Quantum Brain-Computer Interface

Farbod Khoshnoud
Electromechanical Engineering Technology Department, College of Engineering,
California State Polytechnic University, Pomona, CA
Center for Autonomous Systems and Technologies, Department of Aerospace Engineering,
California Institute of Technology, Pasadena, CA
Department of Mechanical Engineering, University of California, Riverside, CA, USA

Marco B. Quadrelli
Mobility and Robotic Systems Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109-8099, USA

Enrique Galvez
Department of Physics and Astronomy, Colgate University, Hamilton, New York 13346, USA

Clarence W. de Silva
Department of Mechanical Engineering, University of British Columbia, Vancouver, Canada

Shayan Javaherian
Department of Mechanical Engineering, California State Polytechnic University, Pomona, CA, USA

Behnam Bahr
Department of Mechanical Engineering, California State Polytechnic University, Pomona, CA, USA

Maziar Ghazinejad
Department of Mechanical and Aerospace Engineering, University of California, San Diego, CA, USA

Anas Salah Eddin
Department of Electrical and Computer Engineering, College of Engineering,
California State Polytechnic University, Pomona, CA, USA

Mohamed El-Hadedy
Department of Electrical and Computer Engineering, College of Engineering,
California State Polytechnic University, Pomona, CA, USA

Abstract

As the importance of quantum technologies is rapidly rising, e.g., in cyber security domain, further surge applications of such systems in various domains are expected in near term. In fact, the integration of quantum technologies with classical systems is inevitable in many disciplines, particularly as quantum devices are becoming more accessible. Among the various areas in which quantum technologies can potentially provide important complementary contributions, the area of Brain Computer Interface (BCI) has yet to be explored. The two areas of experimental photon quantum mechanics and BCI are brought together in this paper, for the first time. The applications of EEG signals to the control of mechanical systems, for example controlling drones remotely with brain wave signals, have been studied by various researchers. This paper presents the mechanism in which an EEG device is used to control the quantum properties in quantum experimental setups. In particular, a brain wave signal is used in changing the polarization of photons using a motorized half-waveplate in pre-built quantum entanglement and quantum cryptography experiments. This, in fact shows the mechanism on how quantum-BCI can be integrated as a system, before BCI-based control can be applied to hybrid classical-quantum systems, such as quantum experiments mounted on robotic platforms. The mechatronics of such systems is explained in this paper. This paper also outlines the necessary educational aspects of quantum related topics for students who have not traditionally exposed to quantum mechanics in their discipline, such as mechanical, aerospace, and electromechanical engineering students, which indeed is an essential step in preparing the next generation of engineering workforce for the fast-changing industry, the R&D sectors and academia. The quantum mechanics education and training steps in the mechatronics course and senior design projects are particularly promoted and discussed here.

1. Introduction

Brain-computer interface (BCI) and EEG systems have been utilized in many Biomedical Engineering applications [1], and beyond. In systems engineering, control of mechanical systems, such as drones, has been addressed by various research groups (e.g., [2]). Integrating brain function and quantum devices have recently been investigated in association with non-invasive brain function mapping through magnetoencephalography, where superconducting quantum interference devices and optically-pumped magnetometers are used to measure brain responses [3]. On the other hand, indications of non-classical brain functions have been reported [4]. A study shows that proton spins of bulk water, which most likely interfere with any brain function, can act as a quantum system [4]. This makes the study of the integration of quantum devices with brain wave signals even more appealing.

Another aspect of this paper is associated with the integration of quantum capabilities with the robotics domain. Various studies have been reported in recent years, for instance, the applications of drones in quantum key distribution ([5]-[10]). Furthermore, the integration of quantum systems and classical physical mechanical systems has been implemented with applications in control and autonomy of classical dynamical systems ([11]-[17]), which provides access to quantum advantages in macroscale mechanical domain.

In this paper, we implement, for the first time, a brain-computer interface mechanism to manipulate the quantum state of photons in quantum entanglement and cryptography setups.

2. Quantum-BCI setup

The introduction to the integration of experimental quantum techniques into classical mechanical systems with applications to control of dynamical systems and autonomy has been presented by the authors in several of their previous publications, [11]-[17], where they propose accessing quantum advantages at the macroscale in classical mechanical domain.

