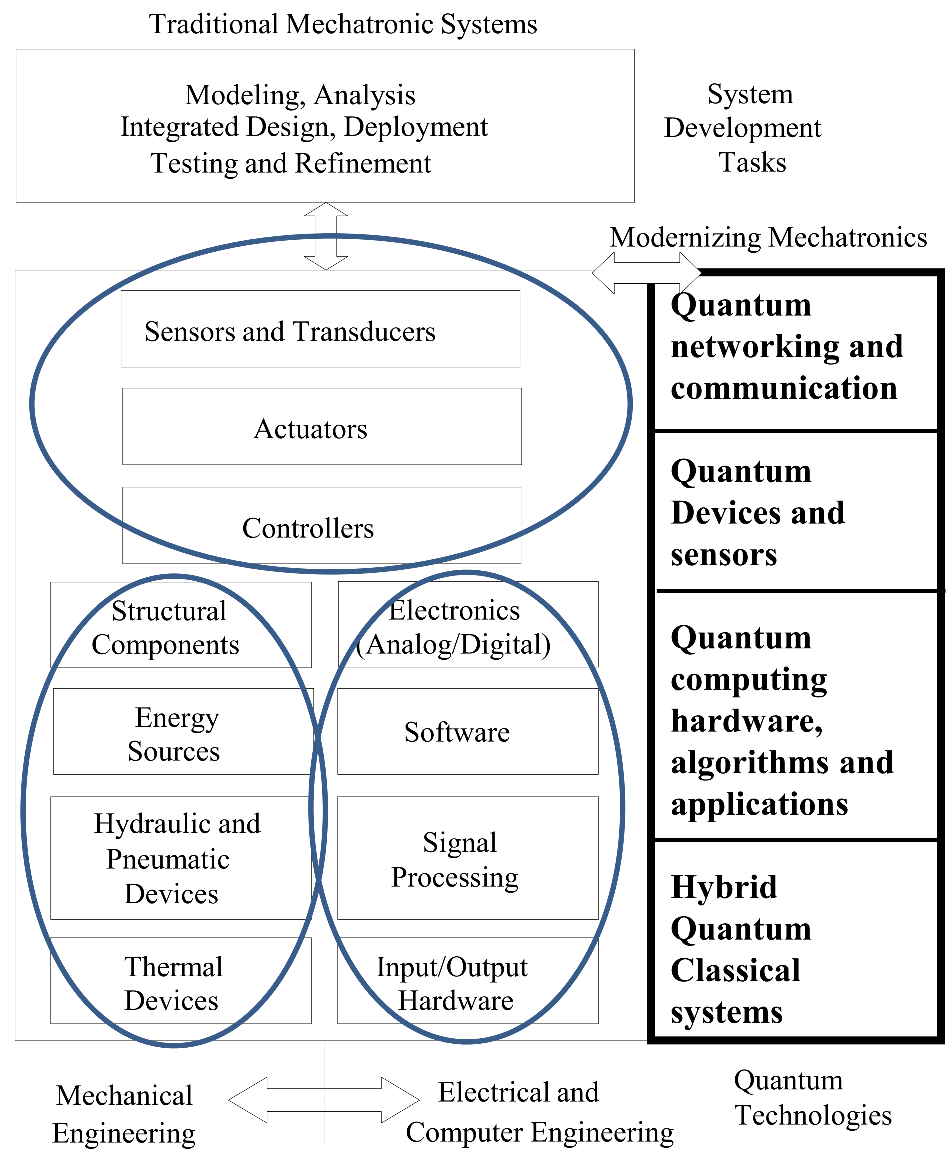
- **Synergistic** application of mechanics, electronics, control engineering, and computer science in the development of **electromechanical** products and systems, through **integrated design**.



Reference (with permission): http://www.sites.mech.ubc.ca/~ial//MECH550X/

Modernized Mechatronics

- **Synergistic** application of mechanics, electronics, control engineering, computer science, and **Quantum Technologies** in the development of **electromechanical** products and systems, through **integrated design**.



Reference:
Farbod Khoshnoud, Clarence W. de Silva (UBC), Marco B. Quadrelli (JPL), Lucas Lamata (Seville), Behnam Bahr, Clarice D. Aiello (UCLA), Sanjay Padhi (Amazon), Ibrahim I. Esat (Brunel), Maziar Ghazinejad (UCSD), **Modernizing Mechatronics course with Quantum Engineering**, *American Society for Engineering Education PSW 2021 Conference*, April 23-25, 2021, Virtual conference hosted by UC Davis, CA, Paper ID # 35205. [PDF]

Quantum topics that could be included in mechatronics

Categories of activities based on the responses from interview study, public websites, and the literature on the quantum industry

(Michael F. J. Fox, Benjamin M. Zwickl, H. J. Lewandowski, 2020)

- Quantum sensor technologies

a quantum clock, magnetometer, gravimeter, or accelerometer, with higher precision compared to equivalent classical sensors.

- Quantum networking and communication technologies

quantum-key distribution technologies, entangled state distribution, and quantum teleportation.

- Quantum computing hardware or quantum computers, as well as using classical software to simulate a quantum computer.

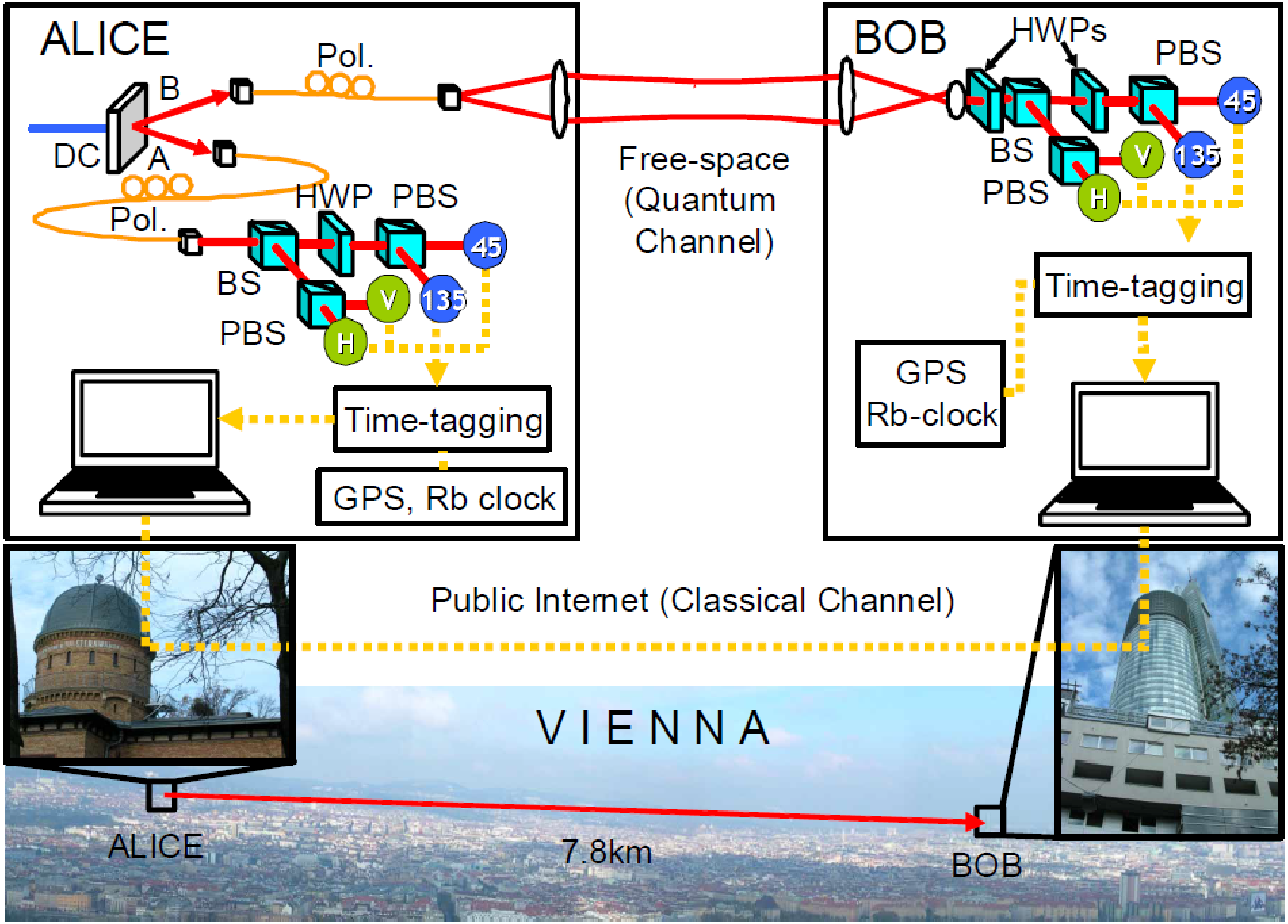
- Quantum algorithms based on investigations and solving computational problems faster than classical computer algorithms.

Quantum Technologies

- Quantum sensors: sensor, such as a clock, magnetometer, gravimeter, or accelerometer, that has improved precision, compared to existing technology, by taking advantage of the ability to finely control the quantum states of the system, while still being able to be used for commercial applications.
- Quantum networking and communication: quantum-key distribution technologies or software, or is engaged in the development of hardware technologies to distribute entangled states, and quantum teleportation.
- Quantum computing hardware: building a quantum computer using any one of many different hardware approaches, such as: superconducting, trapped-ion, or photonic qubits. Additionally, this includes the software development required for the hardware to operate, including, but not necessarily, all the way to a full-stack provision of quantum programming languages to end users who want to run their own quantum algorithms. At the current time, these technologies may also be developing software to simulate the operation of a quantum computer on a classical machine.
- Quantum algorithms and applications: taking a real-world problem and apply knowledge of quantum computation to that problem in an attempt solve it, or at least to demonstrate that it is possible to solve, with the goal of achieving a solution faster than a classical computer.

Preparing for the quantum revolution -- what is the role of higher education? (https://arxiv.org/abs/2006.16444)

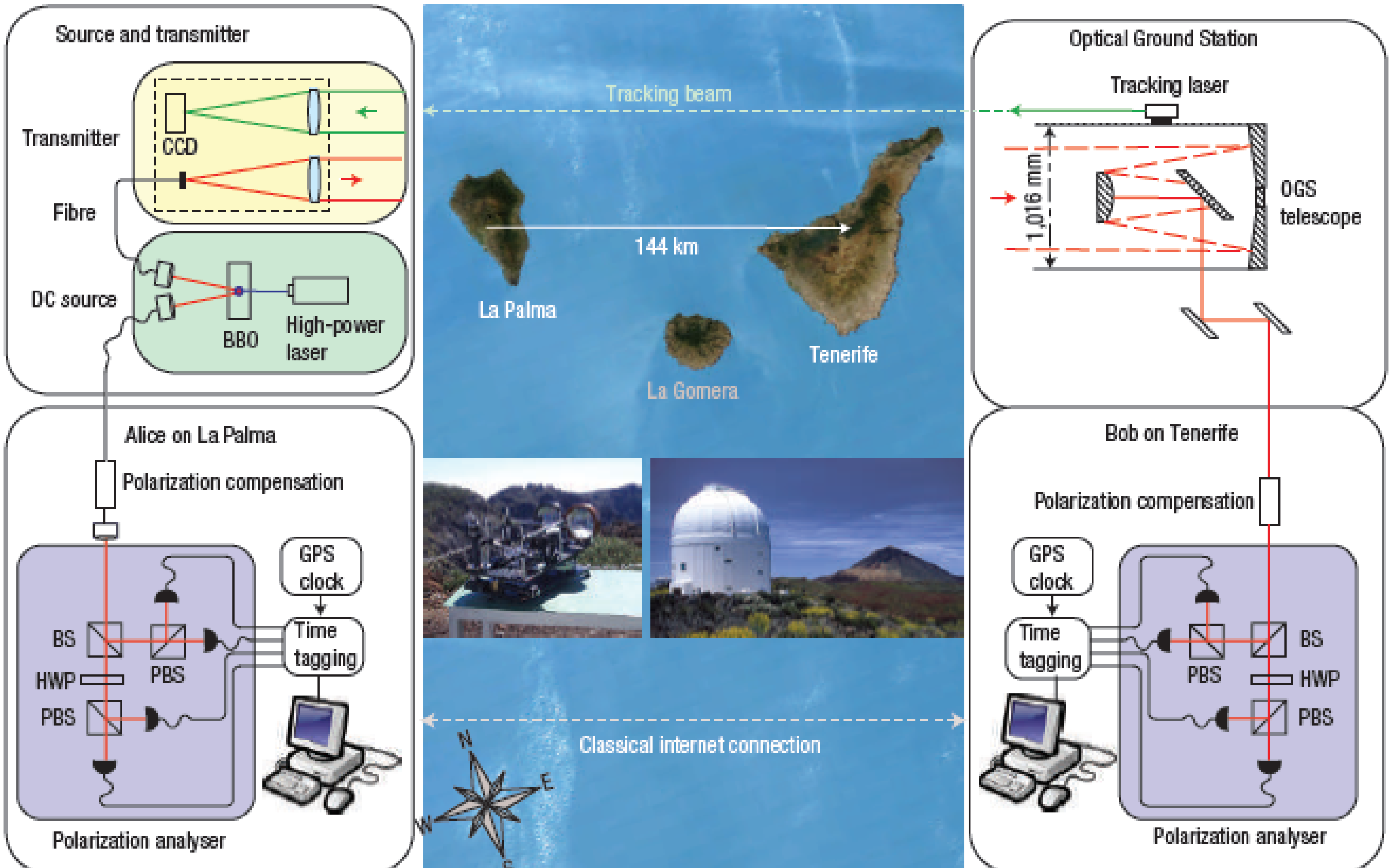
Free-space entanglement distribution



The layout for free-space entanglement distribution in Vienna.

Ref: K. Resch, M. Lindenthal, B. Blauensteiner, et. al, *Distributing entanglement and single photons through an intra-city, free-space quantum channel*, Opt. Express 13, 202-209 (2005).

Entanglement-based quantum communication



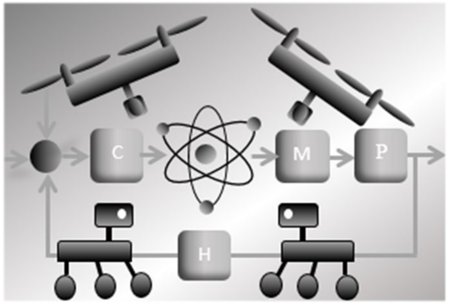
The free-space link between the Canary Islands La Palma and Tenerife in a picture taken from a satellite. Polarization-entangled photon pairs were produced in a type-II parametric down-conversion (DC) source by pumping a β-barium-borate crystal (BBO) with a high-power ultraviolet laser. One photon was measured locally on La Palma; the other one was sent through a 15 cm transceiver lens over the 144 km free-space optical link to the 1m mirror telescope of the (OGS) on the island of Tenerife.

Ref: Ursin, R., Tiefenbacher, F., Schmitt-Manderbach, T. et al*. Entanglement-based quantum communication over 144 km*. Nature Phys **3,** 481–486 (2007).

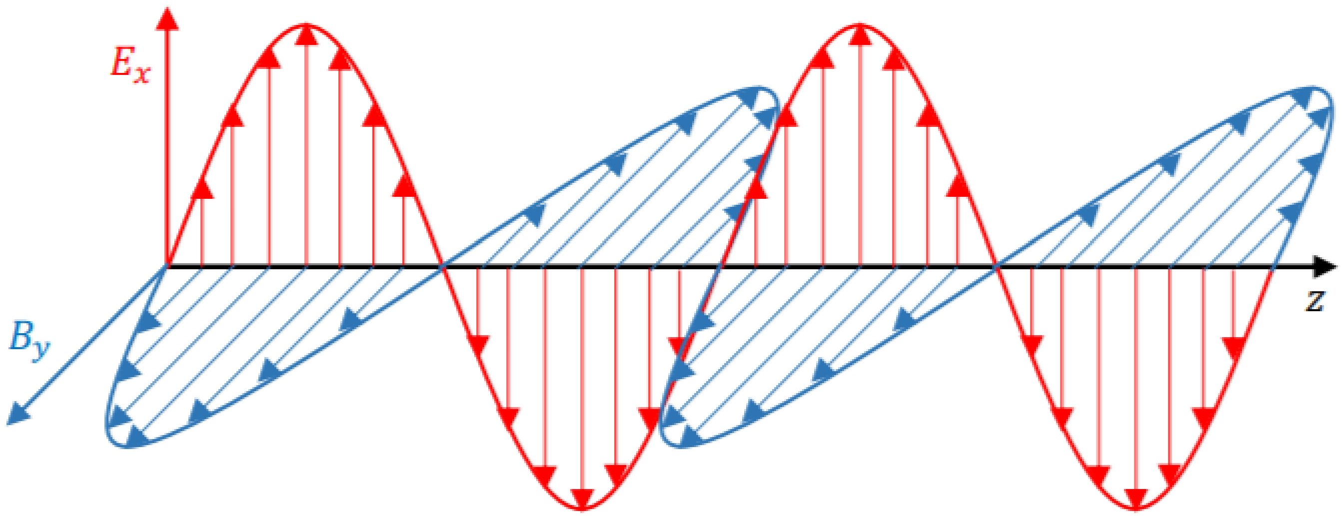
Integration of quantum technologies in mechanical systems is inevitable

- How the quantum technologies are integrated to mechanical systems (e.g., robots, autonomous systems)
  - when quantum technologies/computers become available in a multi-agent robotic system

- Hybrid quantum-classical technologies for autonomous systems
  - quantum is useful for solving some problems and classical for others



Photon Quantum Mechanics



Electromagnetic wave

V: Vertical Polarization

H: Horizontal Polarization

Polarization of light:

https://www.youtube.com/watch?v=6_C8KyU67RU

Quantum Entanglement Lab - by Scientific American:

https://www.youtube.com/watch?v=Z34ugMy1QaA&t=

Resources

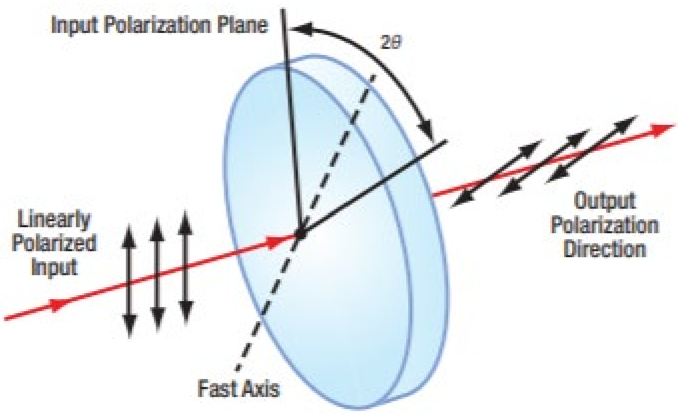
Electromagnetic Waves:
https://ophysics.com/em3.html

Polarization of an Optical Wave through Polarizers and Wave Plates:
https://demonstrations.wolfram.com/PolarizationOfAnOpticalWaveThroughPolarizersAndWavePlates/

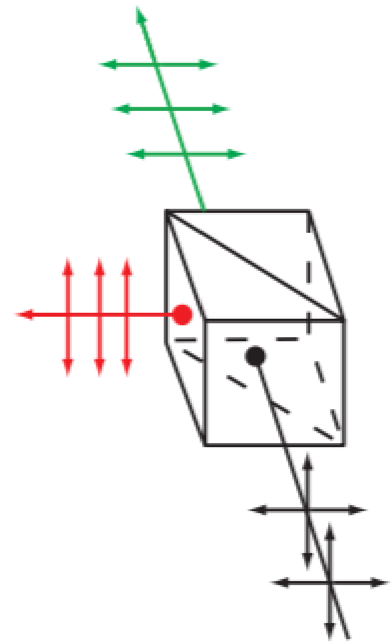
Polarizing beamsplitter cube:
https://www.youtube.com/watch?v=9RLQnQMdqX0 (2m 53s)

Parametric Down-Conversion Process Barium borate (BBO) Crystal:
https://qutools.com/spdc-animated-source/

Half-wave plates and Polarizing beamsplitters



A half-wave Plate



A Polarizing beamsplitter cube

Ref: Thorlabs:
https://www.thorlabs.com/drawings/7dc1a0a51f66aa9b-610D055E-0A11-1562-E8F38E3EDDF533AA/EDU-QCRY1_M-EnglishManual.pdf

