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Engineering the Quantum Future: Impact of Electrical Engineering in the Field of Quantum Mechanics

Sree Veda Mahanita Kaza, Omar Ali Beg*

College of Engineering and Sciences, The University of Texas Permian Basin, Odessa, Texas, USA
Email: kaza_s74729@utpb.edu, *beg_o@utpb.edu

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Abstract

Electrical Engineering (EE) and Quantum Mechanics (QM) have gone hand in hand for many years, with each field helping the other advance. Many developments in EE, like transistors, lasers, and Magnetic Resonance Imaging (MRI), rely on quantum mechanical effects for their fundamental operation. Similarly, development in EE enabled progress in experimental quantum physics. With devices and circuits shrinking to the nanoscale level, engineers have had to come across quantum phenomena directly. For example, at the 7-5 nm transistor technology nodes, the behavior of the transistor is significantly affected by quantum tunneling and energy quantization. Even though these effects were once negligible at the classical circuits design scale, they have now become increasingly difficult to manage as feature sizes approach atomic scales. Therefore, EE gave rise to the emerging field of quantum engineering by providing tools and techniques to harness, control, and measure quantum systems. This paper reviews the literature on how EE methods have impacted quantum mechanics' research.

Keywords

Electrical Engineering, Quantum Mechanics, Quantum Computing, Quantum Communication, Quantum Sensing, Quantum Control, Superconducting Qubits, Photonics, Quantum Engineering

1. Historical Context

The photoelectric effect played a significant role in sparking the concept of quantum mechanics. This effect depended on measuring the electric currents ejected by the photons on metal surfaces, which shows how electrical instrumentation has been crucial for revealing quantum theory. From Frank-Hertz tubes to Stern-Gerlach magnet setups, early quantum experiments like these were possible because of the electronic detectors, vacuum tubes, and precision power supplied, which early 20th-century physicists and engineers engineered. On the other hand, the invention of the transistor in 1947, which applied concepts like solid-state band theory and tunneling, was a triumph of using quantum physics in EE. Semiconductor devices are inherently quantum devices since understanding band gaps, carrier statistics, and tunneling is essential for transistor design [1] [2]. From an electrical engineering perspective, many of these early quantum experiments were only possible because of improvements in basic electrical measurement techniques. Concepts such as improving signal-to-noise ratio, proper impedance matching between detectors and measurement circuits, and the use of low-noise amplification were critical for detecting extremely weak signals. In experiments like Stern-Gerlach, the measured deflections or currents were very small, and without careful noise reduction and signal conditioning, these effects would have been difficult to observe reliably. This shows that even at the earliest stages of quantum mechanics, progress depended strongly on electrical engineering principles.

The transistor gate oxides thinned to only a few atoms as fabrication technologies advanced, which led to leakage via quantum tunneling that forced innovations like high-k dielectrics [3]. Semiconductor band structure becomes quantized at extremely small dimensions, allowing only discrete energy levels of carriers [1]. These quantum-confinement effects alter threshold voltages, carrier densities, and velocities in nanoscale transistors [4]. Electrical engineers have responded to this by modifying materials and device architectures, such as adopting Fin Field-Effect Transistor (FinFETs) and gate-all-around nanowires, in order to fix deleterious quantum effects [1] [5]. Therefore, the continued scaling of microelectronics has been a practical exercise in quantum mechanics. EE's ability to "fashion ever smaller transistors and circuits" has driven computing for decades, but as devices now approach atomic scales, classical strategies hit physical limits [6].

Apart from microelectronics, EE has also laid the foundation for technologies like the laser and atomic clock. The laser is an optical oscillator based on quantum transitions, while the atomic clock utilizes the quantum hyperfine splitting of cesium atoms. These devices revolutionized both engineering and physics. Lasers enabled countless experiments in quantum topics, whereas atomic clocks demonstrated the power of quantum precision measurement. Nuclear Magnetic Resonance (NMR) is another emblematic example. It was developed in the 1940s to address nuclear spin transitions in matter using radio-frequency circuits. This technology, which was essentially an EE implementation of quantum two-level systems, led to the MRI scanners later on [7]. In all the discussed cases, engineers built devices that could manipulate and detect quantum states like spins and photons with exquisite control, which allowed both fundamental tests of quantum theory and impactful applications.

2. The Engineering Science of Quantum Information Devices

Quantum Computing Hardware is the most prominent intersection of EE and quantum physics today. Quantum Bits (Qubits) are the basic building blocks of Quantum Computing. Qubits are used to store information and are physically realized by two state quantum devices. Qubits require maintaining and manipulating their quantum states, which are extremely sensitive to environmental noise, unlike classical bits in conventional circuits. Since achieving this demands sophisticated electrical and electronic engineering, several hardware platforms for qubits have been made.

2.1. Superconducting Qubits (Circuit QED)

These devices are often based on the Josephson Junction, which is a nonlinear superconducting tunnel junction, and behave as “artificial atoms” with discrete quantum energy levels [8]. These are essentially nonlinear LC circuits where the Josephson Junction provides an inductance that depends on the quantum phase, enabling a two-level qubit subspace to be isolated within an oscillator’s spectrum. This field has grown from basic physics experiments to a mature engineering endeavor over the past two decades [9]. Krantz *et al.* (2019)’s paper mentions how superconducting quantum circuits have evolved, noting that what began as “predominantly basic research” is now “engineering of larger-scale superconducting quantum systems”, including aspects like qubit design, noise mitigation, control electronics, and readout techniques [8]. In the framework of cQED, qubits such as the transmon, flux qubit, or phase qubit are coupled to microwave resonators for control and measurement. Recent experimental milestones highlight the EE-QM synergy. For example, Google’s 53-qubit superconducting processor demonstrated “quantum supremacy” by performing a task that would take a classical computer a millennium in minutes [10]. This was made possible by integrating many qubits on a chip and controlling them with high-bandwidth electronics. It is important to note that this demonstration involved a specific random circuit sampling task designed to be difficult for classical computers to simulate rather than a practical algorithm with direct real-world applications. Even though this experiment clearly demonstrated a quantum processor outperforming classical systems on a well-defined benchmark, it does not mean that current quantum processors can yet outperform classical computers on useful computational problems.