In the study of this paper, electroencephalogram (EEG) signals can be used in triggering the on/off state of the source laser (in a photon-based quantum experiment), or can trigger an electric motor that rotates a Half-Waveplate (HWP) which is responsible in changing the polarization of the photons (sent from the BBO (Beta Barium Borate) crystal to the Single Photon Counter (SPC) detector Modules).

In this research, the signals generated by EEG systems are implemented to provide some level of control in experimental Quantum Entanglement, Cryptography, and Teleportation processes.

The quantum advantage is typically only realized in the quantum domain, and therefore using such capabilities in classical domain can potentially push the boundaries of current classical engineering systems, for instance control of dynamical systems, beyond any existing technique.

EEG signals are used as a trigger in applications associated with the control of integrated quantum processes (Figure 1) experimentally. In particular, a brain wave signal is used to change the polarization of photons using a motorized HWP in quantum entanglement and quantum cryptography experiments. This, in fact, shows the mechanism on how quantum-BCI can be implemented as an integrated system, and BCI-based control can be applied to hybrid classical-quantum systems, such as quantum experiments mounted on robotic platforms. The mechatronics details of such systems are presented in this paper.

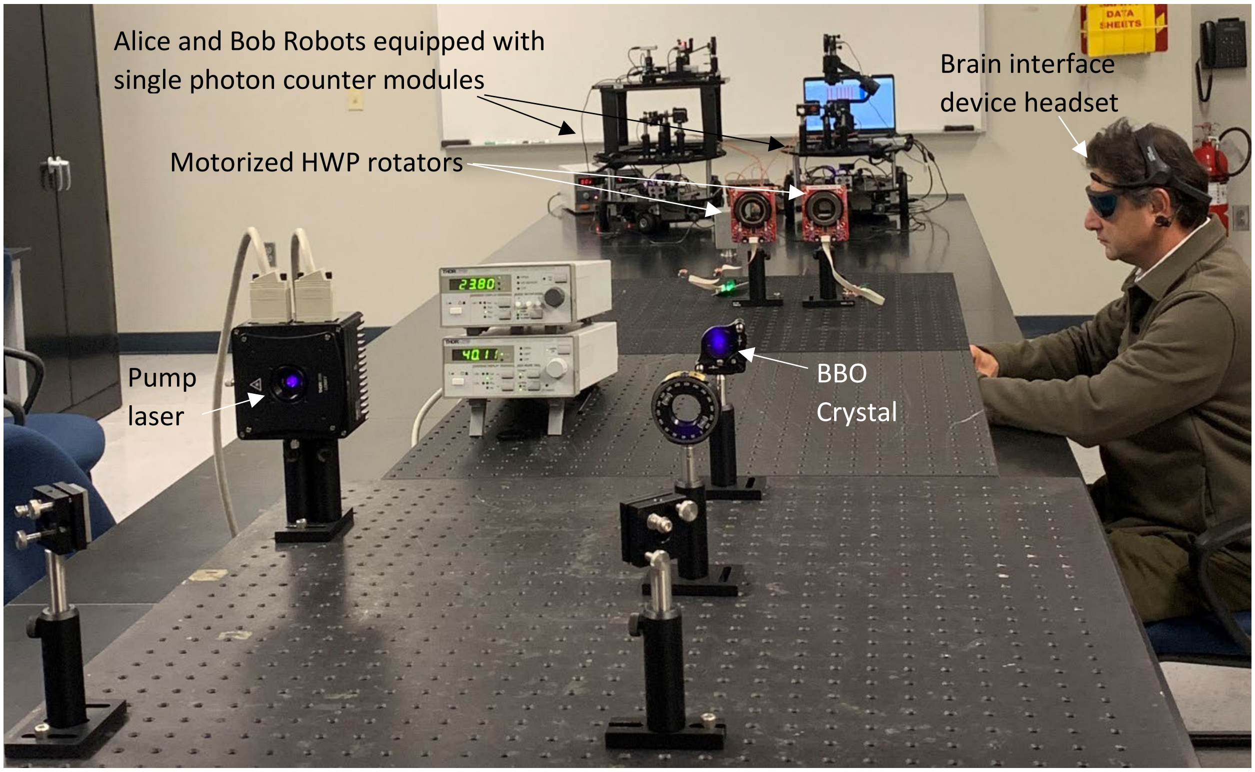

Figure 1. EGG signals in triggering experimental quantum processes.