Parametric Down Conversion Process
Barium borate (BBO) Crystal

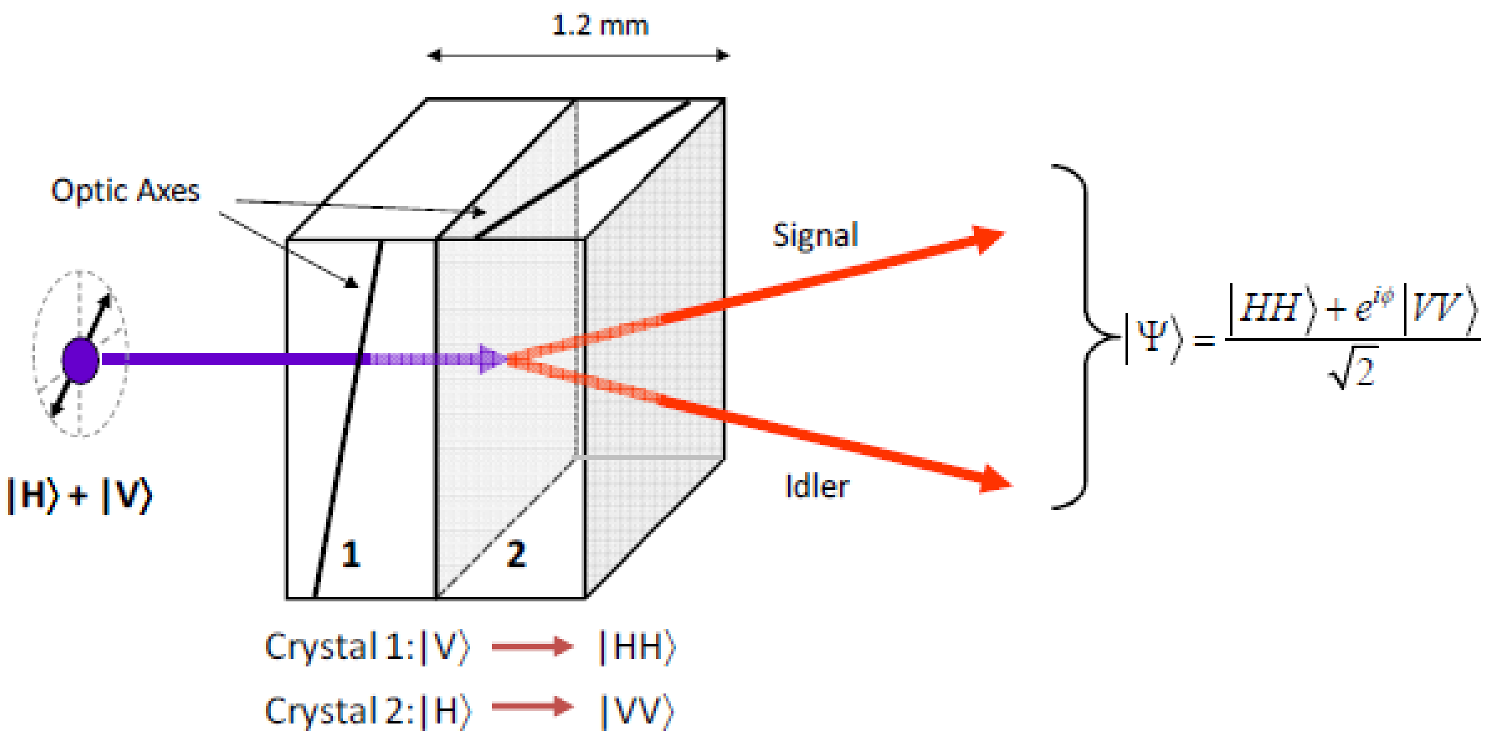
- Parametric Down Conversion Visualization

https://www.youtube.com/watch?v=5Iv6dJD4q4A

- One Photon In, TWO Photons Out

https://www.youtube.com/watch?v=1MaOqvnkBxk

Parametric Down-Conversion Process Barium borate (BBO) Crystal



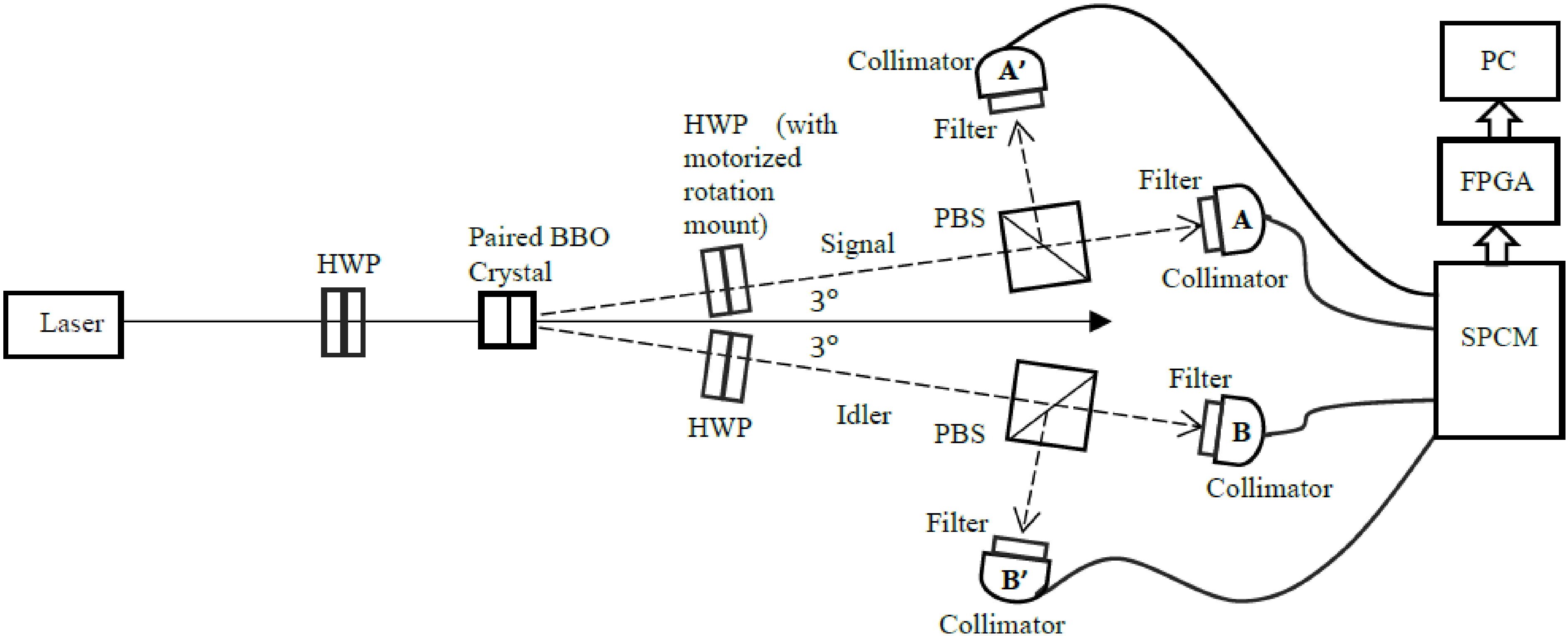
V: Vertical Polarization

H: Horizontal Polarization

R. Rangarajan, M. Goggin, and P. Kwiat, Optimizing type-I polarization-entangled photons, Opt. Express 17, 18920-18933 (2009).

Quantum Entanglement Experiment

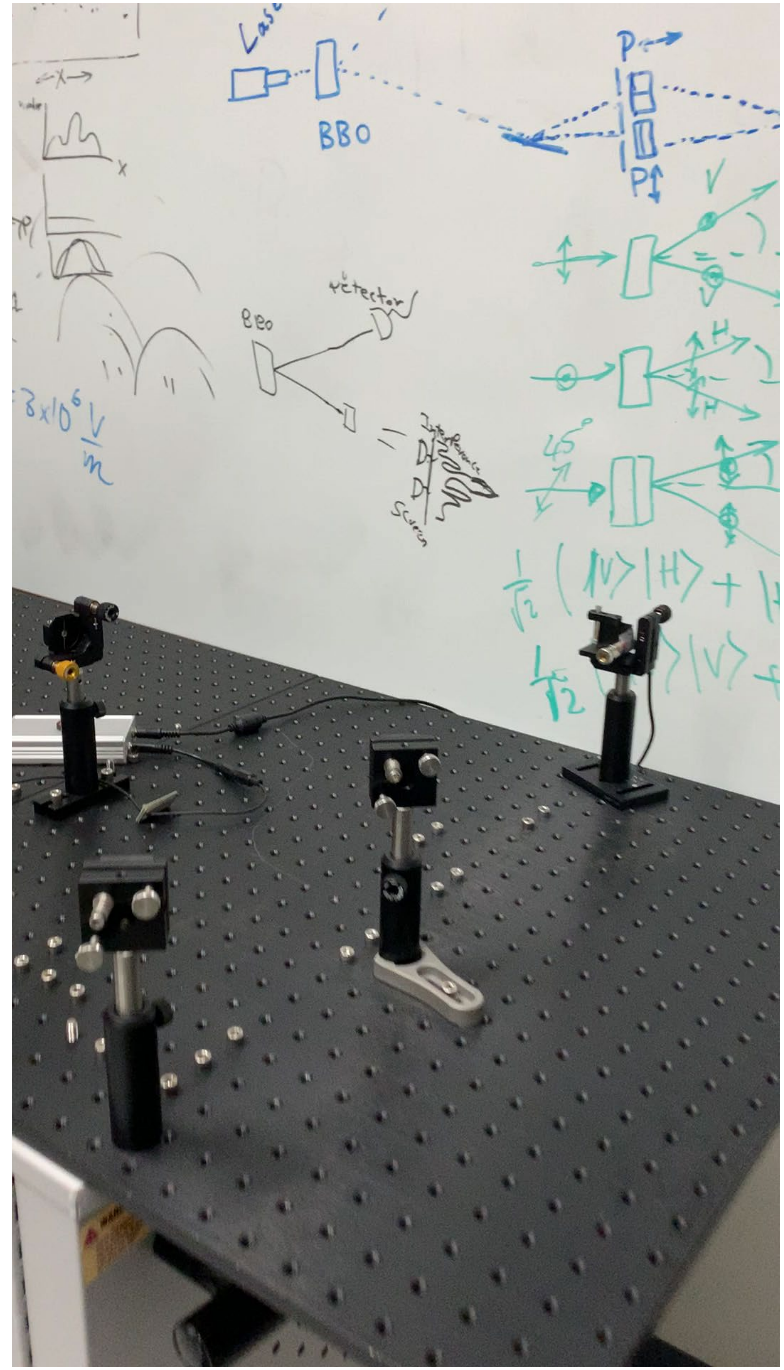
Spontaneous parametric down-conversion (SPDC)



Information about the set up is available in Section 2.1 in “Quantum Teleportation for Control of Dynamic Systems and Autonomy”:
https://arxiv.org/ftp/arxiv/papers/2007/2007.15249.pdf

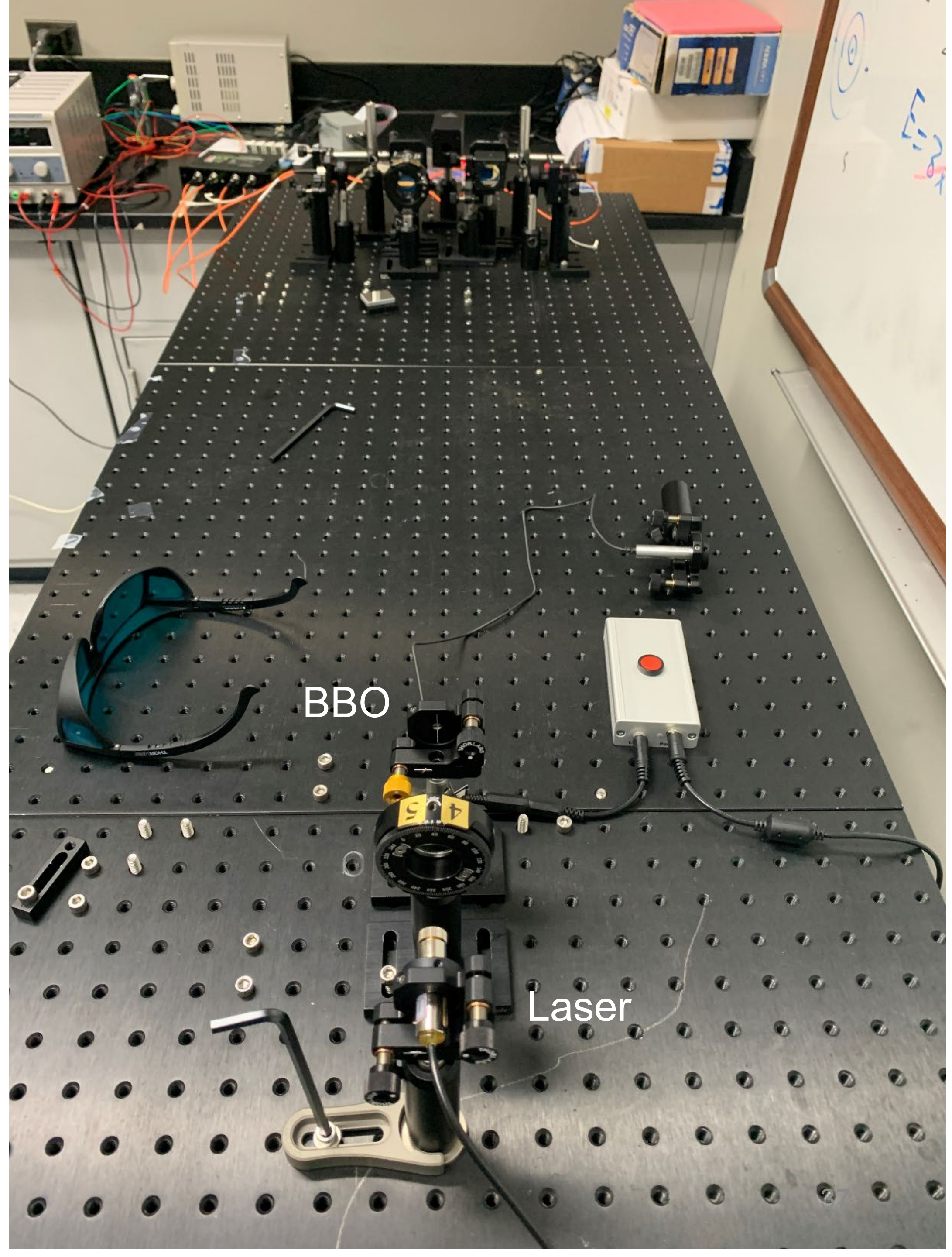
References on “Quantum Robotics and Autonomy”:
https://arxiv.org/search/?query=khoshnoud&searchtype=all&source=header