A basic setup of receiving brain wave signals is used for implementing the BCI in this work. A readily commercially available device, NeuroSky's MindWave Mobile 2 Headset, is used to collect brain wave signals. These signals are electrical impulses that are released by brain neural activities, via a sensor on the forehead and a sensor on the right earloop. The device collects brainwaves data and measure the intensity of concentration and also meditation levels. In the setup in the study of this paper, the headset device sends the data to LabVIEW software using the ThinkGear application and Bluetooth connection. After passing a threshold on concentration level of the received data, the LabVIEW activates the motorized rotators (Figure 1) via a bus distributor, that rotates the HWPs and thus changes the polarization of the photons passing the HWPs.

Implementing quantum entanglement (by spontaneous parametric down-conversion process) into a physical system (at macroscale) can enable two individual systems (e.g. robots, autonomous systems) to share photons that are entangled in their polarizations. Manipulating the polarization of one of the entangled photons alters the state of polarization of the two correlated photons, without any form of communication between the photons. Their correlation is only due to the mutual entangled state they are in. The polarizations of the photons received by a single photon counting detector modules can be converted to digital commands and sent to microcontrollers for control of classical autonomous systems (e.g. robots). Therefore, control inputs can be defined based on horizontal and vertical photon polarizations which will be converted to 0 and 1 digital formats for applications in classical control hardware systems.

The autonomous control system scenario can be referred to, for instance, as a multi-agent robotic scheme, for cooperative robotic or formation tasks. When two robots share entangled photons in such schemes, inputs to the controllers are realized by polarizations of the photons (converted to digital format for classical control applications). We call the robots that share entangled photons “The Alice Robot” and “The Bob Robot” (Figure 2 to Figure 4).

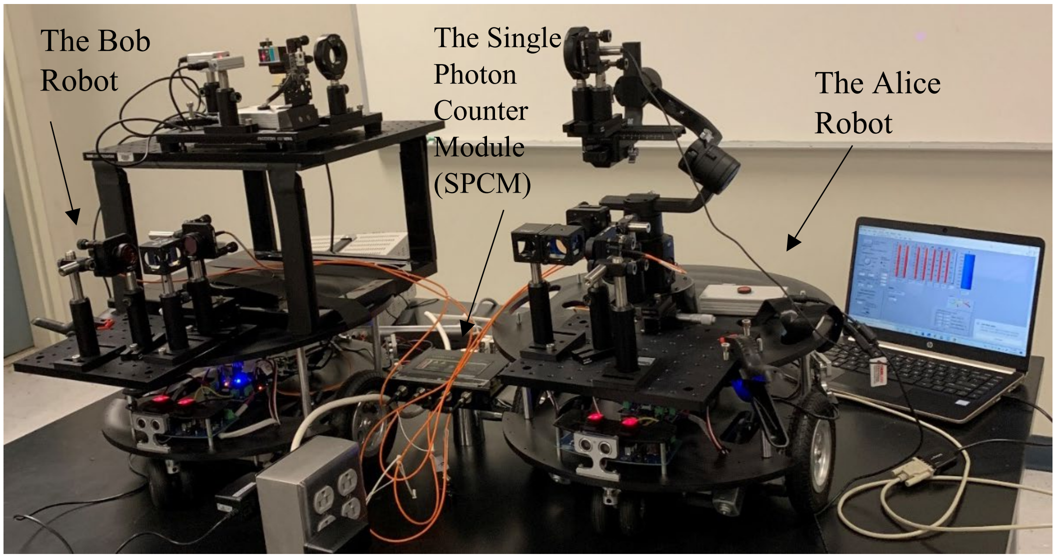

Figure 2. The Alice robot and the Bob robot share quantum entangled photons.

For the details about the quantum entanglement and quantum cryptography setup for the Alice Robot and Bob Robot please refer to [11]-[17]. One of the goals of this research is to pose open questions on the applications of quantum advantages in mechanical systems domain at macroscale for control and autonomy purposes, as well as promoting the research at the interface of quantum and engineering systems as an interdisciplinary research.

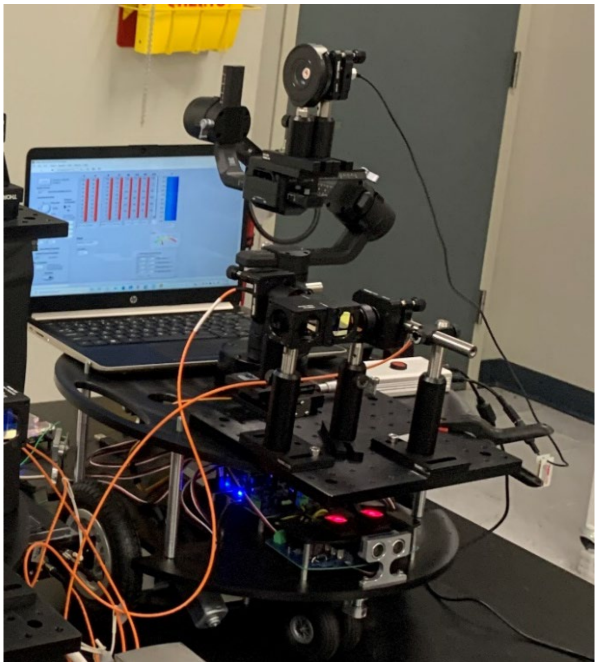

Figure 3. The Alice Robot.

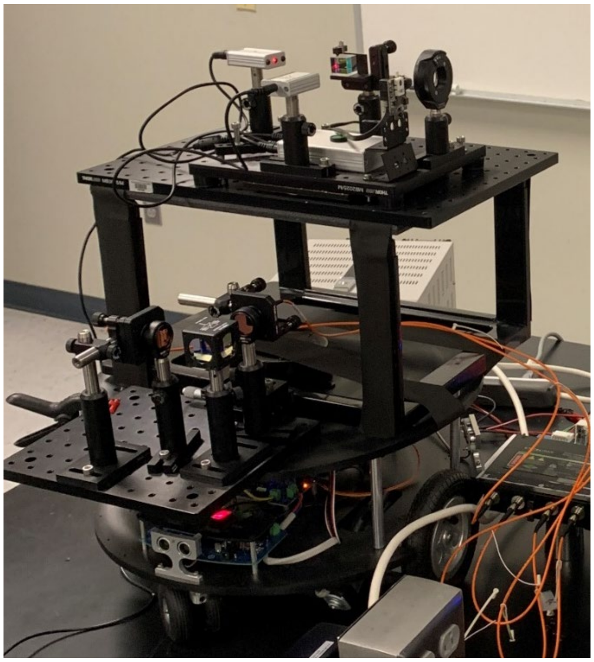

Figure 4. The Bob Robot.

Quantum Cryptography offers guaranteed security in a multi-agent system scenario where security is crucial in control systems and autonomy. Quantum computers are expected to be superior to classical computers in some specific tasks, and are expected to offer complementary solutions by working in conjunction with classical computers in the future. Applications of quantum advantages on classical mechanical systems at macroscale could also be used in conjunction with classical control systems to possibly perform certain tasks better than if the system is only operating by a classical system alone, as complementary solutions. Quantum teleportation could be used in communication between classical mechanical systems, for instance in a network of autonomous multi-agent systems.

3. Experimental quantum entanglement

The details of the experimental setup can be found in our previous articles (e.g., [11]). However, some results are presented as follows. Figure 5 shows the results of polarization entanglement of Alice and Bob. In this figure, AB represents the coincidences of single photon counts of detector A and detector B that are measured by the SPCM detectors for the horizontal polarizations (i.e., projecting onto the state $|H\rangle|H\rangle$). The correlations of the coincidence counts are found for less than 10 ns using a FPGA-based coincidence unit. Correspondingly, A'B' are the coincidence counts of the vertical polarizations (i.e., projecting onto the state $|V\rangle|V\rangle$). The values under the graphs show the accidentals which are very low for the AB and A'B' coincidences. The number of coincidence counts are in the range of 6% of the corresponding single photons, which is acceptable in the spontaneous parametric down-conversion process with a paired BBO crystal.
The variations in the single photon counts and the coincidences, in time domain, seen in Figure 5 is due to the alignment and fine adjustment processes of the BBO, the pump laser, and the detectors for optimum results (The values shown on the top of each window are the final values achieved during the alignment process).