An overview of the Quantum Entanglement Experimental Setup



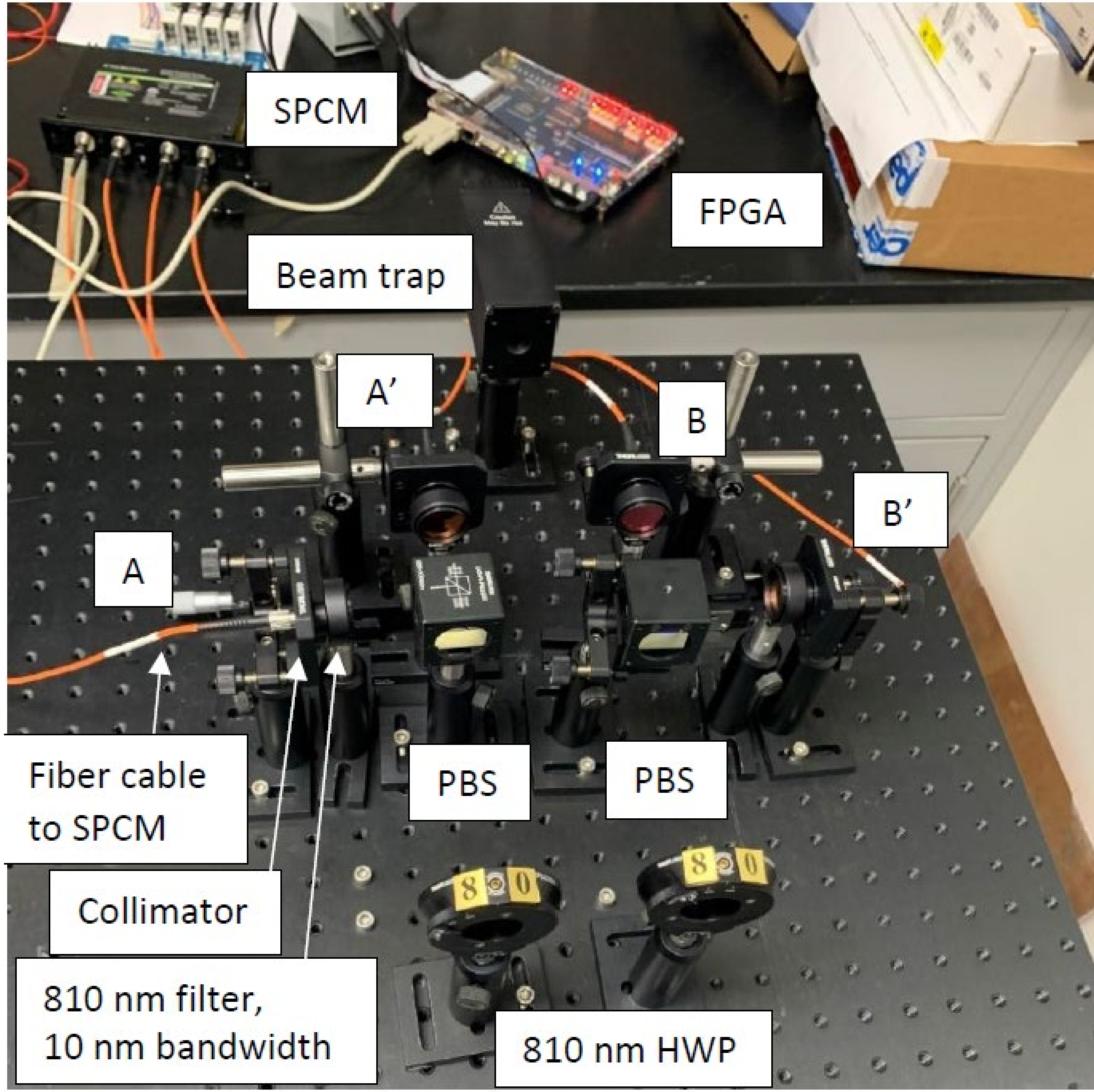
Experimental setup

Quantum Entanglement

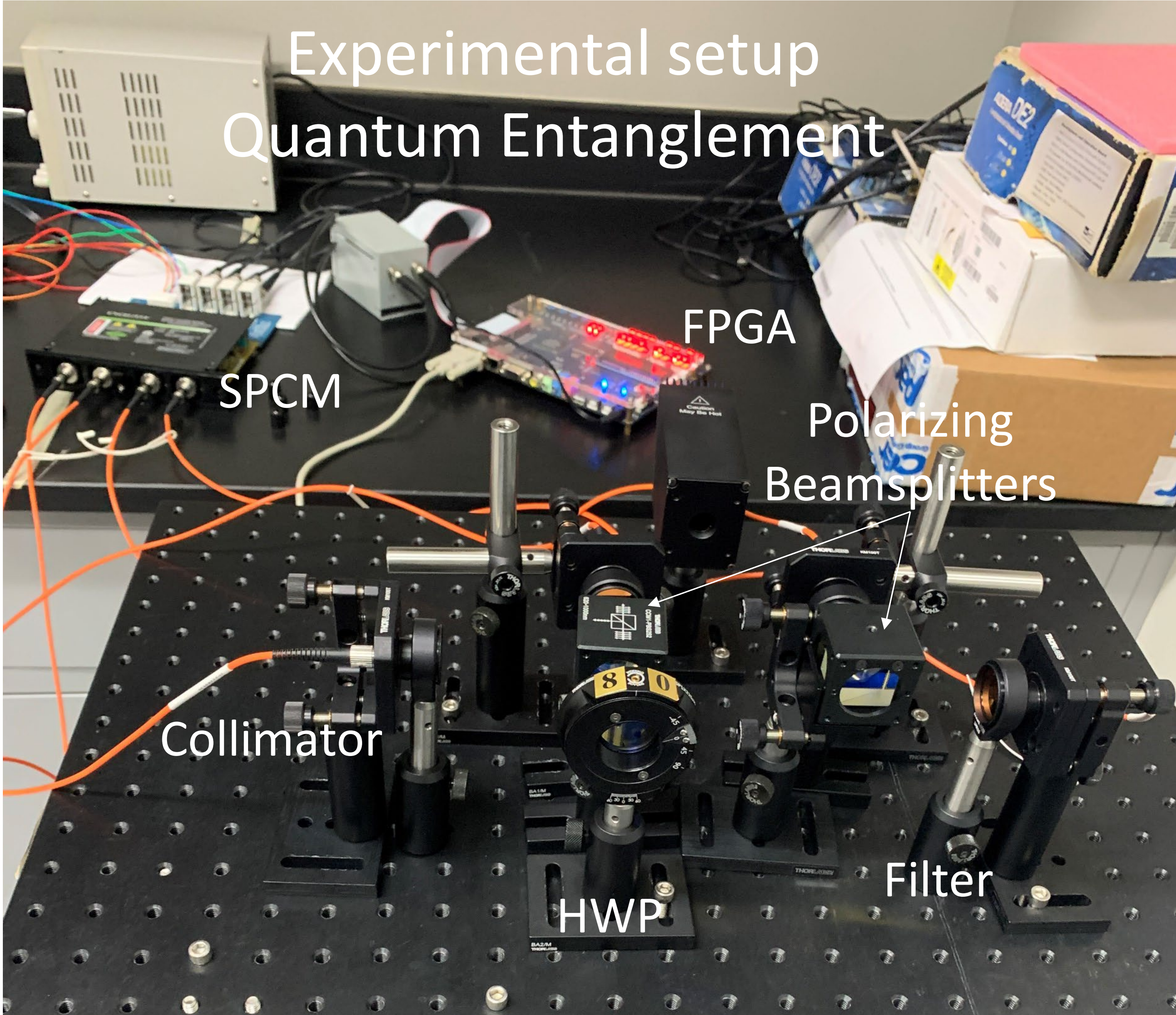


Experimental setup

Quantum Entanglement

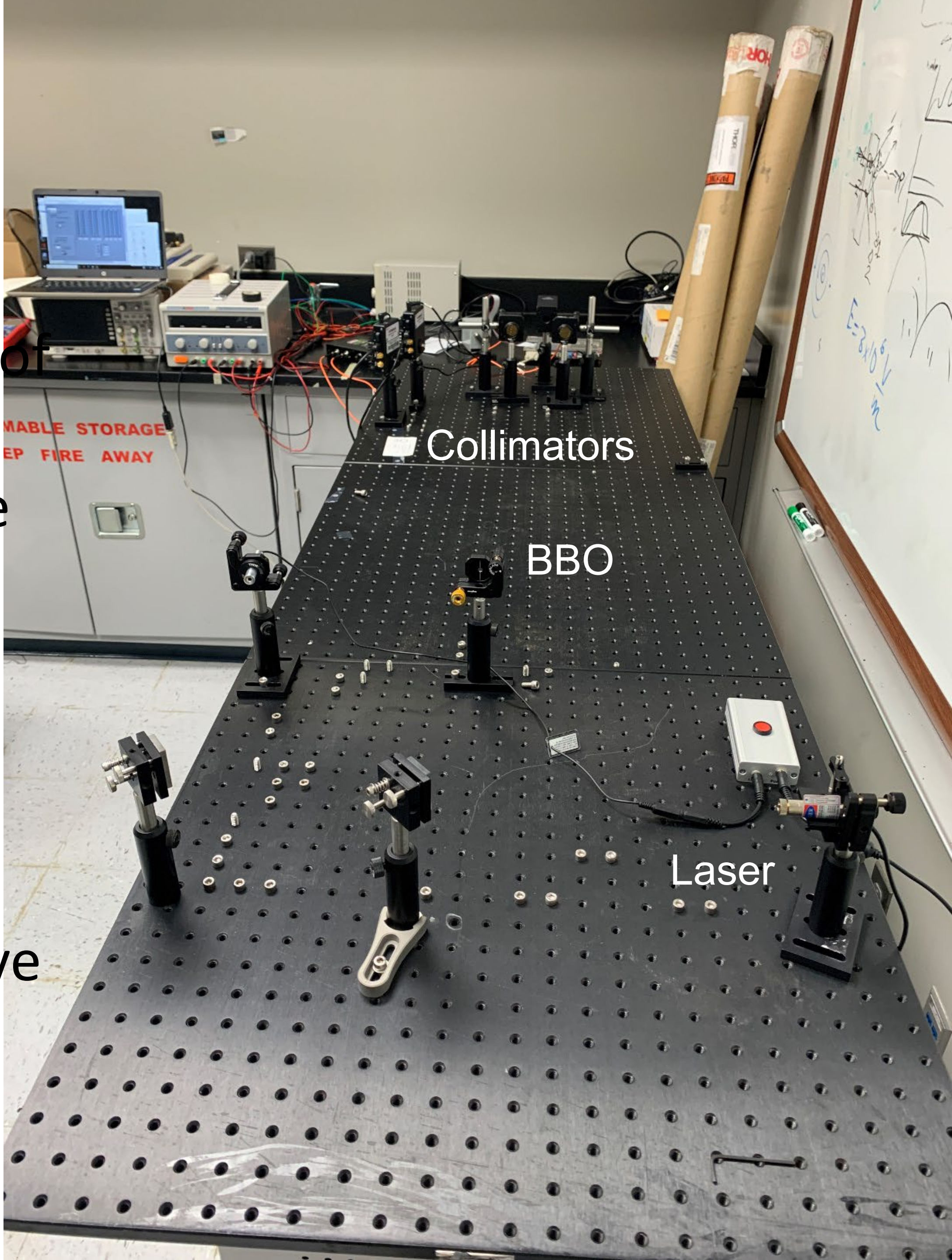


Experimental setup
Quantum Entanglement

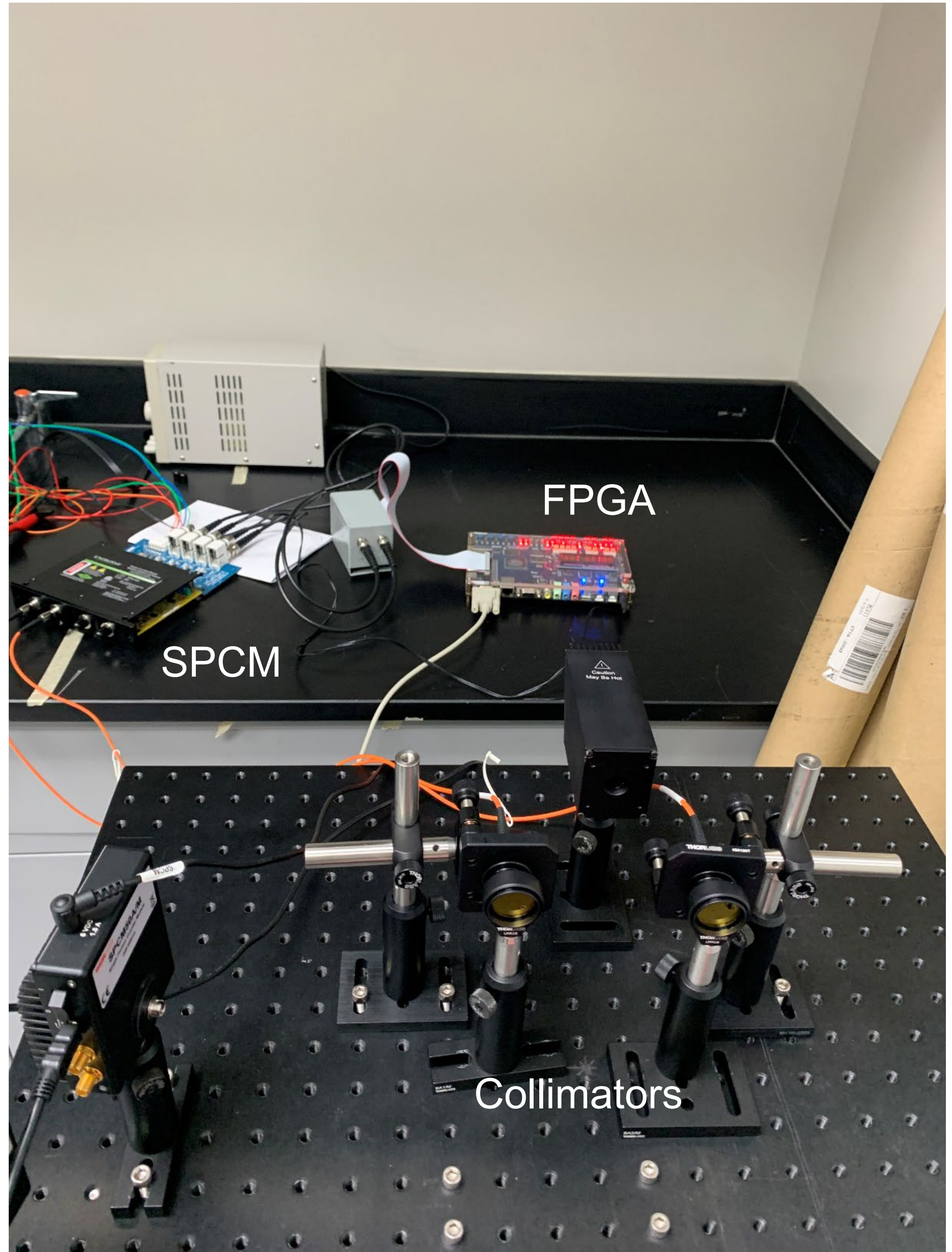


The setup:

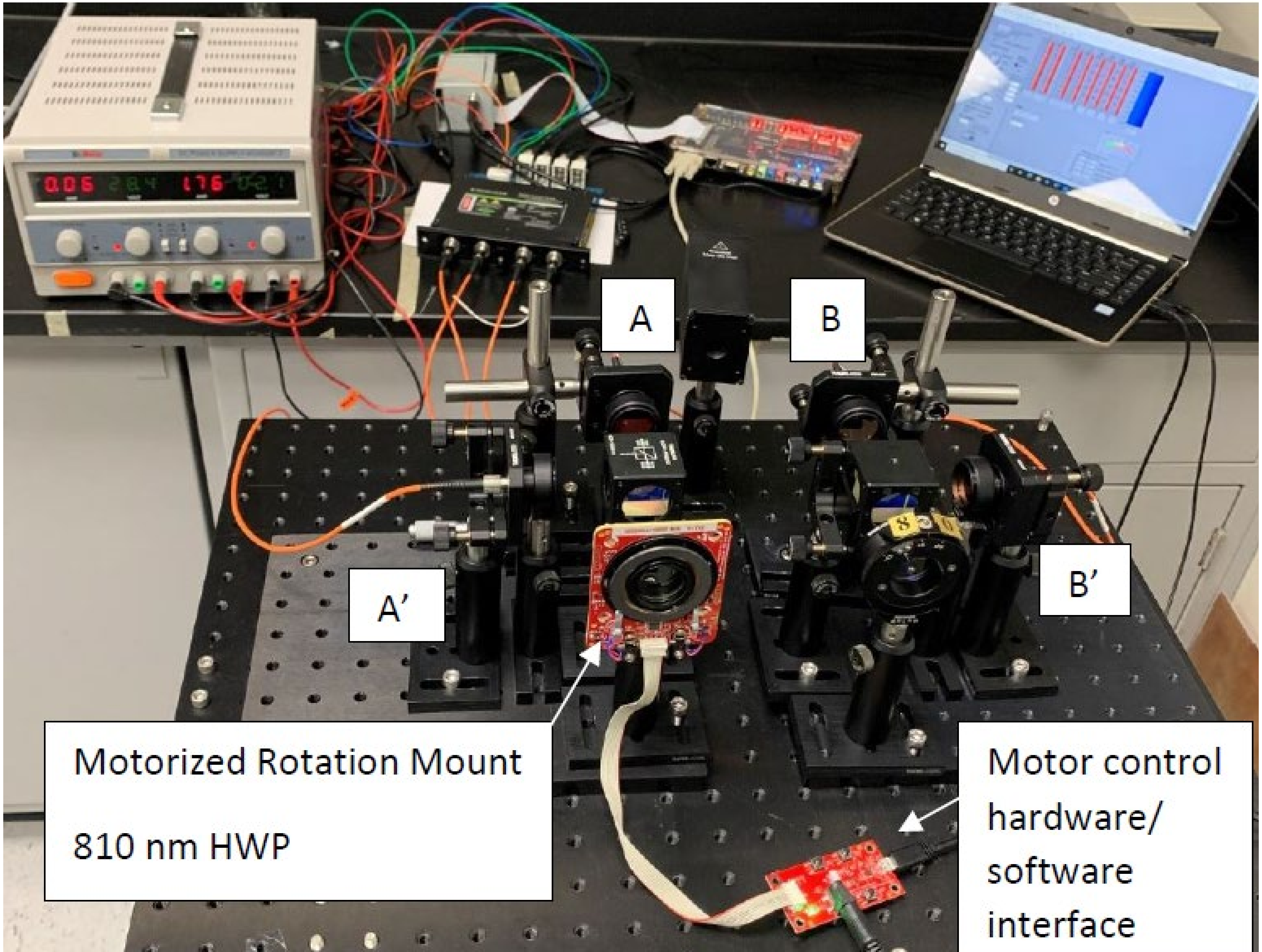
- 405 nm 100 mW Laser
- A BBO crystal
- Two 810 nm filters in front of two Collimators
- Fiber optic cables (from the collimators to the SPCM)
- A Single Photon Counter Module (SPCM-AQ4C)
- FPGA (used as a photon coincidence counter)
- LabView program (to receive and show the data)



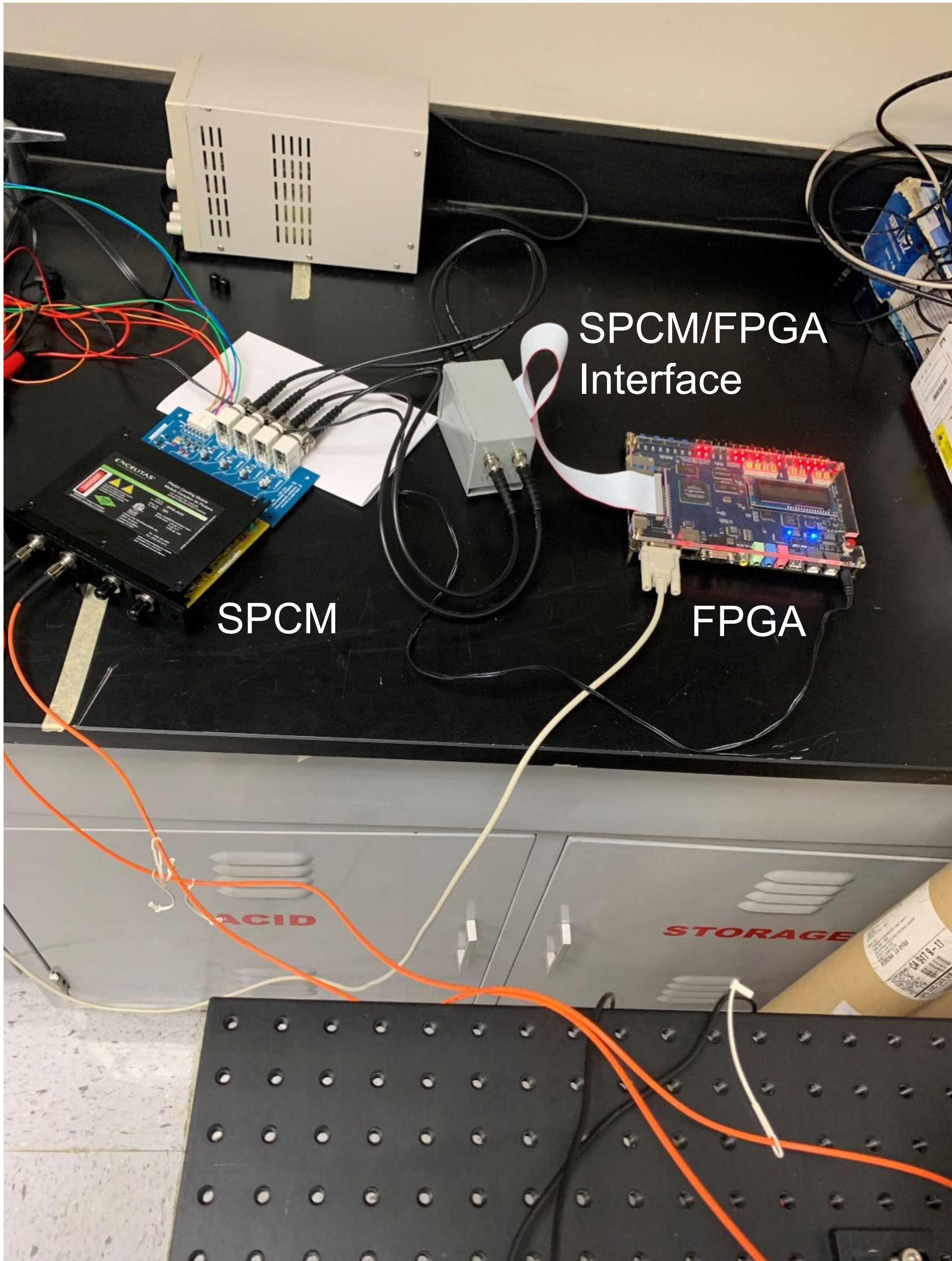
The setup:
Two 810 nm filters in front of two Collimators , Fiber optic cables (from the collimators to the SPCM), a Single Photon Counter Module (SPCM-AQ4C), FPGA (used as a photon coincidence counter), LabView program (to receive and show the data)

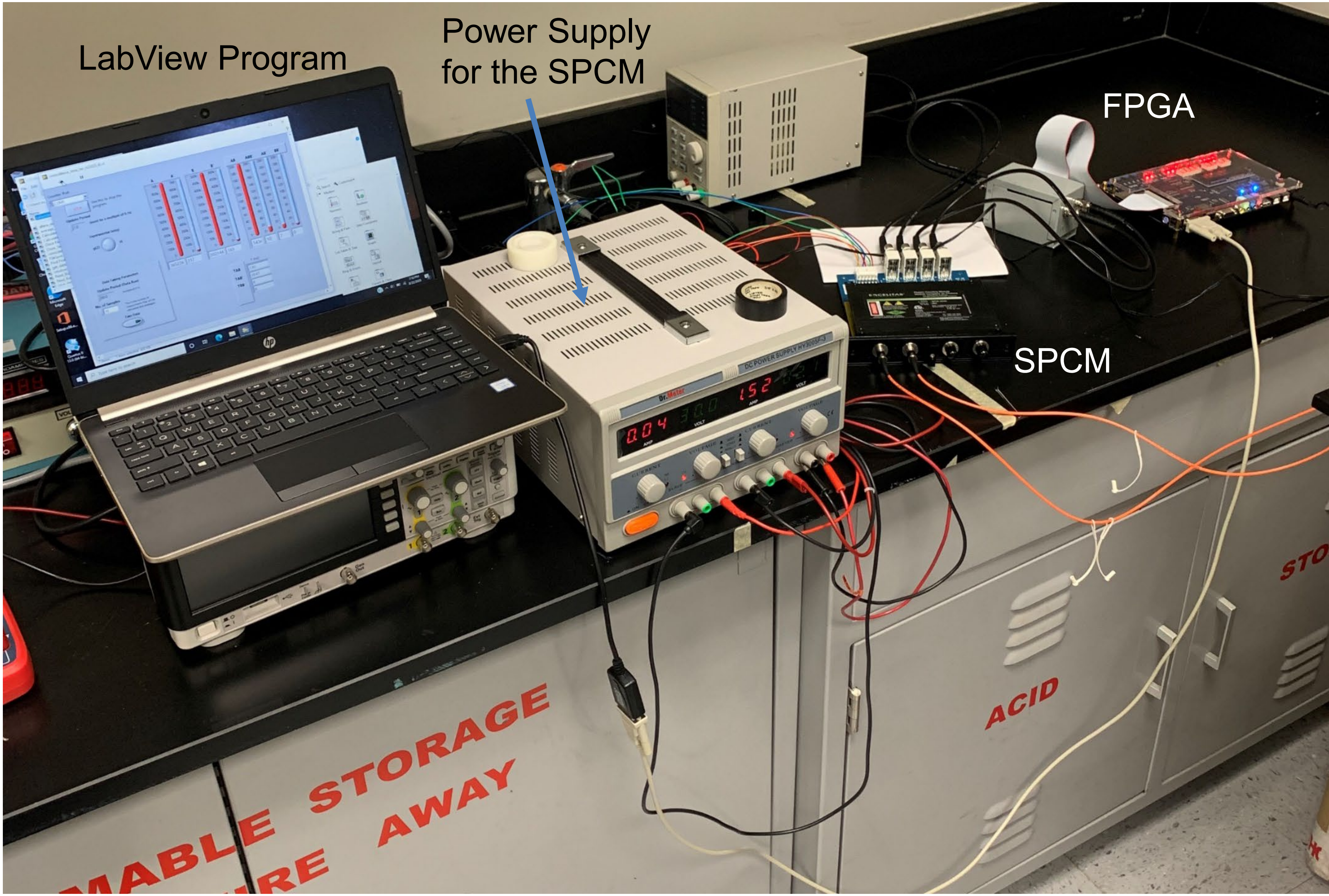


Remote Hands-on Learn-by-doing

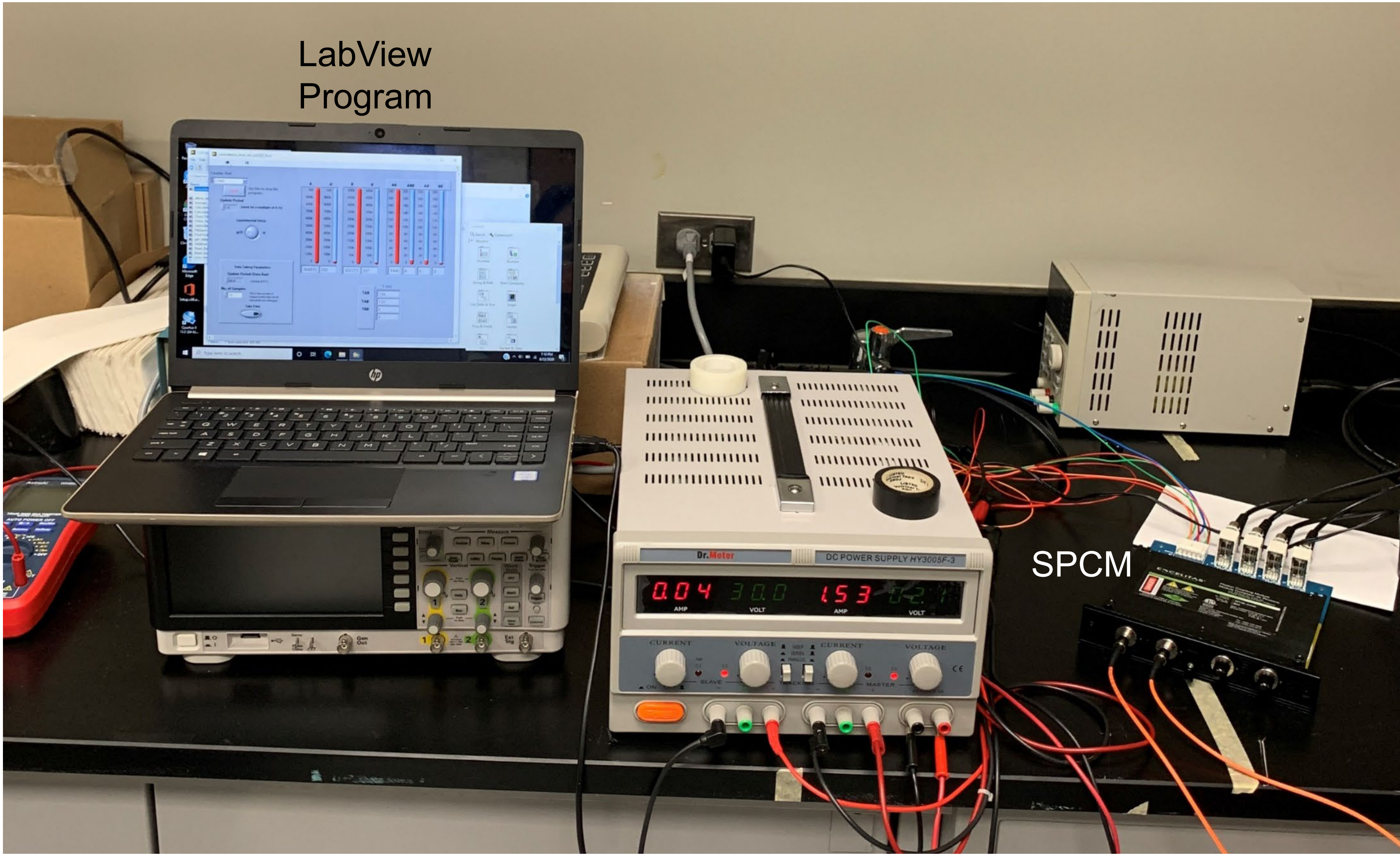


The setup:
A Single Photon Counter Module (SPCM-AQ4C), FPGA (used as a photon coincidence counter)





Labview and FPGA setup by Mark Beck (http://people.reed.edu/~beckm/QM/)



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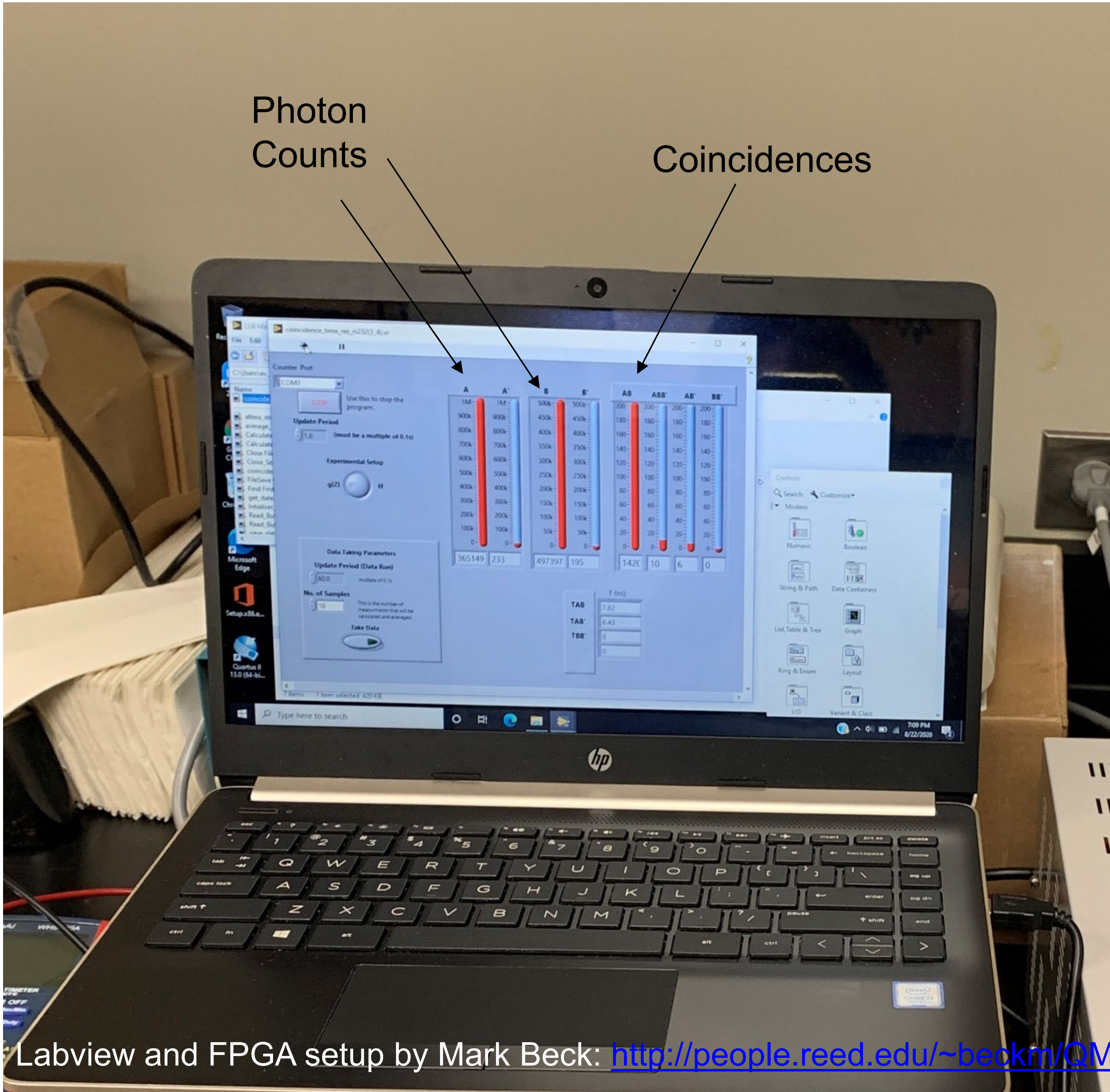
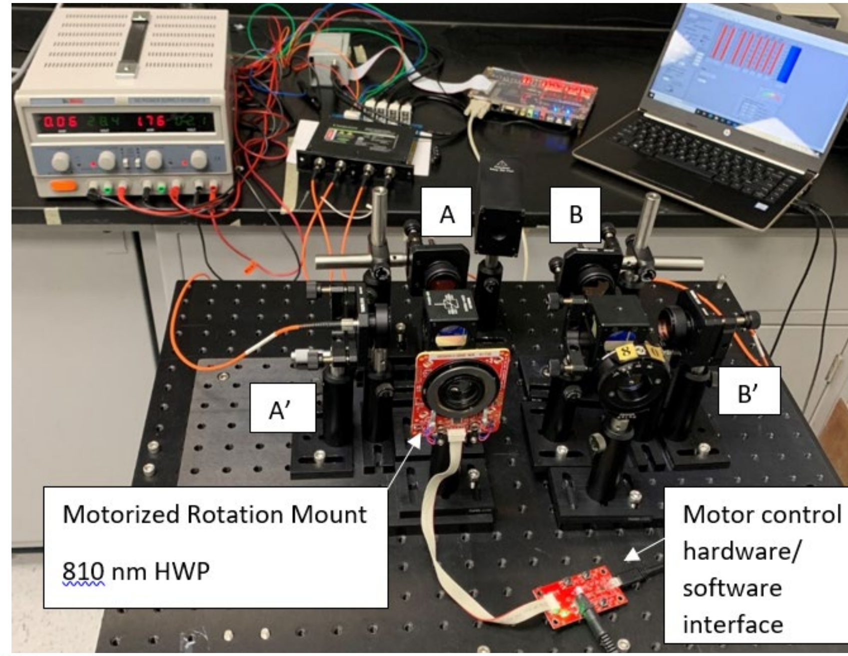


Labview and FPGA setup by Mark Beck: http://people.reed.edu/~beckm/QM/

Quantum Entanglement Experimental Results

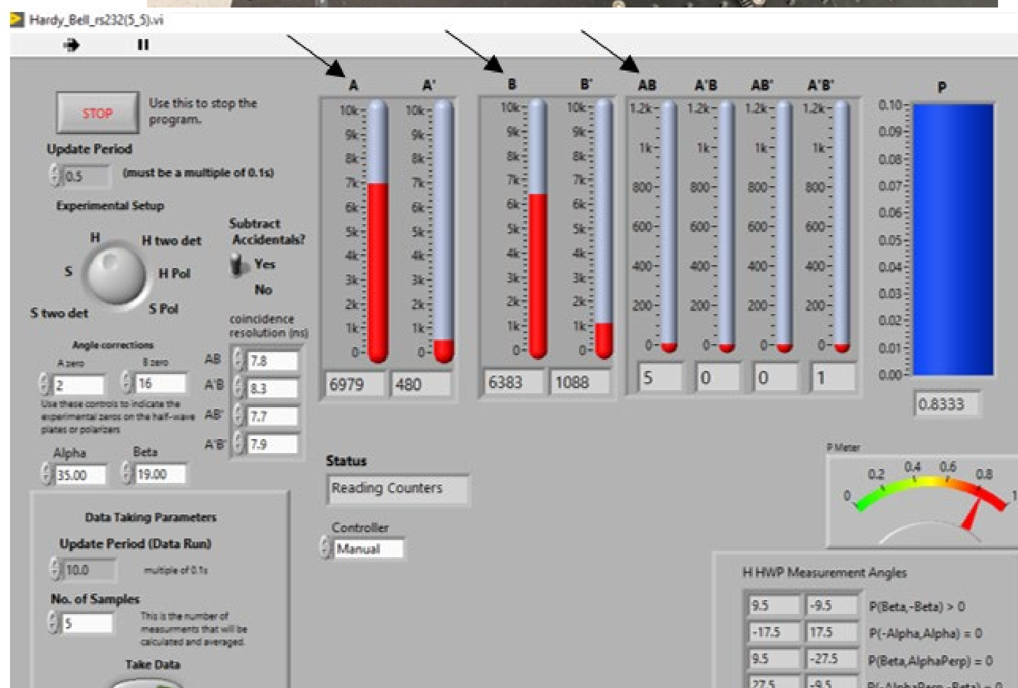


Alice (A, A’): $|H\rangle_A$ and $|V\rangle_A$

Bob (B, B’): $|H\rangle_B$ and $|V\rangle_B$

Coincidences AB, A’B, AB’, A’B’:

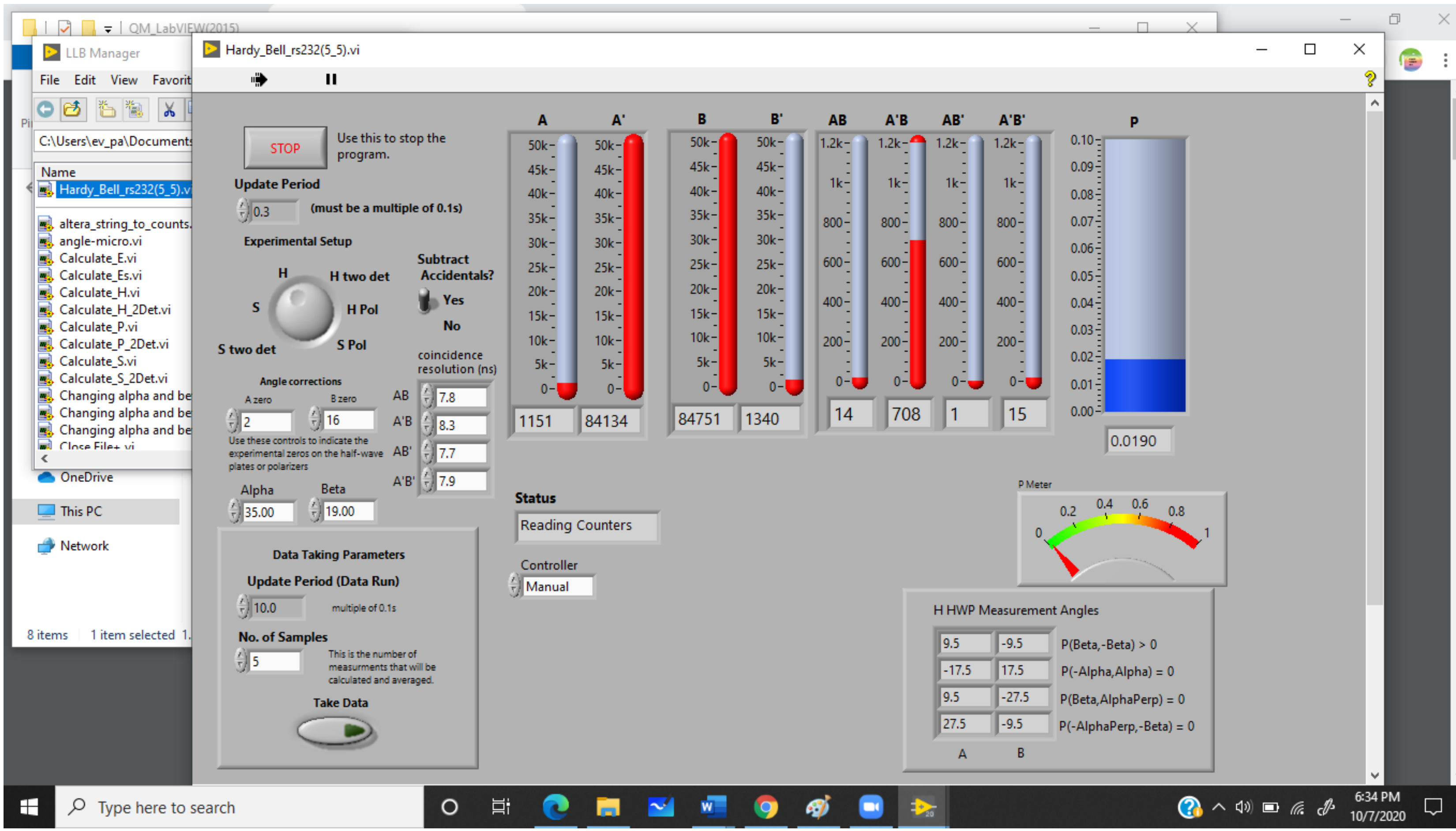
$$\frac{1}{\sqrt{2}}\left(|HV\rangle - |VH\rangle\right)$$



Labview and FPGA setup by Mark Beck
(http://people.reed.edu/~beckm/QM/)

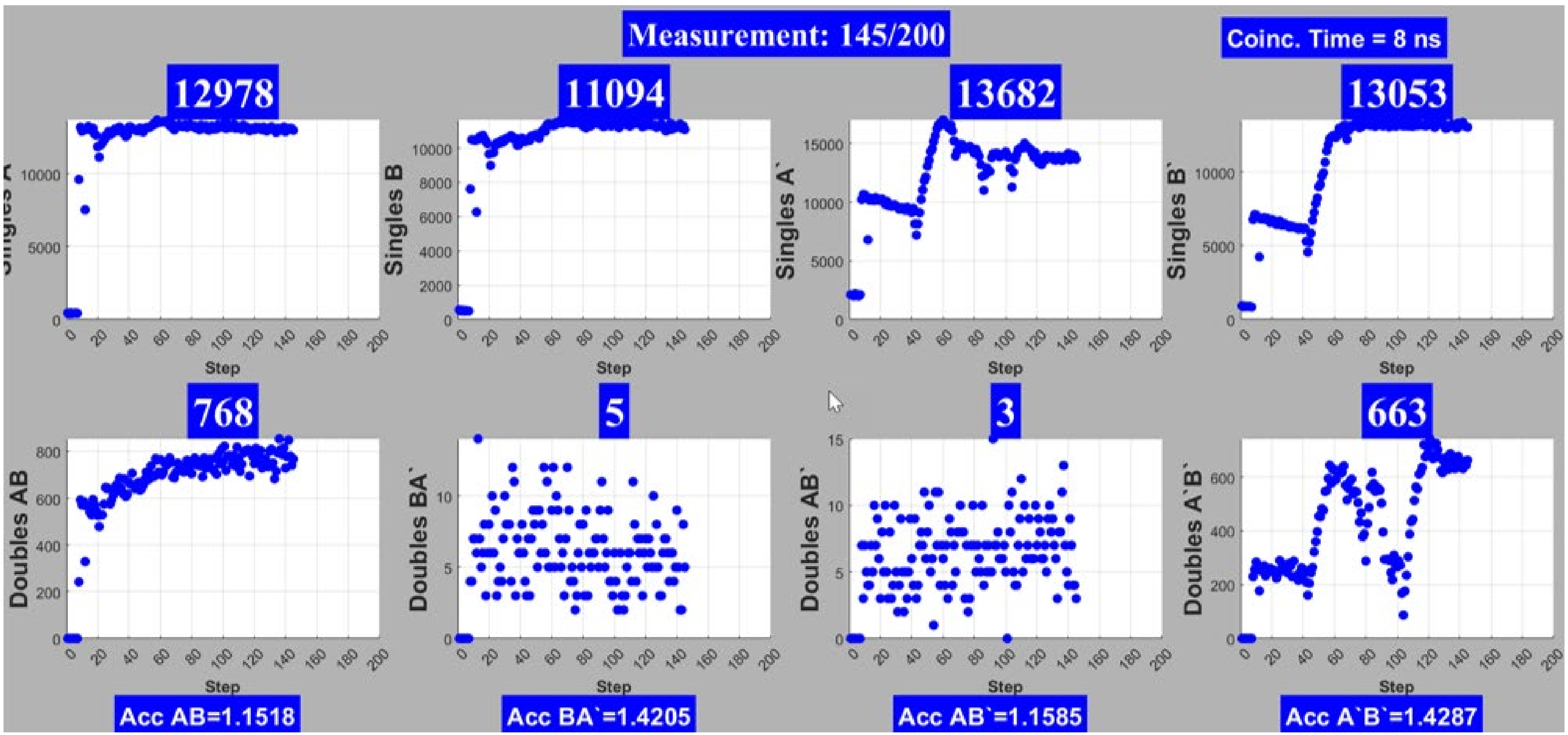
Experimental results

The single counts for two (SPCM) detectors (A’ and B) show 84751 (for A’), and 84751 (for B) and coincidence counts of 708 for A’B coincidences (in Figure below):

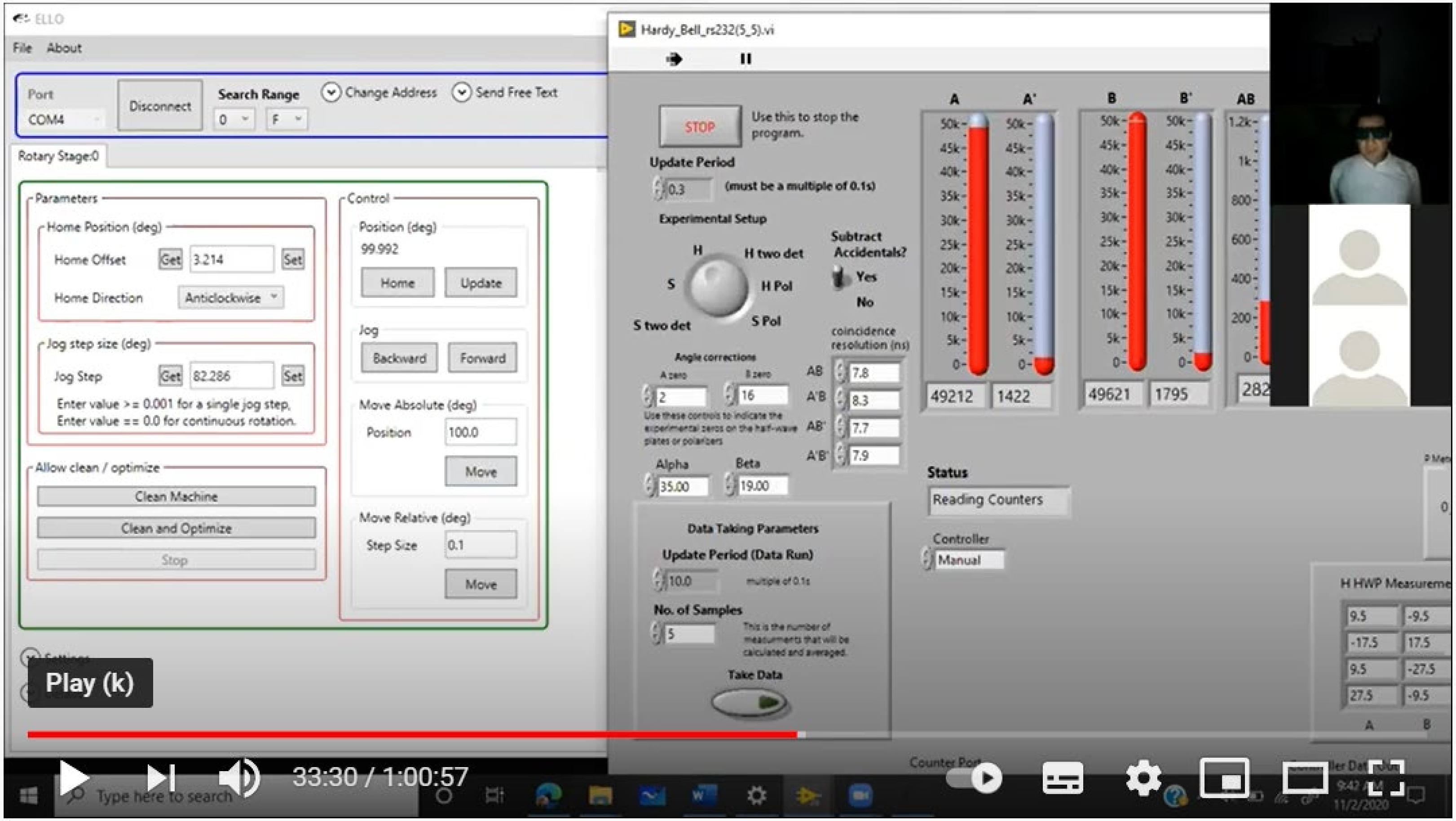


Labview and FPGA setup by Mark Beck (http://people.reed.edu/~beckm/QM/)

Representative experimental quantum entanglement results using polarized states



Remote Hands-on Learn-by-doing



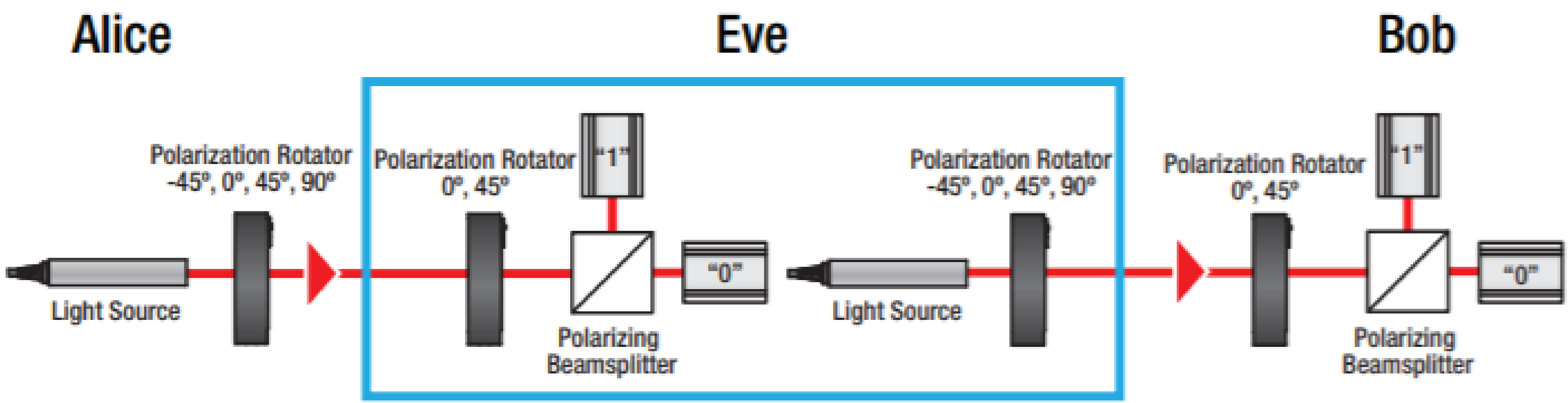
Quantum Entanglement and Cryptography experiments - Quantum Engineering for Mechatronics/Autonomy

https://www.youtube.com/watch?v=UqZqlI44u_8&t=2010s

Quantum Cryptography (demonstration kit)

Ref: Thorlabs:
https://www.thorlabs.com/drawings/7dc1a0a51f66aa9b-610D055E-0A11-1562-E8F38E3EDDF533AA/EDU-QCRY1_M-EnglishManual.pdf

Quantum Cryptography



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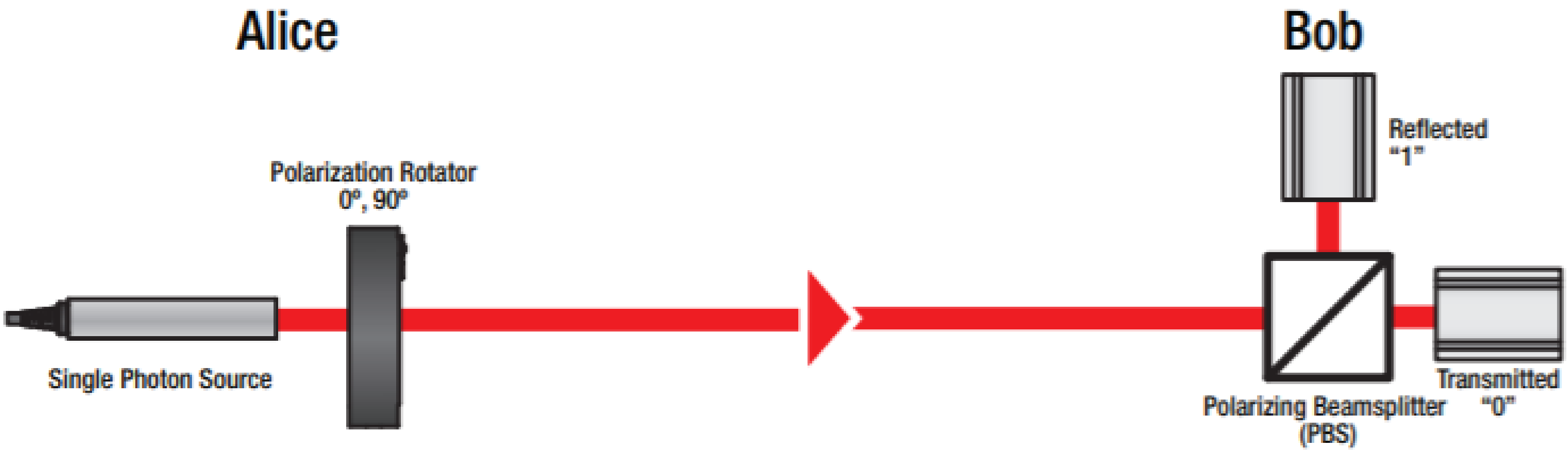