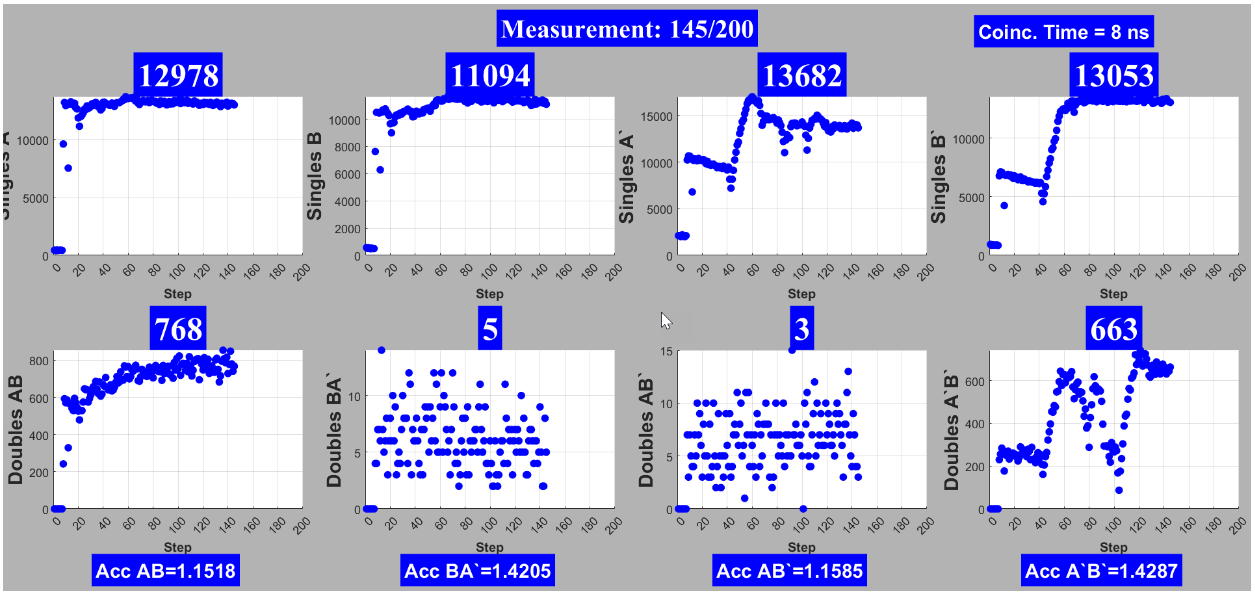

Figure 5. Representative experimental quantum entanglement results using polarized states.

The calibration of the number of photons in states $|H\rangle|H\rangle$ and $|V\rangle|V\rangle$ is carried out by rotating the HWP in front of the 405 nm pump laser. The results of the calibration in Figure 6, shows that the at the angle of 200 degrees the HWP equalizes the amplitudes of the two states.

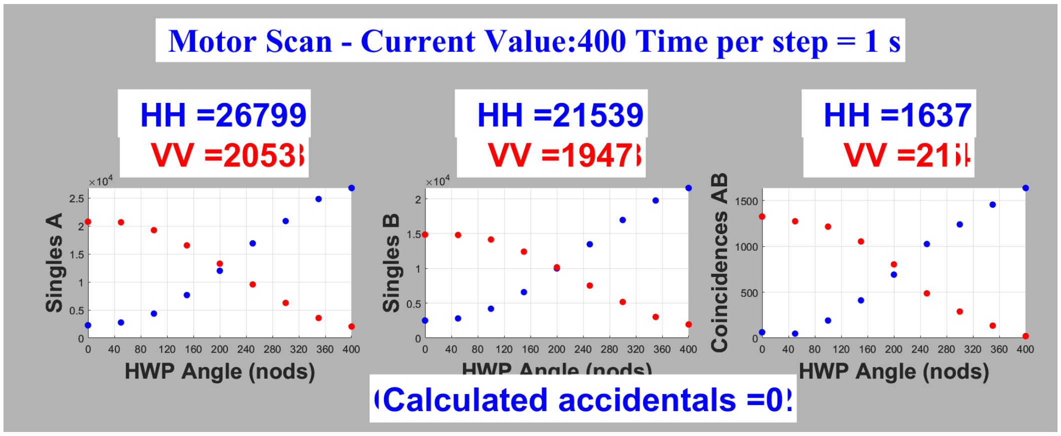

Figure 6. Calibration of the pump laser 405nm HWP.