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Quantum Cryptography (demonstration kit)

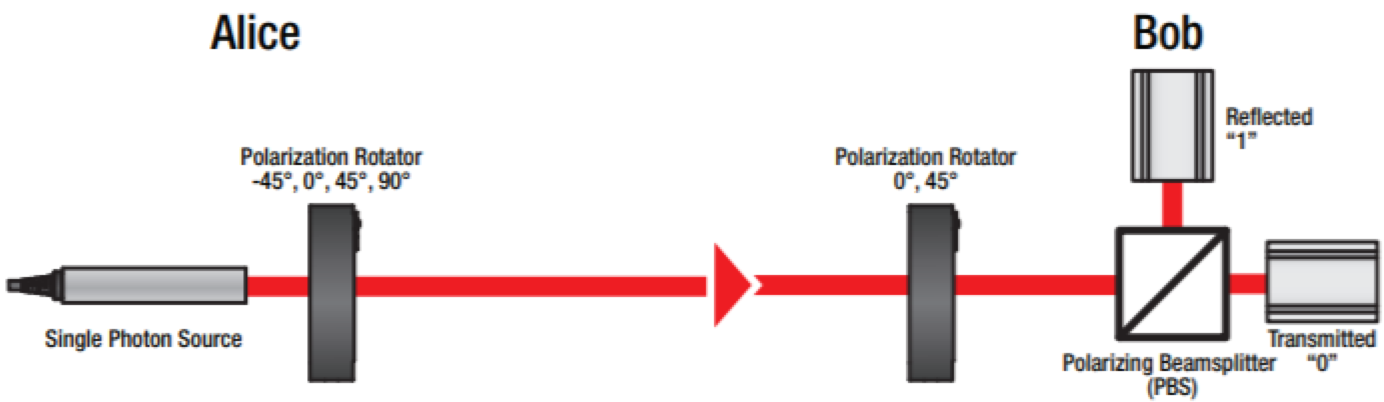


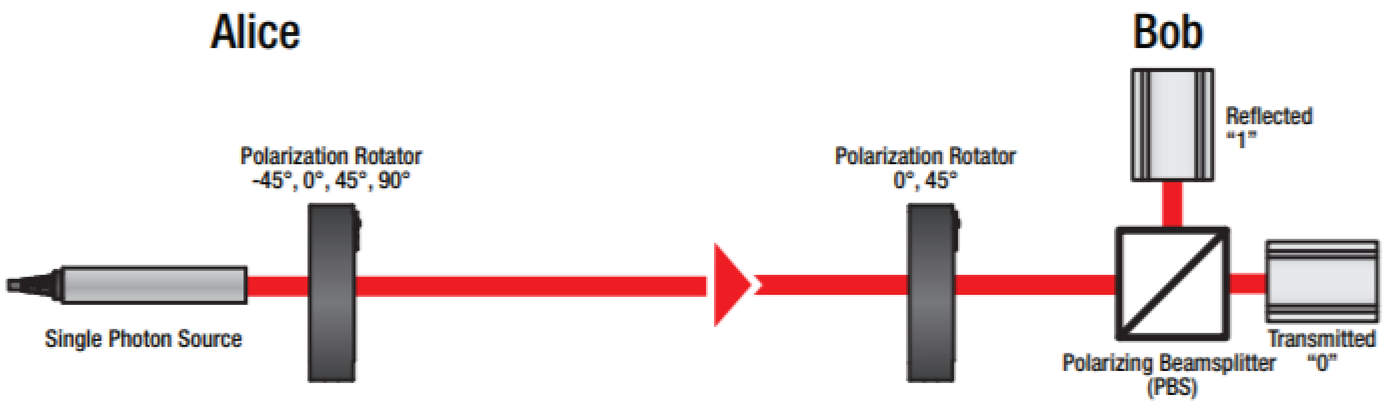
Figure 3 Quantum Cryptography Setup with the Bases + (0° and 90°) and x (-45° and 45°)

Now Alice has to make two *random* decisions for key generation:

- Alice has to select her basis at random, + or x
- Alice has to select a random bit, 0 or 1
  - Selecting 0 with the + basis means the setting 0°
  - Selecting 1 with the + basis means the setting 90°
  - Selecting 0 with the x basis means the setting -45°
  - Selecting 1 with the x basis means the setting 45°

Ref: Thorlabs: https://www.thorlabs.com/drawings/7dc1a0a51f66aa9b-610D055E-0A11-1562-E8F38E3EDDF533AA/EDU-QCRY1_M-EnglishManual.pdf

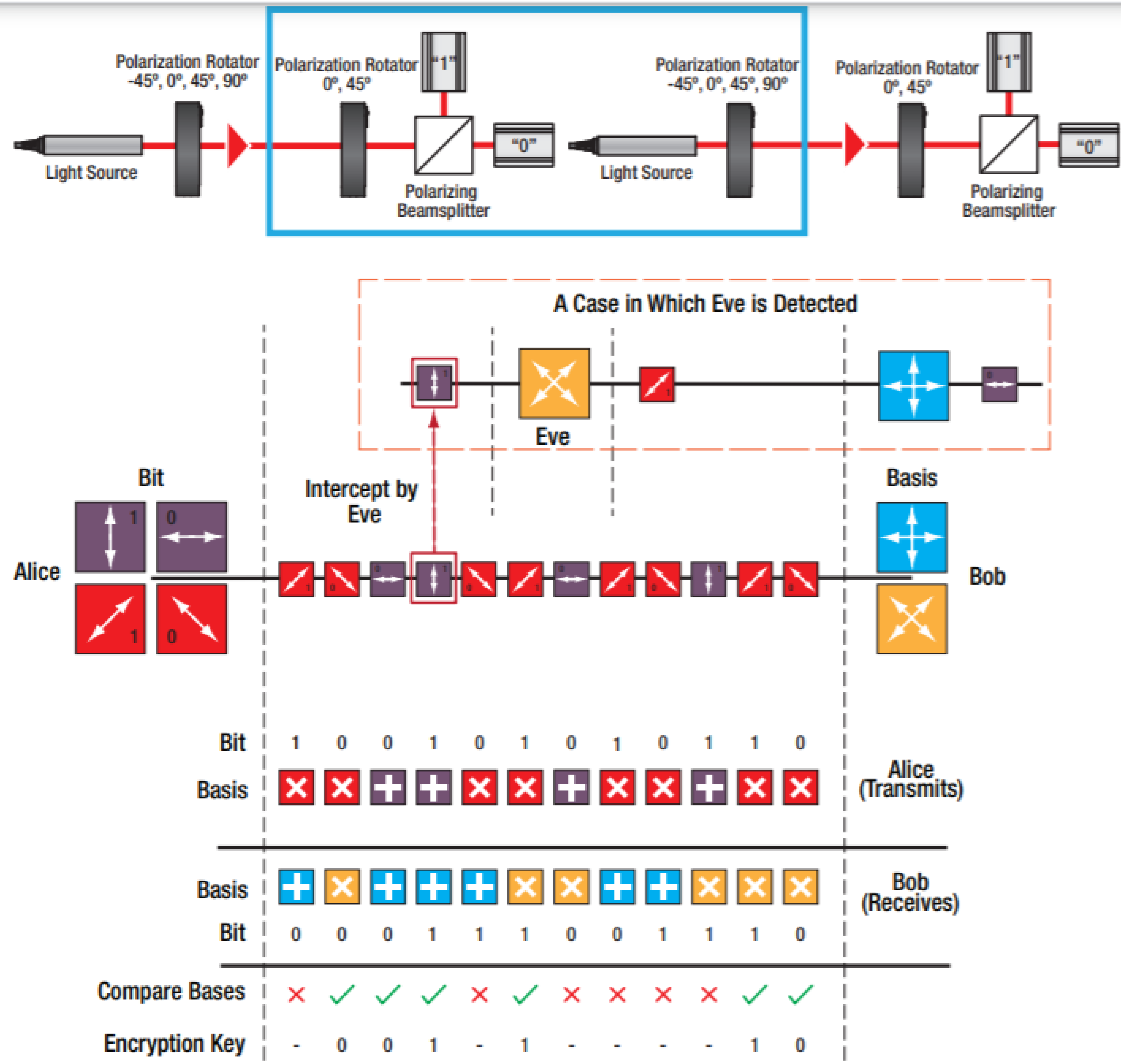
Quantum Cryptography



Alice			Bob				Same basis?
Basis	Bit	Angle	Basis	Angle	Detector "0"	Detector "1"	
+	0	0°	+	0°	**100%**	0%	Yes
+	1	90°	+	0°	0%	**100%**	Yes
x	1	45°	+	0°	50%	50%	No
x	0	-45°	+	0°	50%	50%	No
+	0	0°	x	45°	50%	50%	No
+	1	90°	x	45°	50%	50%	No
x	1	45°	x	45°	0%	**100%**	Yes
x	0	-45°	x	45°	**100%**	0%	Yes

Quantum cryptography, animated: https://www.youtube.com/watch?v=LaLzshIosDk

Ref: Thorlabs:
https://www.thorlabs.com/drawings/7dc1a0a51f66aa9b-610D055E-0A11-1562-E8F38E3EDDF533AA/EDU-QCRY1_M-EnglishManual.pdf



Ref: Thorlabs: [https://www.thorlabs.c EnglishManual.pdf](https://www.thorlabs.c)

Quantum Cryptography (demonstration kit)

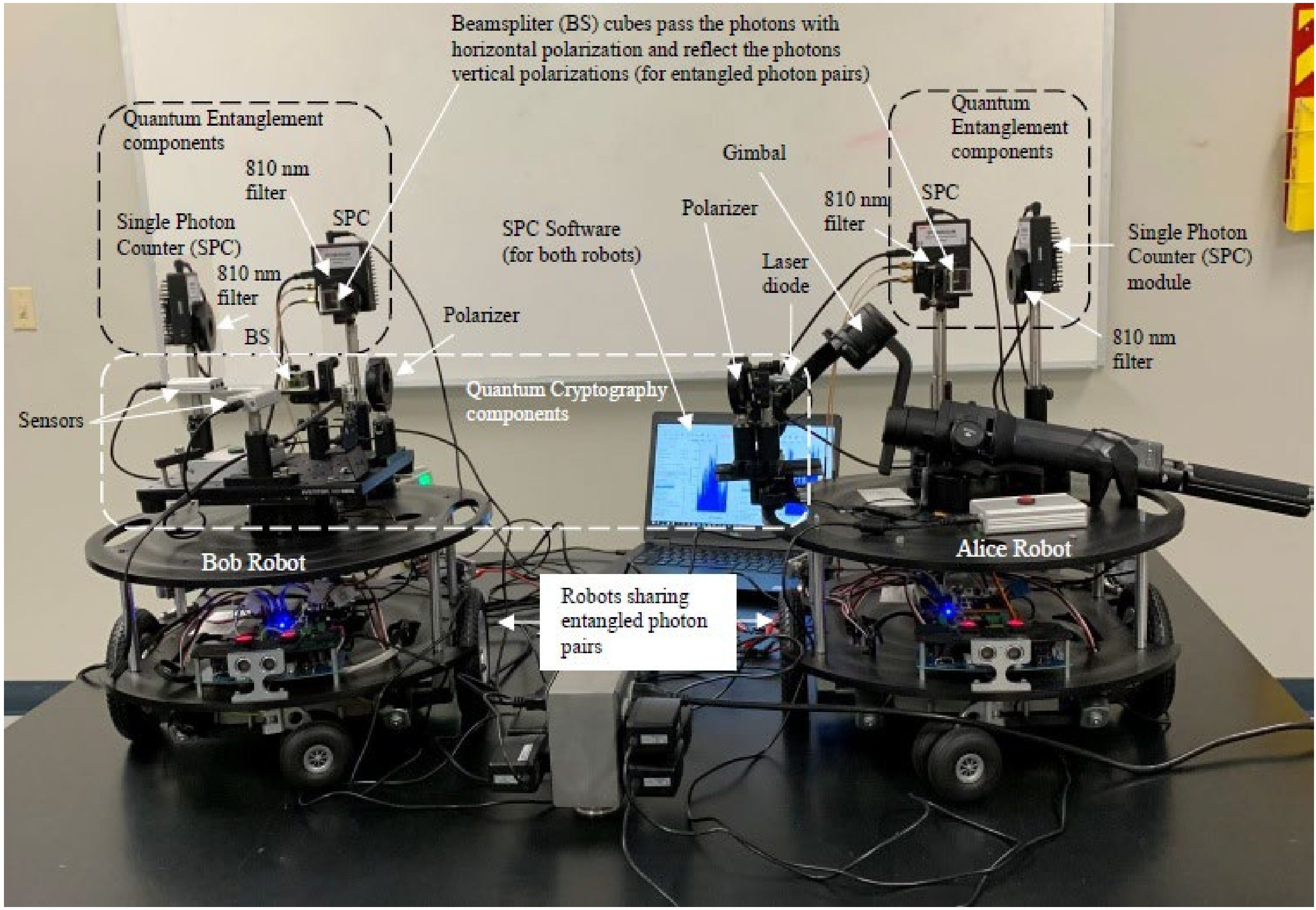
Ref: Thorlabs:
https://www.thorlabs.com/drawings/7dc1a0a51f66aa9b-610D055E-0A11-1562-E8F38E3EDDF533AA/EDU-QCRY1_M-EnglishManual.pdf

Quantum Robotics Initiative

Integrating Quantum Technologies with physical Engineering Systems

Pushing the engineering boundaries beyond classical techniques

- Implementing Experimental **Quantum Entanglement** for Robots to share entangled photons for cooperative autonomy.
- Accessing guaranteed security for cooperative autonomy by **Quantum Cryptography**.
- **Quantum Teleportation** for communications in between multi-agent autonomous



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, in press. [Preprint PDF]

F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal, Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

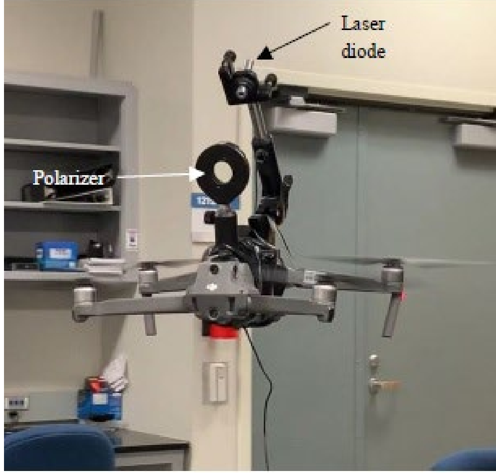
F. Khoshnoud, I. I. Esat, M. B. Quadrelli, D. Robinson, **Quantum Cooperative Robotics and Autonomy**, *Special issue of the Instrumentation Journal, Edited by C.W. de Silva*, Vol. 6, No. 3, pp. 93-111, 2019. VIDEO. [Preprint PDF]

Integration of Quantum Technologies with Engineering Systems to Access Quantum Supremacy at Macroscale

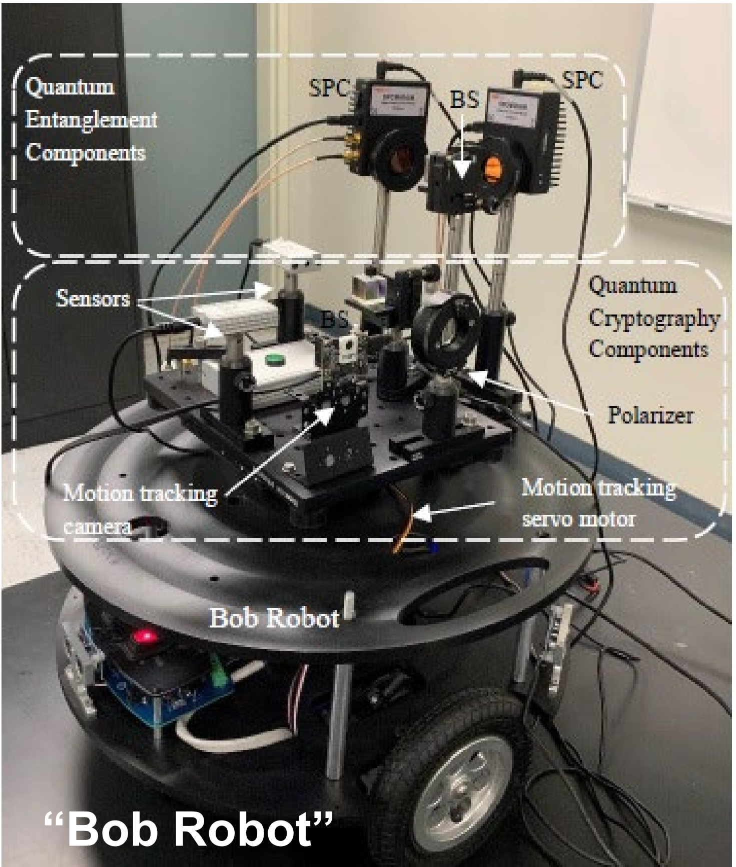
Quantum Entanglement, Cryptography, and Teleportation For Control of Dynamical Systems and Autonomy

- Polarizations of the entangled photons will be converted to classical digital information for digital control and autonomy applications,
- or in case of accessing quantum computers in future, will be used directly by quantum computers* for autonomy

*in fact, using any classical transfer of information between robots equipped with quantum processors/computers (when quantum computers become available in future) can actually defeat the advantage of quantum computers.



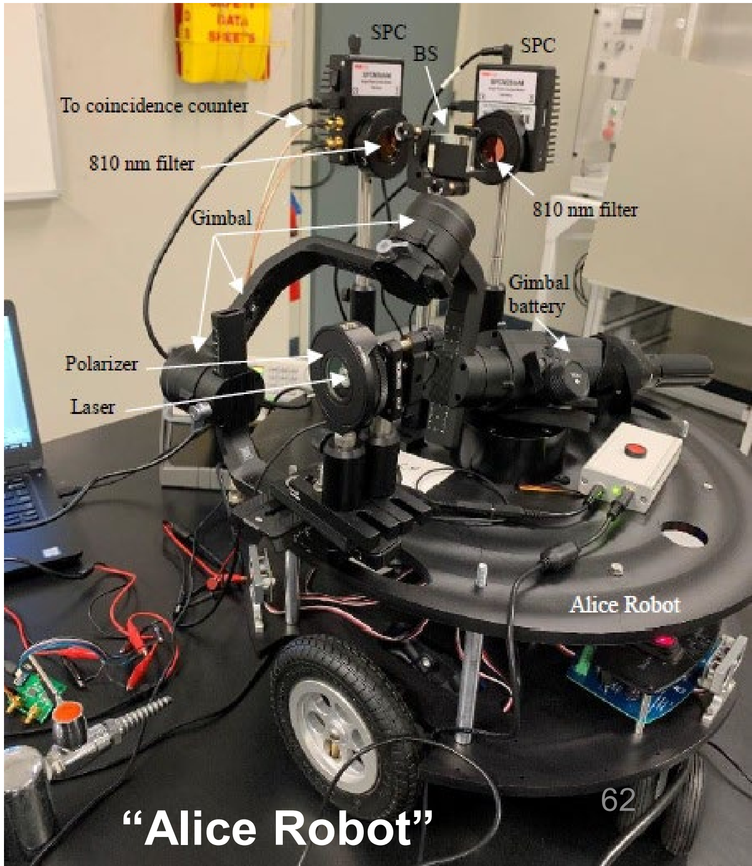
"Alice Drone"



"Bob Robot"

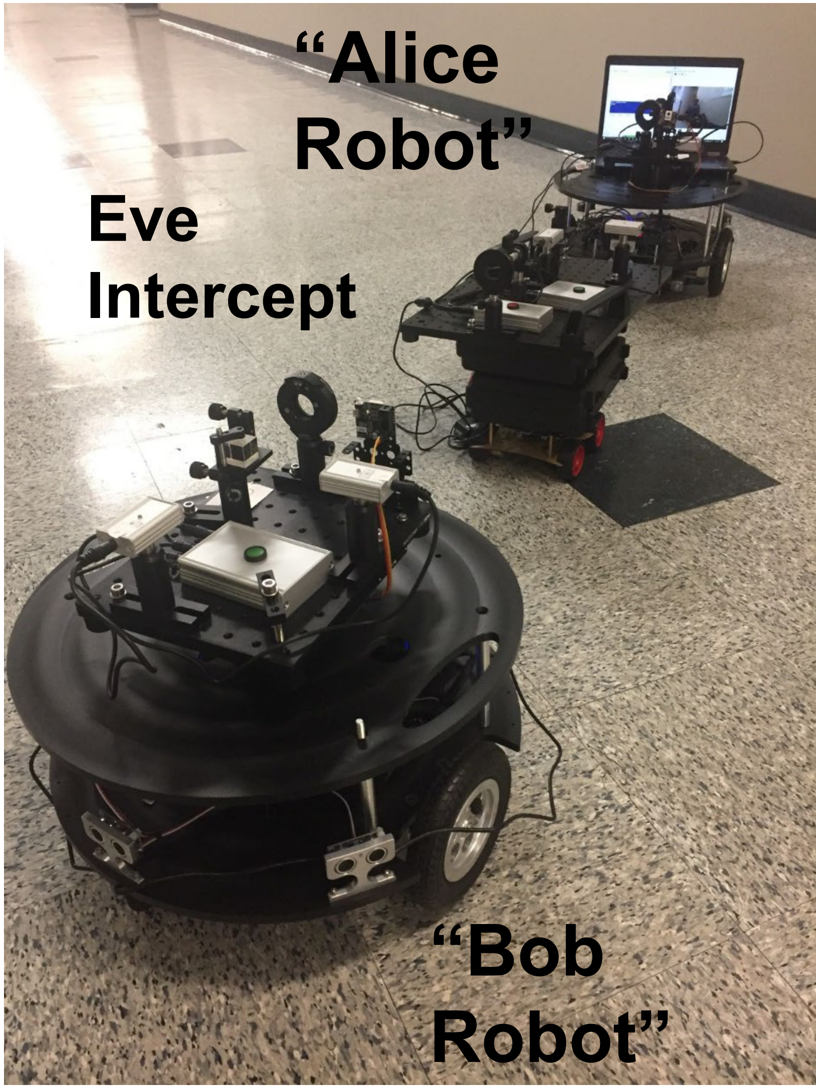
Entangled Photons are generated by 'Spontaneous Parametric Down Conversion', and sent to Alice and Bob Robots

Quantum Entangled Photons will be received by the Single Photon Counter (SPC) modules placed on the robots



"Alice Robot"

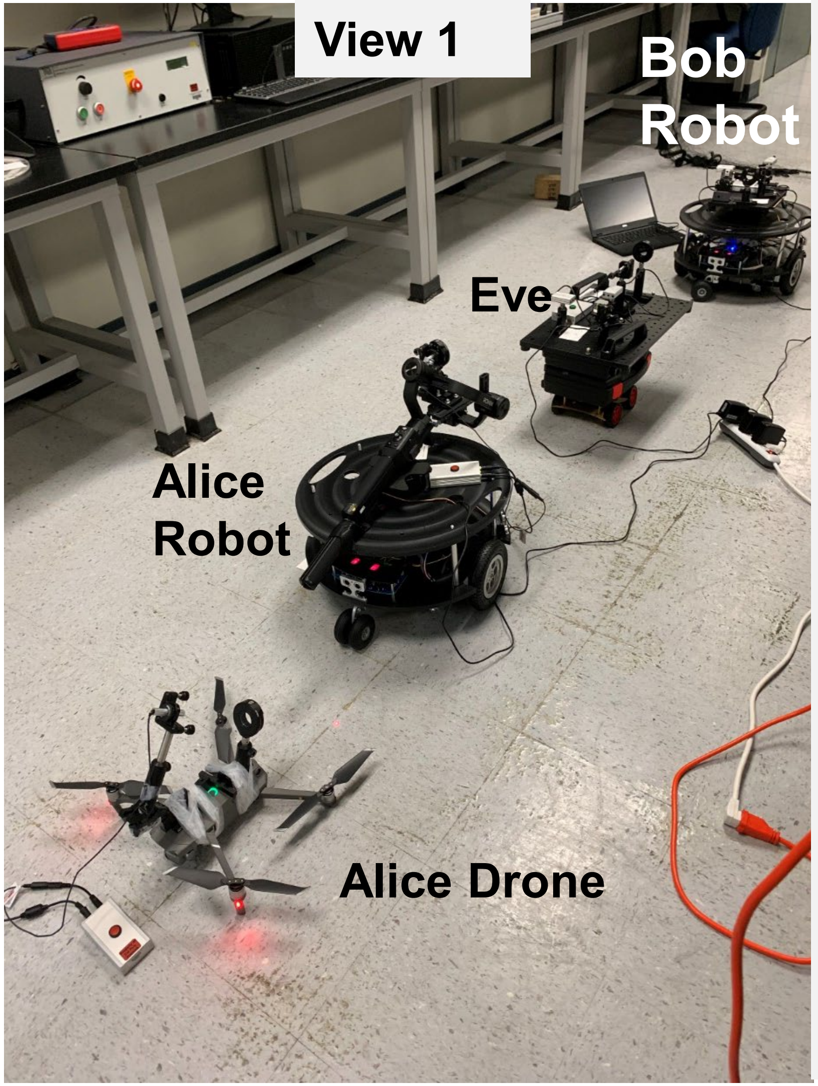
Quantum Cryptography for Cooperative Robotics and Autonomy



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, *Journal of Mechatronic Systems and Control*, Volume 49, Issue 3, pp. 124-131, 2021. [Preprint PDF]

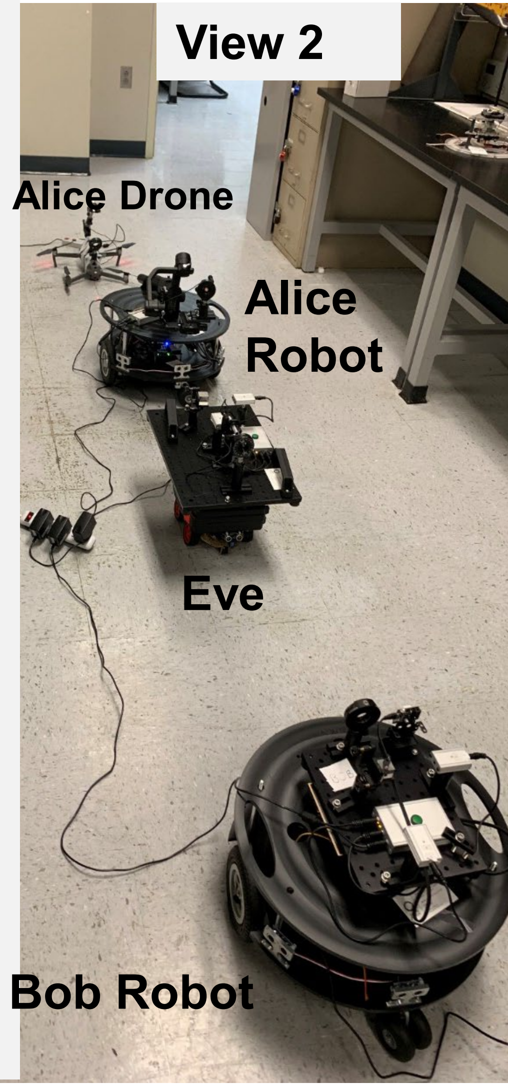
F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

F. Khoshnoud, I. I. Esat, M. B. Quadrelli, D. Robinson, **Quantum Cooperative Robotics and Autonomy**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 3, pp. 93-111, 2019. VIDEO. [Preprint PDF]



Quantum Cryptography for Robotics and Autonomy

Alice or Bob can be Ground or Aerial Robotics (depending on the application)



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, *Journal of Mechatronic Systems and Control*, Volume 49, Issue 3, pp. 124-131, 2021. [Preprint PDF]

F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

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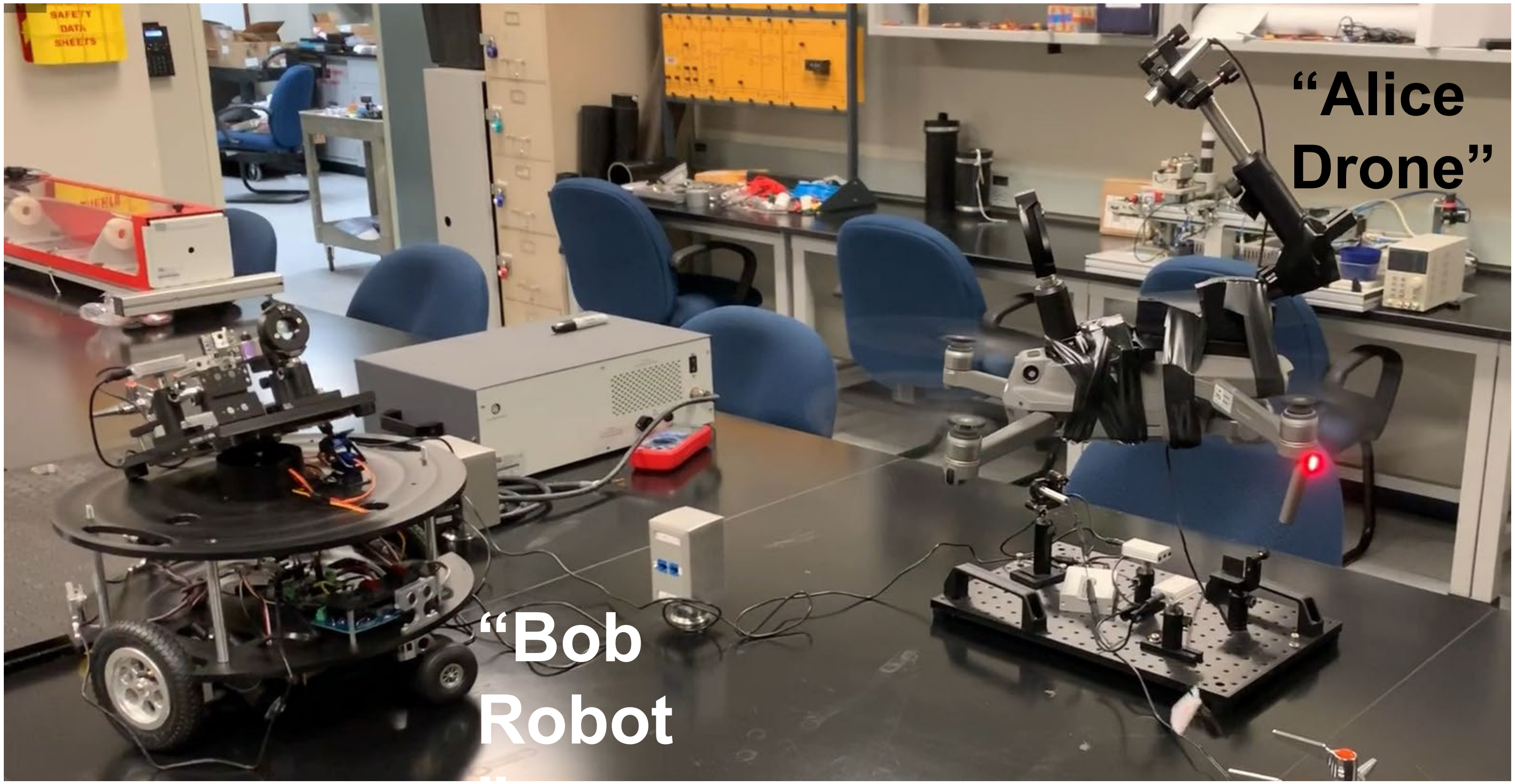
Quantum Cryptography for Robotics and Autonomy



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, *Journal of Mechatronic Systems and Control*, Volume 49, Issue 3, pp. 124-131, 2021. [Preprint PDF]

F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

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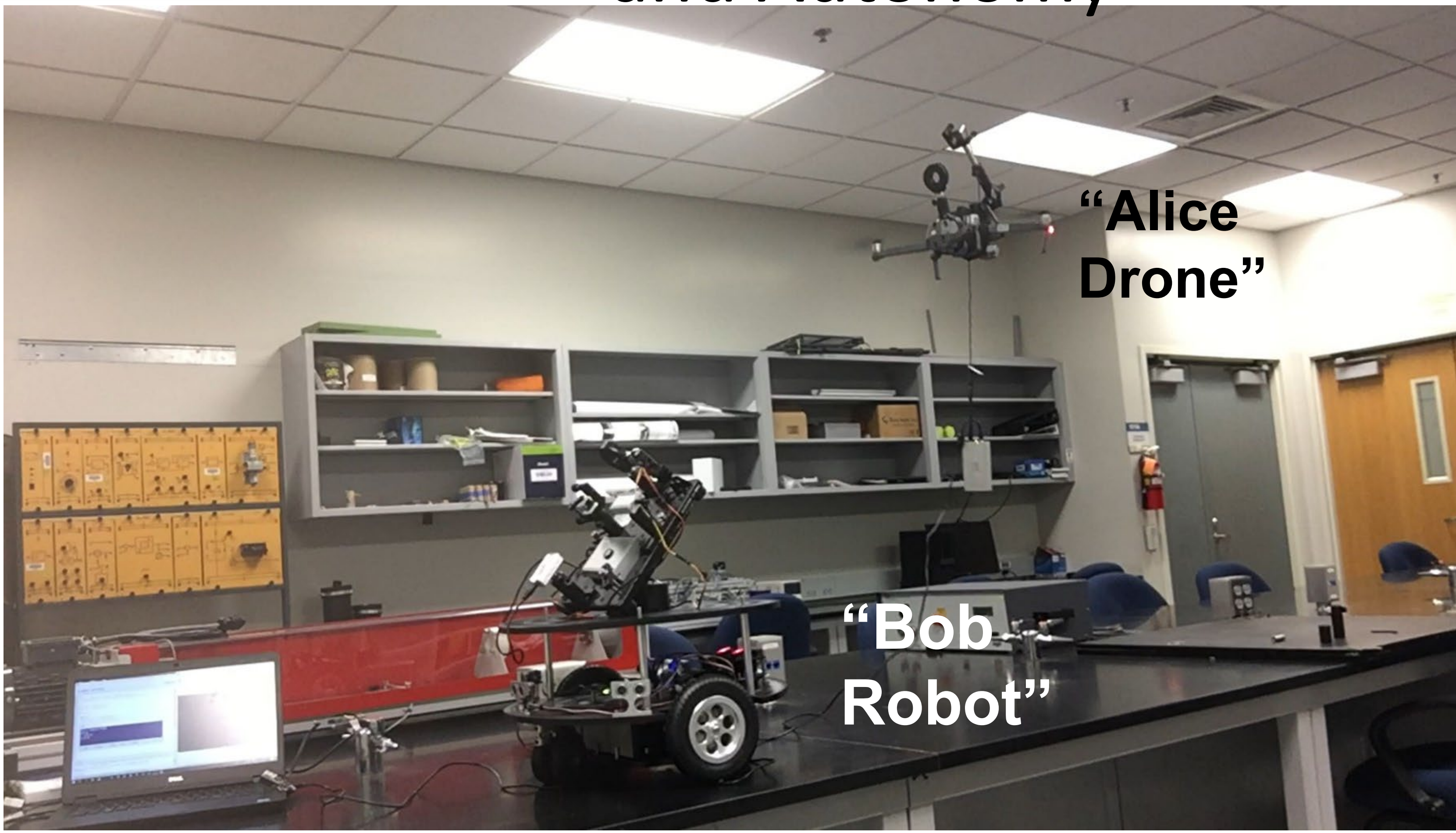
Quantum Cryptography for Robotics and Autonomy



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, *Journal of Mechatronic Systems and Control*, Volume 49, Issue 3, pp. 124-131, 2021. [Preprint PDF]

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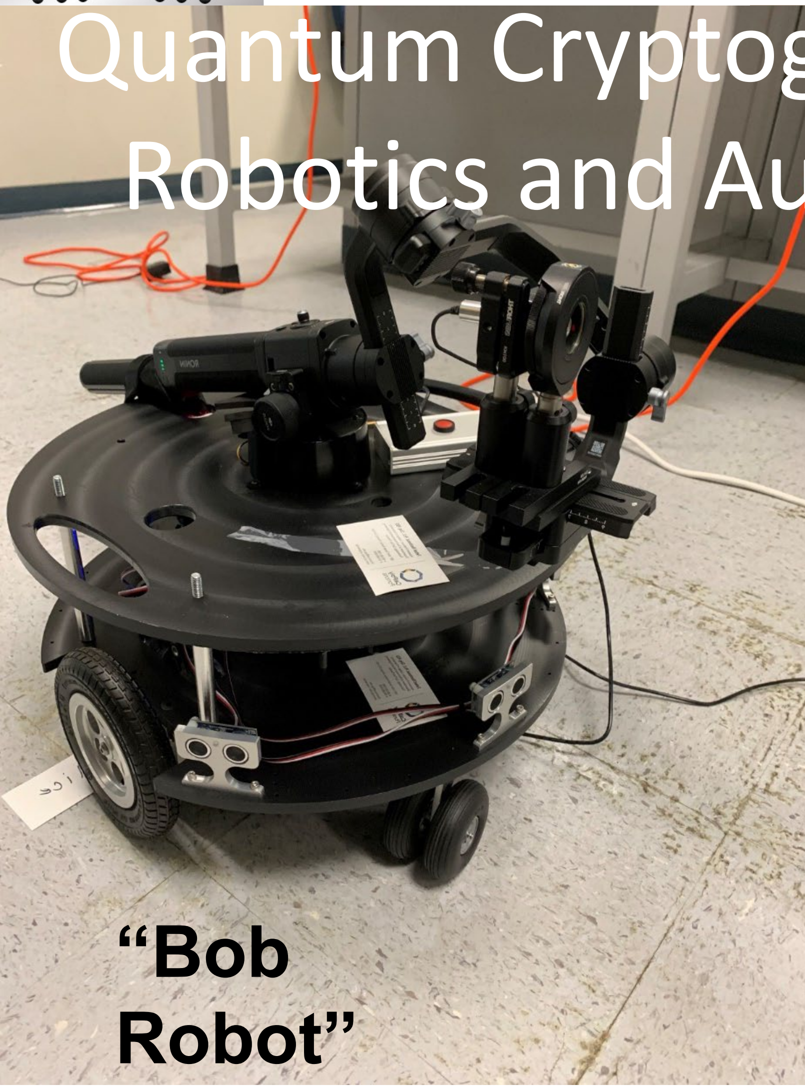
F. Khoshnoud, I. I. Esat, M. B. Quadrelli, D. Robinson, **Quantum Cooperative Robotics and Autonomy**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 3, pp. 93-111, 2019. VIDEO. [Preprint PDF]

Quantum Cryptography for Robotics and Autonomy



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, *Journal of Mechatronic Systems and Control*, Volume 49, Issue 3, pp. 124-131, 2021. [Preprint PDF]

F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

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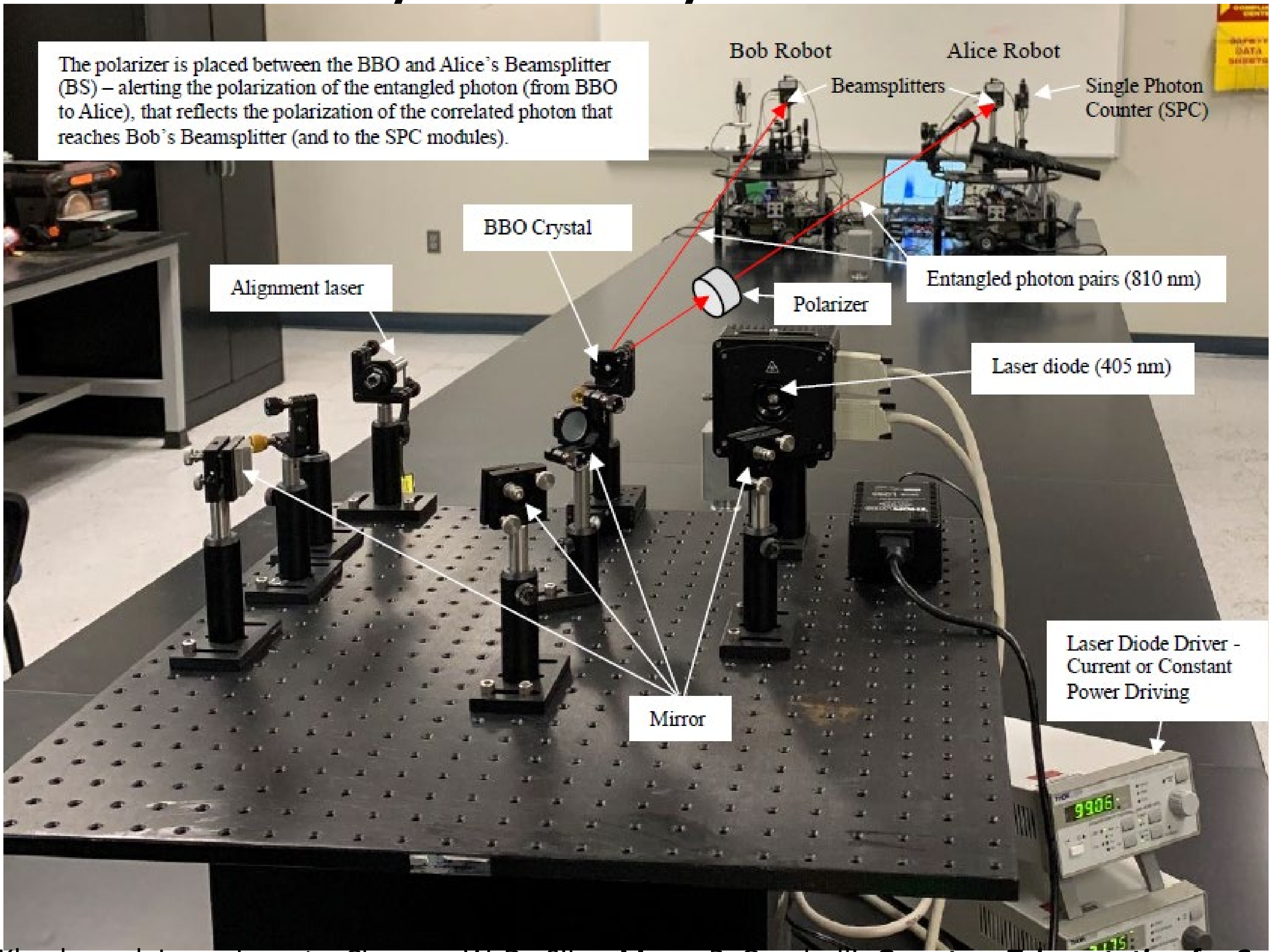
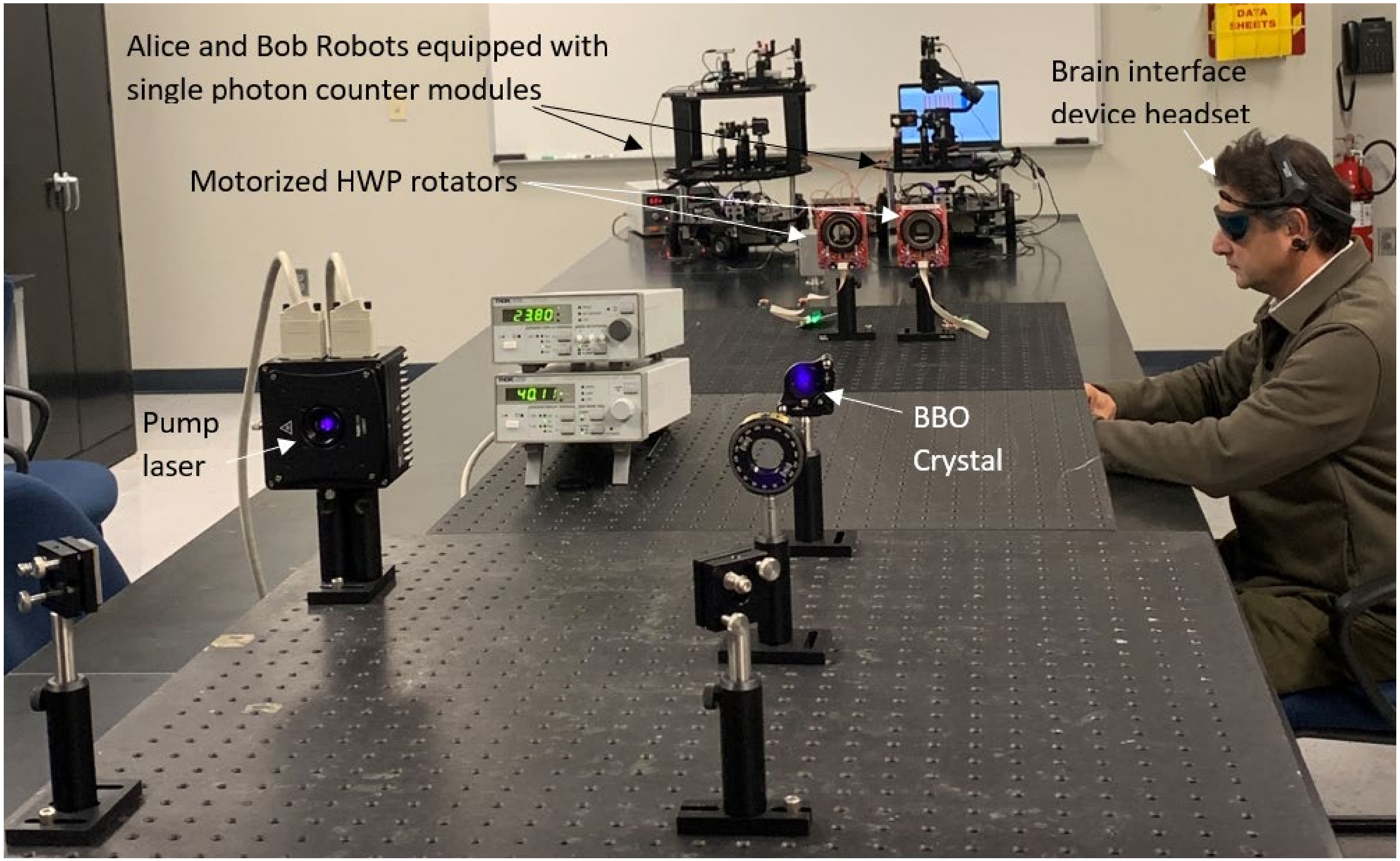
Quantum Teleportation
for Control of Dynamic Systems and Autonomy



Farbod Khoshnoud, Lucas Lamata, Clarence W. De Silva, Marco B. Quadrelli***, Quantum Teleportation for Control of Dynamic Systems and Autonomy,*** *Mechatronic Systems and Control Journal*, 2020,*Journal of Mechatronic Systems and Control*, Volume 49, Issue 3, pp. 124-131, 2021. [Preprint link].