A quartz plate is placed in between the pump laser and the paired BBO in order to remove the phase shift between the $|H\rangle|H\rangle$ and $|V\rangle|V\rangle$ components of the entangled state, and achieving the quantum state: $|\psi\rangle = (1/\sqrt{2})[|H\rangle|H\rangle + |V\rangle|V\rangle]$. The result shows that at the angle of 150 degrees about the vertical axis for the quartz plate (not shown in the figures) minimizes the coincidences when the photon detections are set to detect anticorrelations in the diagonal basis.

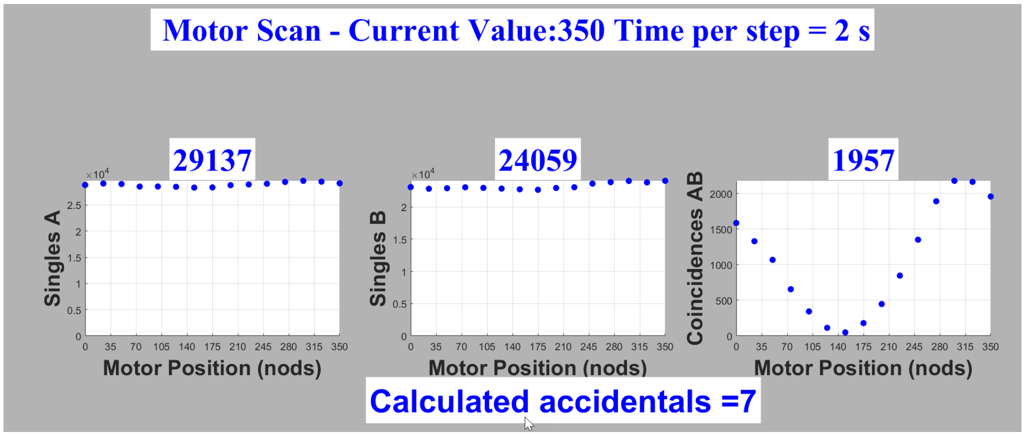

Figure 7. Snapshots of results demonstrating the adjustment of the quartz plate.

We performed a Clauser-Horne-Shimony-Holt Bell inequality test with the photons prepared in the entangled state [18], as described above. The 16 polarization projections for this test are presented in Table 1, and shown in Figure 8, and with the final calculated value of S = 2.766 +/- 0.010. The inequality is violated for S > 2. The result validates the polarization entanglement of the photons.

Table 1. The Bell inequality test (HWP-A: Rotation angle of HWP A, HWP-B: Rotation angle of HWP B, A: single counts for detector A, B: single counts for detector B, AB: coincidence counts for A and B for ~10 ns time window)

Test#	State	HWP-A	HWP-B	A	B	AB	Accidentals
1	a',b	22.5	11.25	62598	52041	3495	26.0613
2	a',b+	22.5	56.25	70929	52087	3995	29.55583
3	a'+,b	67.5	11.25	80280	51820	1067	33.28088
4	a'+,b+	67.5	56.25	71290	52224	362	29.78439
5	a',b'	22.5	33.75	61959	59974	490	29.72743
6	a',b'+	22.5	78.75	70995	60348	4072	34.27525
7	a'+,b'	67.5	33.75	79994	59867	4915	38.31201
8	a'+,b'+	67.5	78.75	72357	59996	1338	34.72904
9	a,b	0	11.25	62332	58799	766	29.32047
10	a,b+	0	56.25	70761	59060	852	33.43316
11	a+,b	45	11.25	80257	59040	4476	37.90699
12	a+,b+	45	56.25	72184	58795	4399	33.95247
13	a,b'	0	33.75	62662	51345	3659	25.73904
14	a,b'+	0	78.75	70853	51210	714	29.02706
15	a+,b'	45	33.75	80373	51076	552	32.84105
16	a+,b'+	45	78.75	72144	50910	3505	29.38281