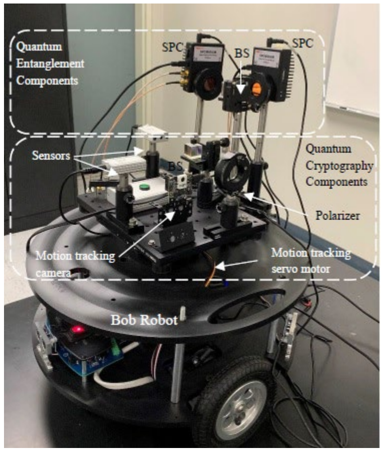
Quantum Brain Computer Interface

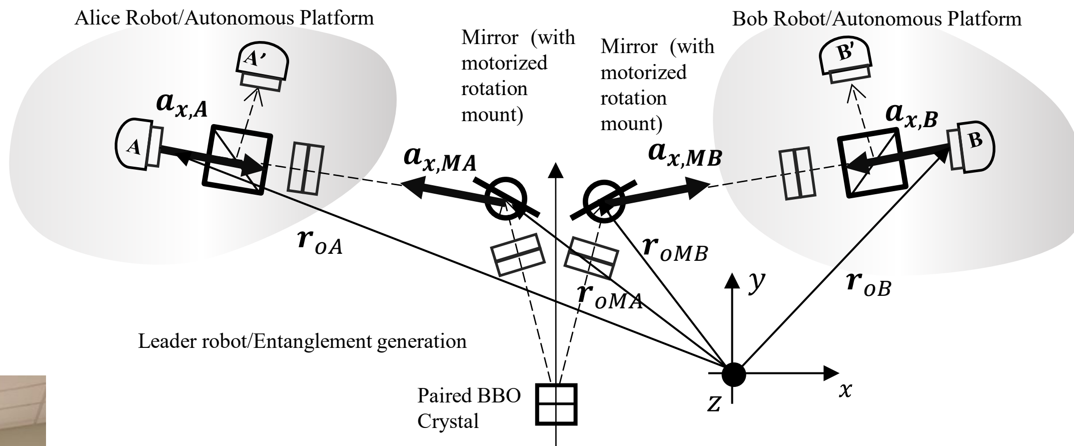


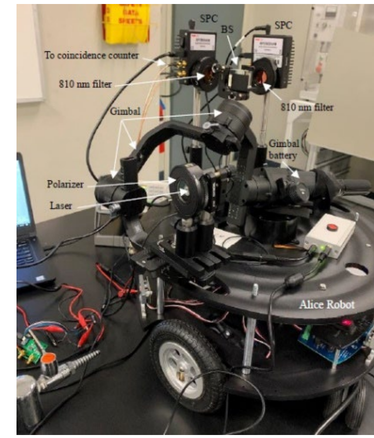
EGG signals in triggering experimental quantum processes

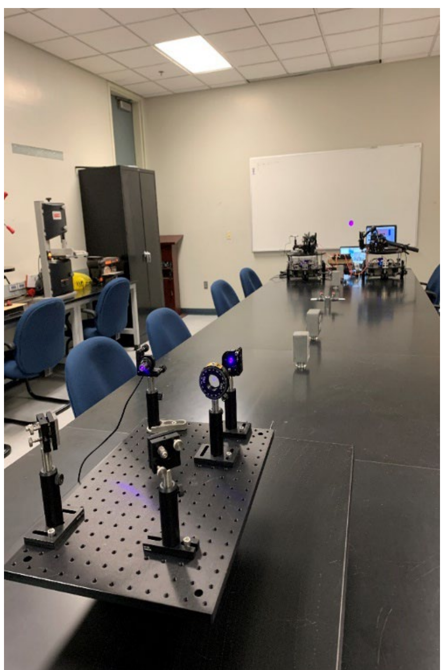
Farbod Khoshnoud, Marco B. Quadrelli, Enrique Galvez, Clarence W. de Silva, Shayan Javaherian, B. Bahr, M. Ghazinejad, A. S. Eddin, M. El-Hadedy, **Quantum Brain- Computer Interface**, ASEE PSW, 2023.

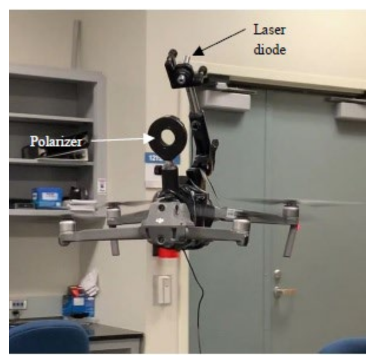
Quantum Entanglement Experiment
Automated alignment for mobile agents





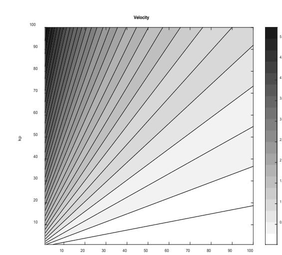






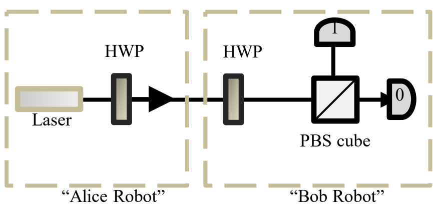
$$\mathbb{P}[P(X) > dia_{collimator}] \leq \epsilon$$

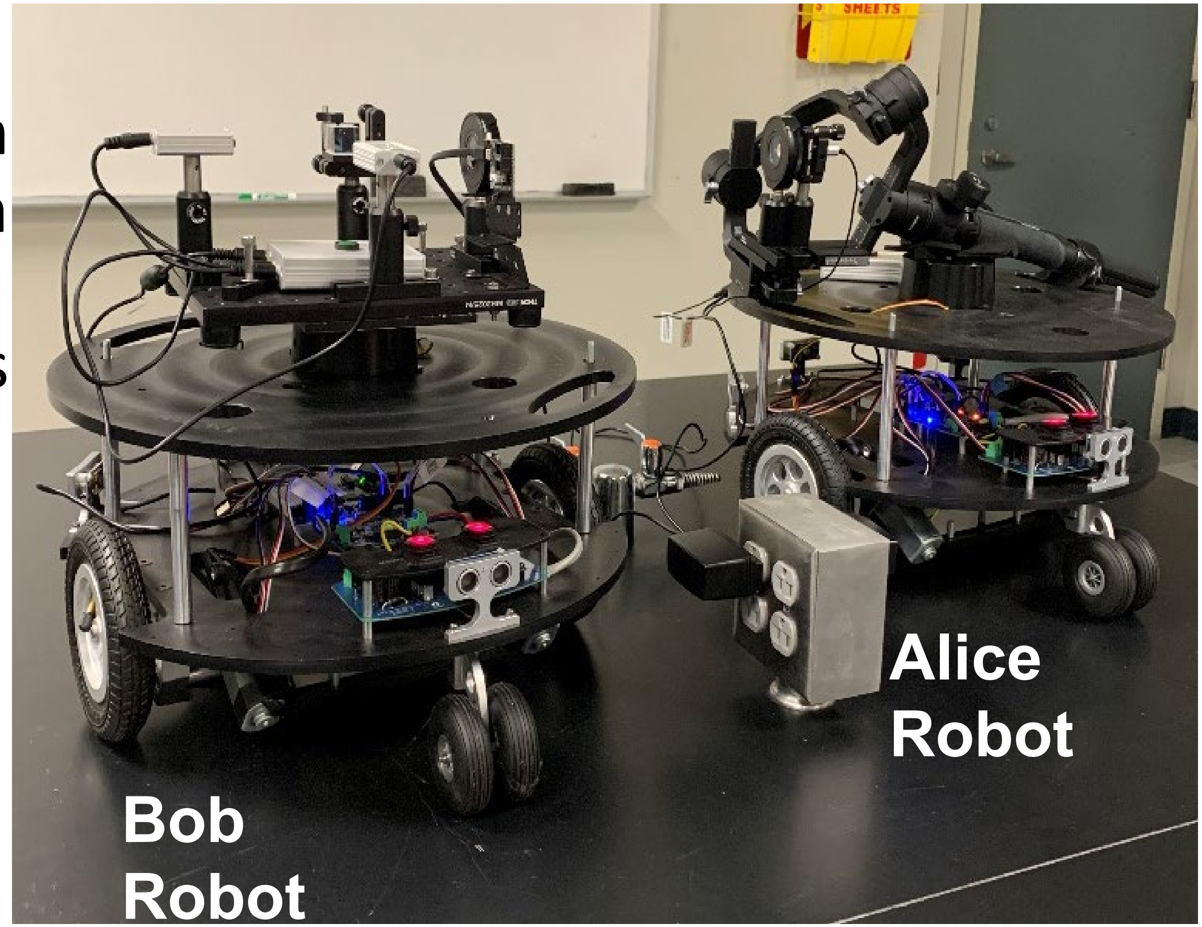
$$\boldsymbol{v_B} \in \boldsymbol{\mathcal{X}}_3 := [\boldsymbol{v}_{\boldsymbol{B}_{min}}, \boldsymbol{v}_{\boldsymbol{B}_{max}}] \text{ m}/s$$



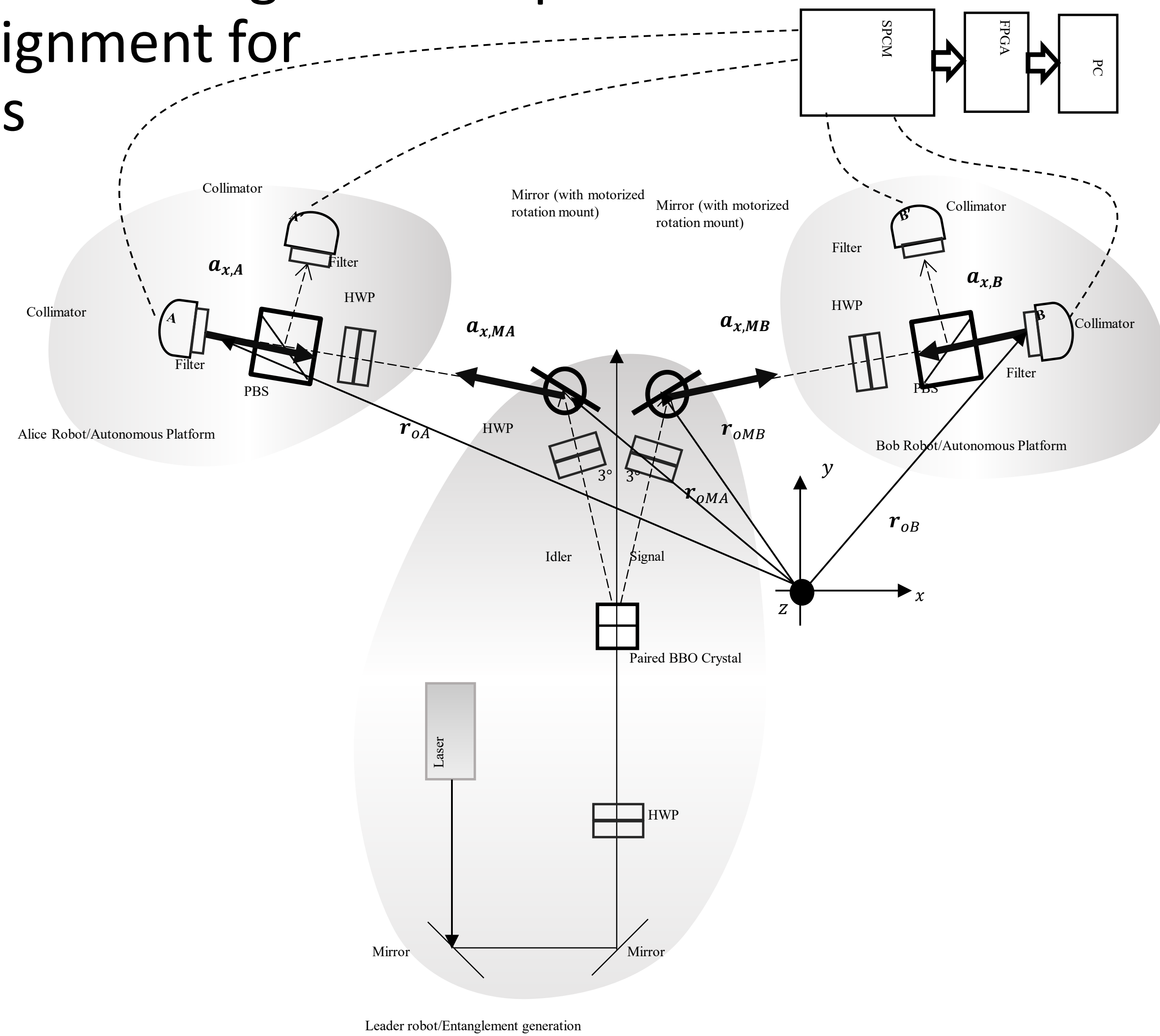
F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, in press. [Preprint PDF]
F. Khoshnoud, M. Ghazinejad, **Automated quantum entanglement and cryptography for networks of robotic systems**, IEEE/ASME, 2021.

Quantum cryptography in communication for control of robotic systems





Photon quantum entanglement experiment – Automated alignment for Mobile Robots



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, in press. [Preprint PDF]
F. Khoshnoud, M. Ghazinejad, **Automated quantum entanglement and cryptography for networks of robotic systems**, IEEE/ASME, in press.

The vide link: https://www.youtube.com/watch?v=ForcnzWzG1M&t=

Quantum **Algorithms** for Multi-agent Autonomous Systems (An example)

Quantum Entanglement of Autonomous Vehicles for Cyber-physical security

Singlet state

$$|\psi\rangle_s = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

$$p^{(s)}_{\uparrow\uparrow} = p^{(s)}_{\downarrow\downarrow} = \frac{1}{2}\sin^2\left(\frac{\alpha}{2}\right)$$

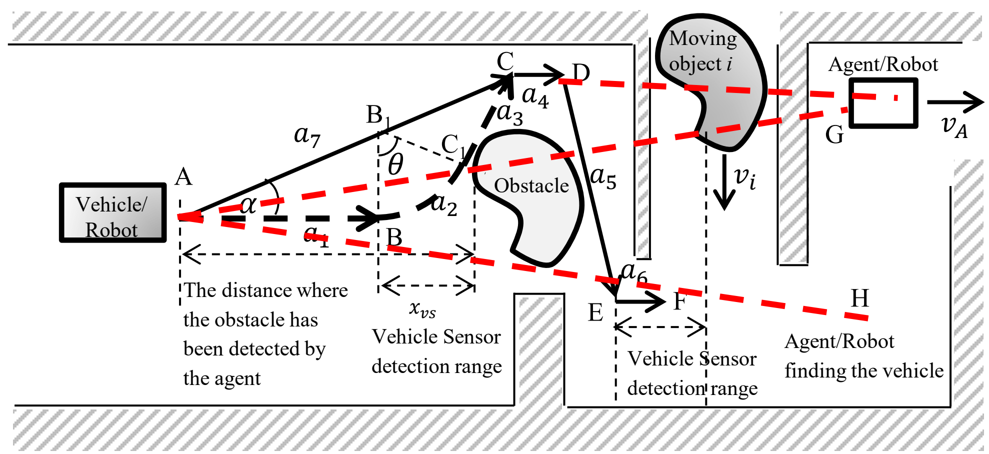
$$p^{(s)}_{\uparrow\downarrow} = p^{(s)}_{\downarrow\uparrow} = \frac{1}{2}\cos^2\left(\frac{\alpha}{2}\right)$$

Triplet state

$$p^{(t)}_{\uparrow\uparrow} = p^{(t)}_{\downarrow\downarrow} = \frac{1}{2}\cos^2\left(\frac{\alpha}{2}\right)$$

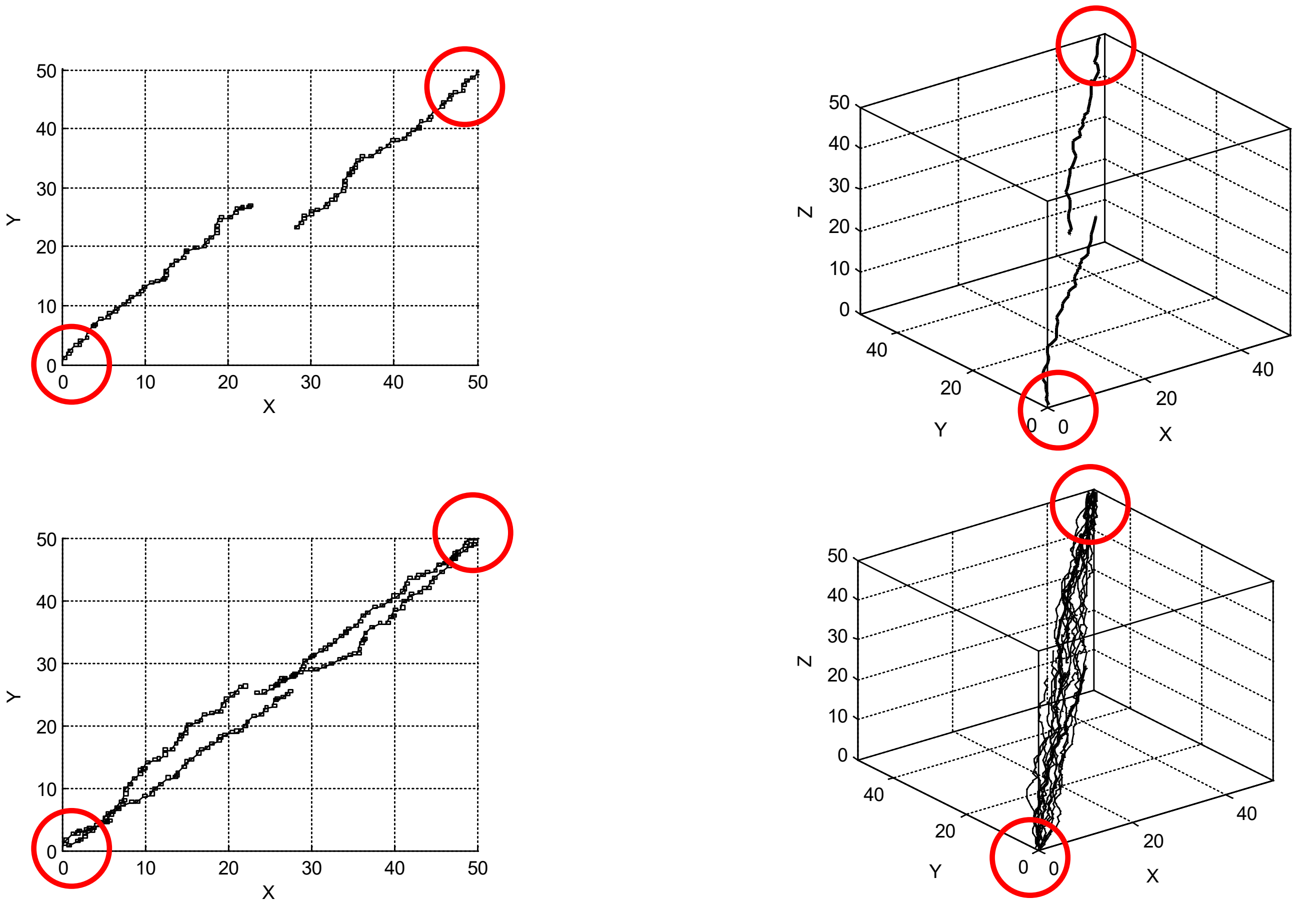
$$p^{(t)}_{\uparrow\downarrow} = p^{(t)}_{\downarrow\uparrow} = \frac{1}{2}\sin^2\left(\frac{\alpha}{2}\right)$$

- *Choose a random direction for a task (e.g., moving, applying force).*
- *The probability of random directions can be enhanced via probability weight factors for "suitable" directions.*
- *Decide to perform the task by the quantum measurement of the spin of the particle (for the vehicle/robot) reserved for this direction.*



Farbod Khoshnoud, C. W. de Silva, and I. I. Esat, Quantum Entanglement of Autonomous Vehicles for Cyber-physical security, IEEE International Conference on Systems, Man, and Cybernetics, Banff, Canada, October 5–8, 2017.