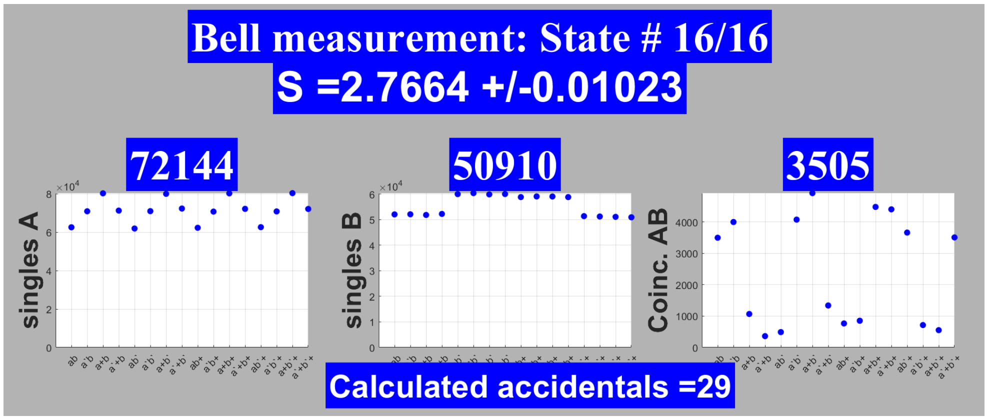

Figure 8. The Bell inequality test result.

4. Educational contributions

As the quantum technologies are rapidly advancing, it is imperative to educate engineering students in this important area. Although, quantum mechanics has been taught in some engineering disciplines, it has only been brought to mechanical engineering and electromechanical engineering undergraduate education course work and senior design projects only recently (e.g., [16]). In this initiative, we have offered experimental quantum entanglement as the fundamentals of quantum mechanics and quantum cryptography as an important application in the Mechatronics course that is offered to the undergraduate students for the first time ([16]). This course is currently offered at California State Polytechnic University, Pomona, as well as various final year undergraduate senior design projects under the topic of "Quantum Communication for Multi-agent Cooperative Robotics and Autonomy" at California State Polytechnic University, Pomona and the University of California, Riverside by the first author. Various student teams have been working on these projects. One of the main aspects of the projects has been focused on automated alignment of the entangled photons to the single photon detectors while the pump laser and the detectors are located on different mobile platforms. Such projects, bring a wide variety of practical and useful mechatronics projects for the students that not only train them for the quantum mechanics area but also continues to enhance their knowledge in traditional engineering topics which is essential for a multidisciplinary engineering project such as mechatronics, controls, automation, robotics, etc. The undergraduate students who take the mechatronics course are normally about 30 junior or senior level students. This is a technical elective course. Although they have no prior background in quantum mechanics, they successfully learn the experimental aspects of quantum entanglement and quantum cryptography. This has been reported by student surveys and exams in reference [16], and it is an ongoing practice. The senior design project teams are teams of 3 to 4 students. The projects can be challenging but the students have been successfully making progress in their projects. This year is the first time that students are actually putting a working prototype of 'quantum communication in multi-agent cooperative robotic scenario' together. We hope to report the results in future publications.

The Bell test experiment, presented in this paper, will be incorporated into the quantum mechanics section of the mechatronics course, which is offered in the Spring semester of 2023 at Cal Poly Pomona, to further enhance the educational aspects for the fundamentals of quantum mechanics for engineering students.

5. Conclusions

In this paper, the idea of bringing the two areas of quantum entanglement and BCI together as the proposed quantum-BCI topic is first presented. In this proposed system the polarizations of the entangled photons are altered via motorized HWPs that are controlled by brain signals. Then, the experimental setup for quantum communication in a robotic scenario was presented, together with quantum entanglement experimental results and the corresponding Bell's inequality test. Finally, the significance of the educational aspects of fundamentals of quantum mechanics in undergraduate education, particularly for those disciples that are not traditionally exposed to quantum mechanics education was discussed. The opportunity of bringing the fundamentals of experimental photon quantum mechanics such as quantum entanglement, and related applications such as quantum cryptography in mechatronics course was presented, as well as offering senior design projects in the related topics such as 'quantum communication for multi-agent cooperative robots'.

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