Quantum Entanglement of Autonomous Vehicles for Cyber-physical security



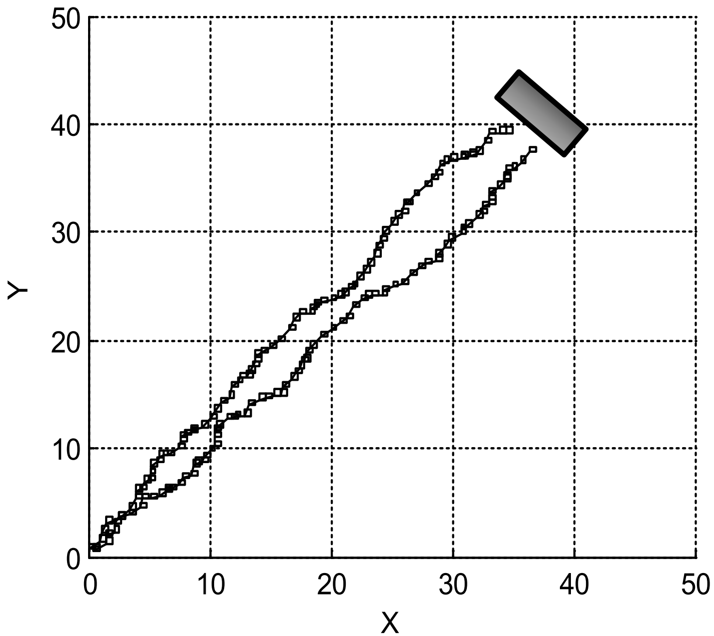
2D problems

3D problems

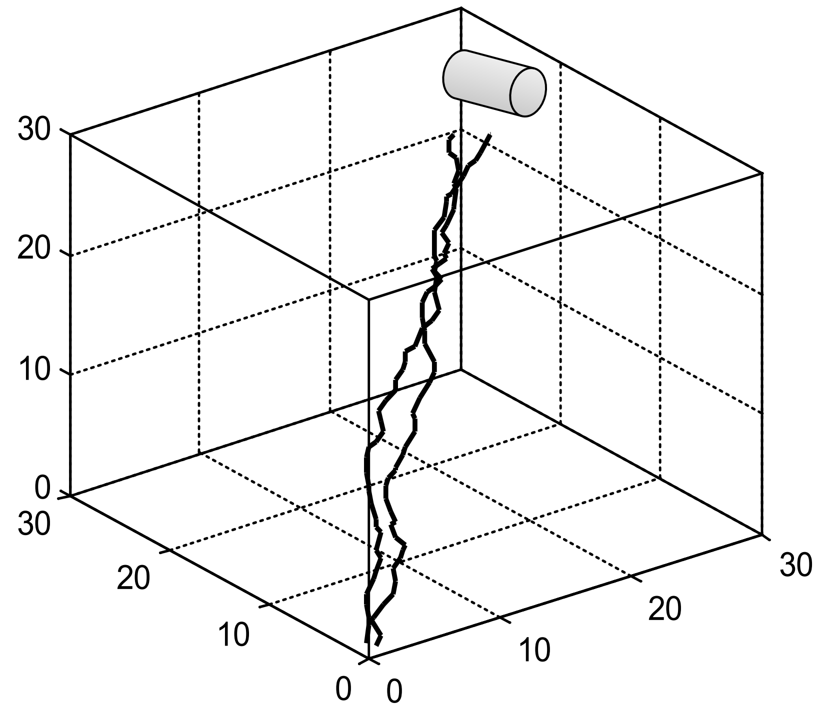
Autonomous Vehicles finding each other with no communication

Farbod Khoshnoud, C. W. de Silva, and I. I. Esat, Quantum Entanglement of Autonomous Vehicles for Cyber-physical security, IEEE International Conference on Systems, Man, and Cybernetics, Banff, Canada, October 5–8, 2017.

Quantum Entanglement of Autonomous Vehicles for Cyber-physical security



2D Simulation

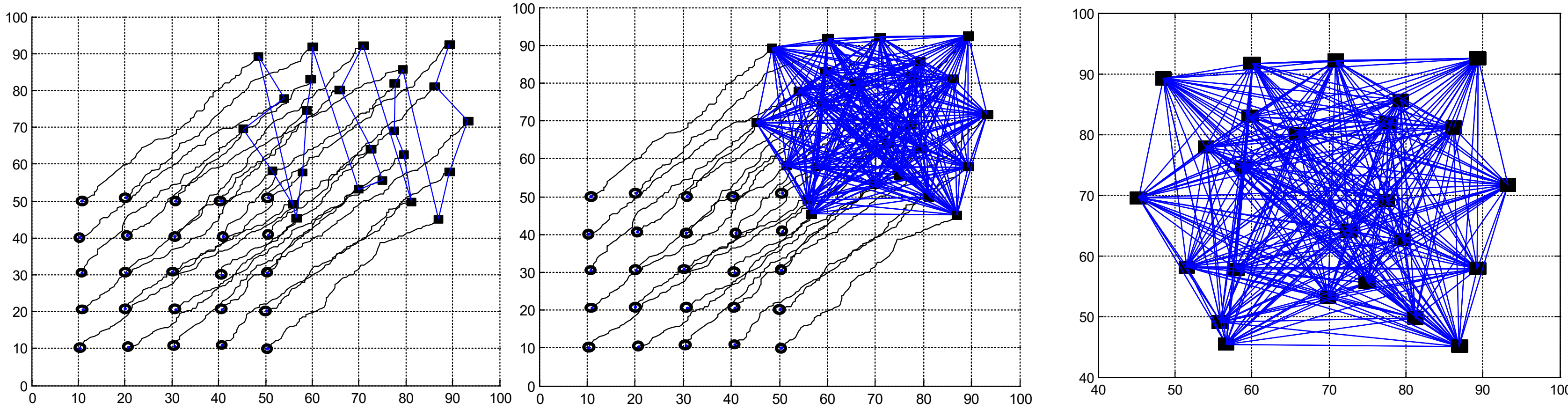


3D Simulation

Autonomous Vehicles performing a task (pushing an object) with no communication.

Farbod Khoshnoud, C. W. de Silva, and I. I. Esat, Quantum Entanglement of Autonomous Vehicles for Cyber-physical security, IEEE International Conference on Systems, Man, and Cybernetics, Banff, Canada, October 5–8, 2017.

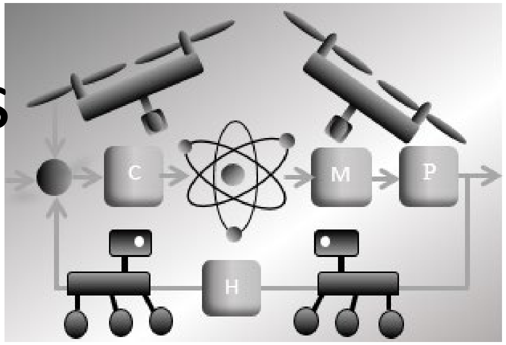
Quantum Network of Autonomous Vehicles for Cyber-physical security



- 25 UVs at the starting locations at the nodes are shown with circles
- Final positions of the UVs are shown by the filled squares
- The trajectories of the UVs are shown from each initial location to the final position
- Horizontal and vertical axes represent x and y coordinates associated with the two dimensional motion.

Farbod Khoshnoud, I.I. Esat, C.W. De Silva, M.B. Quadrelli, **Quantum Network of Cooperative Unmanned Autonomous Systems**, *Unmanned Systems journal*, Vol. 07, No. 02, pp. 137-145 (2019).

Theoretical Foundation of Quantum Multibody Dynamics



Quantum Mechanics

Schrödinger Equation

$$i\hbar \frac{d}{dt}|\psi(t)\rangle = \hat{H}|\psi(t)\rangle$$

Classical Dynamics

Newton's Equations of Motion

$$\{\mathbf{F}\} = [\mathbf{M}]\{\mathbf{a}\}$$

The Feedback Control System?

$$TF = \frac{C(|\psi(s)\rangle)M(\{\mathbf{F}(\mathbf{s}), |\psi(s)\rangle\})P(\{\mathbf{F}(\mathbf{s})\})}{1 + C(|\psi(s)\rangle)M(\{\mathbf{F}\}(\mathbf{s}), |\psi(s)\rangle)P(\{\mathbf{F}(\mathbf{s})\})H(s)}$$

F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, in press. [Preprint PDF]

F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

F. Khoshnoud, I. I. Esat, M. B. Quadrelli, D. Robinson, **Quantum Cooperative Robotics and Autonomy**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 3, pp. 93-111, 2019. VIDEO. [Preprint PDF]

Quantum Computing

- Research
  - Quantum algorithms/computing

- **Quantum Games** (multi-agent robotic systems preforming tasks)
  - There is a higher chance of wining a quantum game compare with a corresponding classical game
  - When robot sensors fail or limited in performing a task, quantum game can enhance the probability of successfully complete the task
- **Quantum Annealing** for multi-agent robotic trajectory optimization
  - Quantum optimization can help in optimizing a trajectory of robots in a multi-agent robotic scenario
- Implementing the quantum algorithms
- Testing the algorithms
- Uploading the quantum algorithms on classical microcontrollers on the robots

Quantum Mechanics experiments for education

Interference with correlated photons: Five quantum mechanics experiments for undergraduates

E. J. Galvez, C. H. Holbrow, M. J. Pysher, J. W. Martin, N. Courtemanche,
L. Heilig, and J. Spencer
Department of Physics and Astronomy, Colgate University, Hamilton, New York 13346

(Received 15 March 2004; accepted 29 July 2004)

We describe five quantum mechanics experiments that have been designed for an undergraduate setting. The experiments use correlated photons produced by parametric down conversion to generate interference patterns in interferometers. The photons are counted individually. The experimental results illustrate the consequences of multiple paths, indistinguishability, and entanglement. We analyze the results quantitatively using plane-wave probability amplitudes combined according to Feynman's rules, the state-vector formalism, and amplitude packets. The apparatus fits on a $2' \times 4'$ optical breadboard.
[DOI: 10.1119/1.1796811]

I. INTRODUCTION

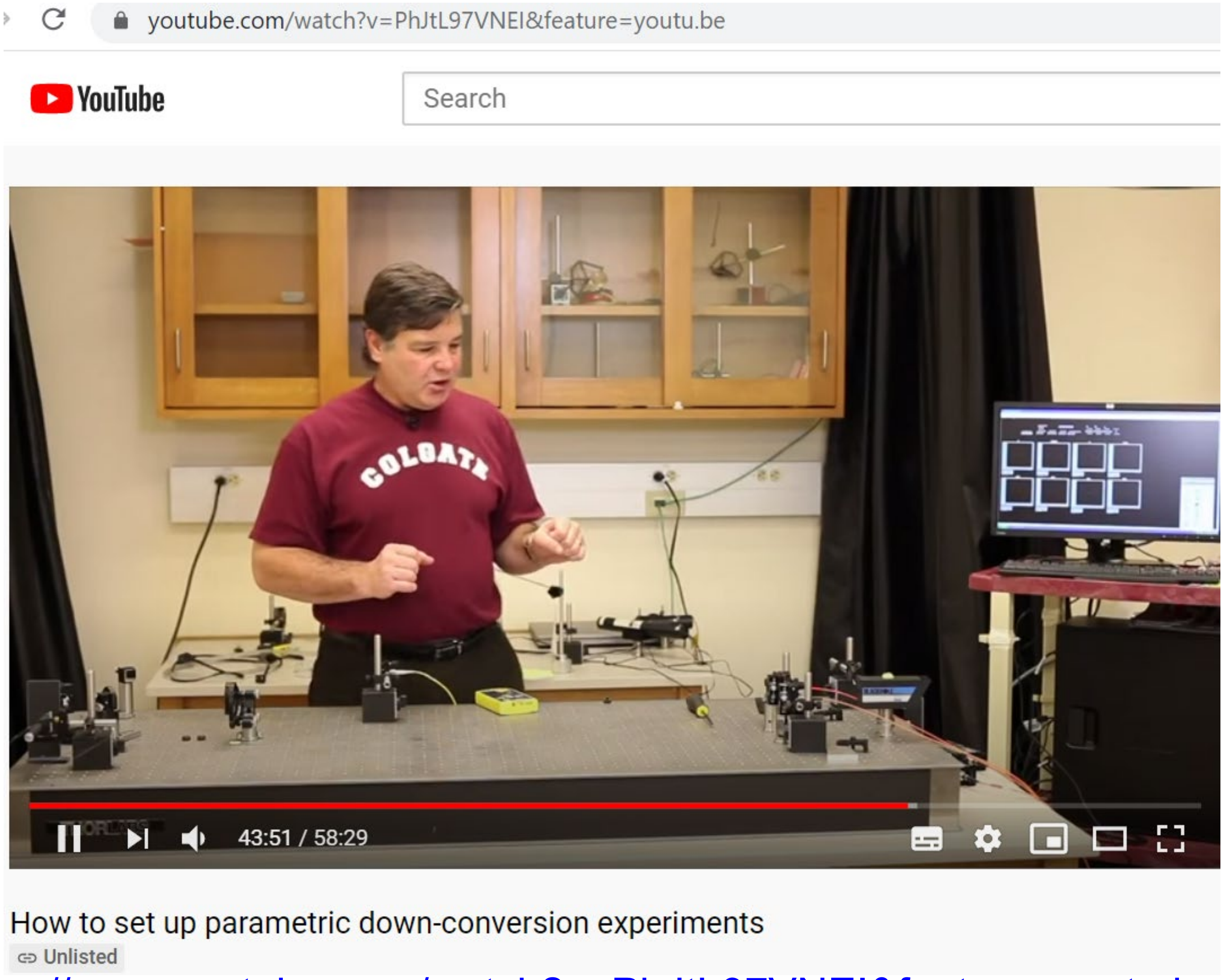
Advances in laboratory techniques for doing experiments with single photons have stimulated studies of the fundamentals of quantum mechanics that underlie such interesting applications as quantum cryptography and quantum computing.[1] In particular, the ability to produce pairs of correlated photons allows us to bring beautiful laboratory demonstrations of quantum superposition to an undergraduate setting where simplicity and affordability are primary concerns.[2]

In this article we describe five table-top experiments that involve the interference of photons detected by a counting apparatus. The experiments involve photons passing through an interferometer, where alternative paths can be made distinguishable or indistinguishable. These experiments can provide the basis for an undergraduate laboratory on the fundamentals of quantum mechanics as proposed in Ref. 3. They go beyond transforming interferometer fringes into counter clicks and challenge classical intuition with results that are unquestionably nonclassical. By incorporating these larization states and manipulate these states as examples of the formation, projection, and transformation of quantum states. We also cause the interference pattern to disappear by manipulating the polarization states of the photons to make the paths through the interferometer distinguishable. A fourth experiment, the quantum eraser, demonstrates how interference can be made manifest in subsets of events that together exhibit no interference. Finally, we perform a conceptually simple experiment that can show that the photon does not split.

Most of our experiments and layouts are based on published landmark experiments on the fundamentals of quantum mechanics. Our references show the sources that we consulted, but they are not chronological or comprehensive.

The cost of the experiments ranges from \$14,000 to \$35,000 depending on the equipment at hand. The cost is dominated by the price of a blue laser (\$2000–\$6000) and two avalanche photodiode detectors (\$4000 each). These prices are likely to decrease in the near future as the technologies mature. The cost of the remaining items depends on the availability of optical hardware and conventional elec-

How to set up parametric down-conversion experiments



https://www.youtube.com/watch?v=PhJtL97VNEI&feature=youtu.be

Remote laboratory

- Online remote teaching - Online Quantum Entanglement experiment at Colgate University: https://medialibrary.colgate.edu/Watch/Hw6b2A5R

- Quantum Entanglement and Cryptography experiments - Quantum Engineering for Mechatronics/Autonomy

  Remote quantum experiments for mechatronics course at California State Polytechnic University, Pomona:

  https://www.youtube.com/watch?v=UqZqlI44u_8&t=

Modernizing Mechatronics Education

Future work: Five quantum engineering experiments for undergraduates for Mechatronics Courses

- **Experimental Photon Quantum Entanglement**
- **Quantum Cryptography**
- **Quantum algorithms using Amazon Braket.**
- **Quantum Communication for multi-agent robotics**
- **Quantum Classical Integration.**

Bell's Theorem

Experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science

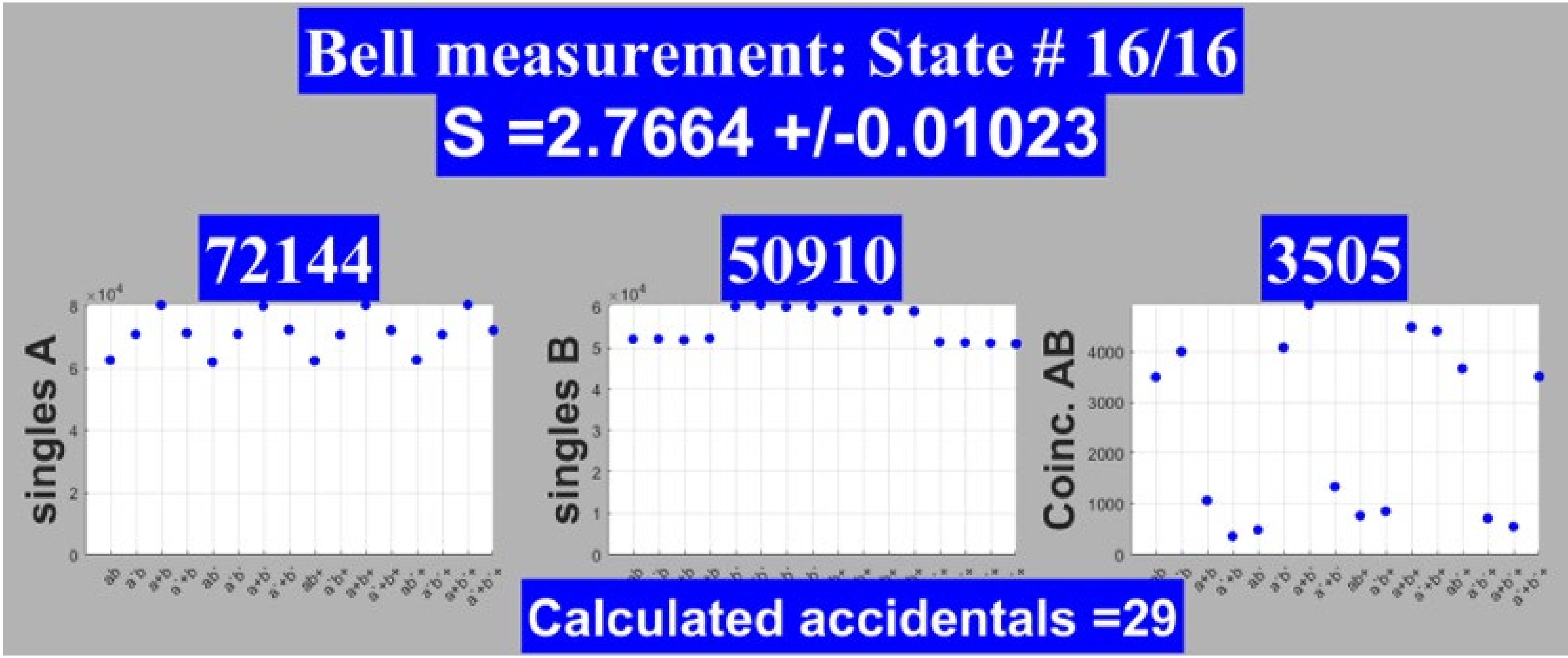
The Nobel Prize in Physics 2022

https://www.nobelprize.org/prizes/physics/2022/summary/

Bell's Theorem: The Quantum Venn Diagram Paradox

https://www.youtube.com/watch?v=zcqZHYo7ONs&t=615s

The Bell inequality test result



Alice (A, A'): $|H\rangle_A$ and $|V\rangle_A$

Bob (B, B'): $|H\rangle_B$ and $|V\rangle_B$

Coincidences AB, A'B, AB', A'B':

$$\frac{1}{\sqrt{2}}\left(|HV\rangle - |VH\rangle\right)$$

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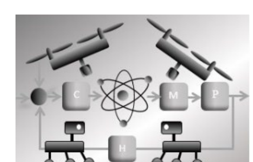

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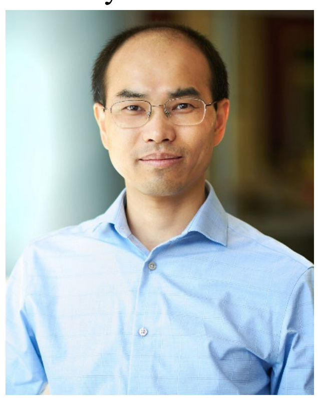

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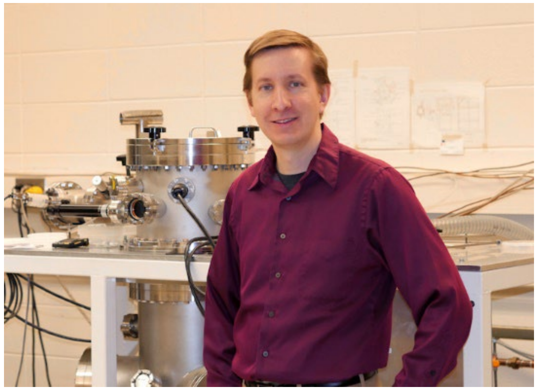

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The Annual Quantum Engineering Workshops

2021:

Link to the workshop flyer 2021

Recording of the workshop

2021: https://www.youtube.com/watch?v=e3PMLmu4mEU

2022:

For the detailed program flyer please click here (2022)

Recording of the Workshop

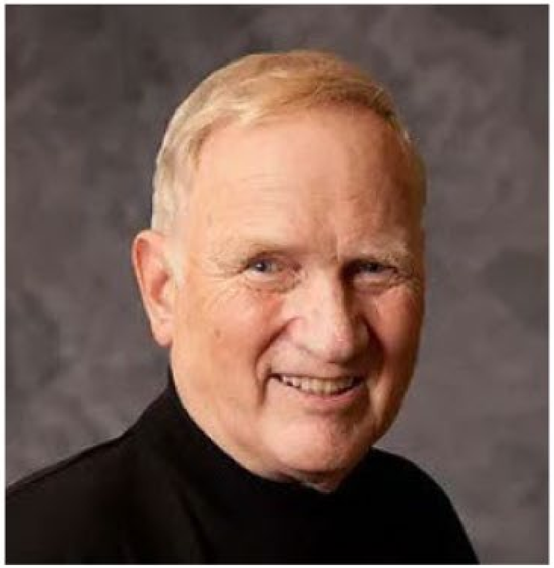
2022: https://www.youtube.com/watch?v=LYwZexenI-Q&t=12578s

2023:

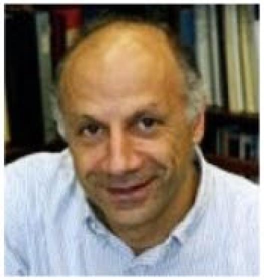
For the Workshop Flyer (2023) with the Program Details, Click Here

For the Video of the recording of the workshop (see the timestamps for each talk on the YouTube link), Click here

Quantum Engineering Workshop



The Nobel Laureate
Dr. John Clauser



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Professor Paola Cappellaro

Dr. Spyridon Michalakis

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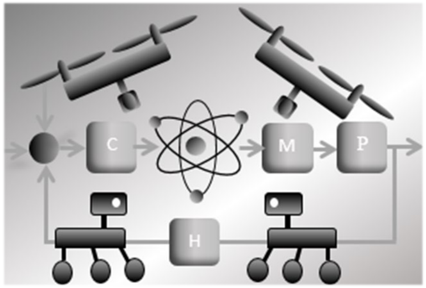

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