Improving such processors requires dealing with crosstalk, signal integrity, and scaling issues, which are familiar in classical RF engineering but now in the quantum domain. As the qubit counts rise, the control wiring and electronics, which are considered “the most expensive component in a superconducting qubit quantum computing laboratory” [11], have become a significant concern. Engineers have tried to solve this issue by developing specialized control hardware like the Quantum Instrumentation Control Kit (QICK). This is built on a Xilinx RFSoC, which integrates fast digitizers, FPGA (Field-Programmable Gate Array) logic, and processors on one chip to directly synthesize microwave pulses and readout signals for qubits [12]. A typical FPGA structure is shown in **Figure 1**, adopted from [13]. By doing this, separate mixers and local oscillators can be eliminated, which simplifies the control stack dramatically [14]. This and similar open-source platforms have enabled multi-qubit experiments with significantly reduced cost and complexity [15]. They can output precisely shaped pulses for qubit rotations and capture qubit readouts with sub-nanosecond timing, all synchronized by FPGA logic. This is a prime example of EE techniques like digital signal processing and high-speed electronics being applied to meet quantum computing's experimental needs.

Moreover, superconducting qubit research benefits from classical microwave engineering practices in filter design and cryogenic amplifier design, and because of these efforts, state-of-the-art superconducting qubits now achieve coherence times in the 0.1 - 1 ms range and gate fidelities above 99.9% [16].

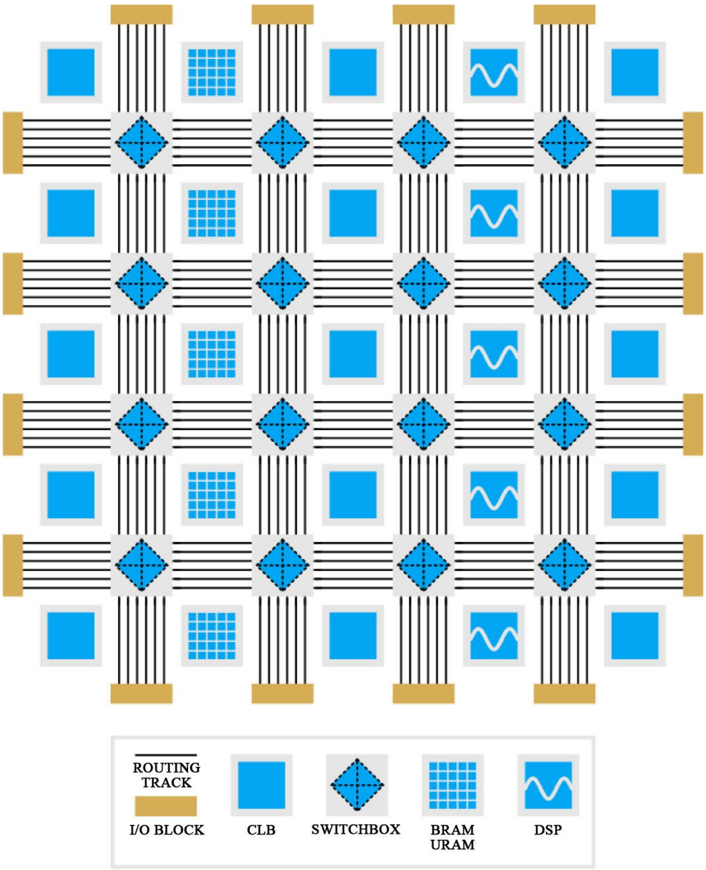

Figure 1. FPGA architecture consisting of a 2-D grid of Configurable Logic Blocks (CLBs), surrounded by programmable interconnect, switch matrices, and peripheral input/output (I/O) blocks [13]. This schematic illustrates how modern FPGAs route signals through configurable routing channels to implement arbitrary digital logic.

2.2. Semiconductor Spin Qubits (Quantum Dots)

Quantum dots are appealing because they have the potential to leverage existing

CMOS (Complementary Metal-Oxide-Semiconductor) fabrication techniques, which promise high-density integration. However, they pose control challenges. For example, manipulating an electron spin usually requires microwave or radio-frequency magnetic fields, fast gate electrodes for electric tuning, and cryogenic readout electronics such as single-electron transistors or charge sensors. Harvey (2022) provides a comprehensive review of semiconductor spin qubits in his paper [17]. He mentions that a spin qubit is formed by confining an electron in a static potential well such that it has a quantized energy spectrum [18]. A practical way to visualize the quantum state of a single qubit is using the Bloch sphere. A qubit can be in a linear combination of the $|0\rangle$ and $|1\rangle$ states with complex coefficients, referred to as a superposition. The qubit's quantum state (**Figure 2**) is encoded in the electron's spin or sometimes in the spin of an atomic nucleus or a pair of spins. This can be controlled through the electron spin resonance, which involves applying an AC magnetic field at the spin's Larmor frequency and causes coherent rotations.

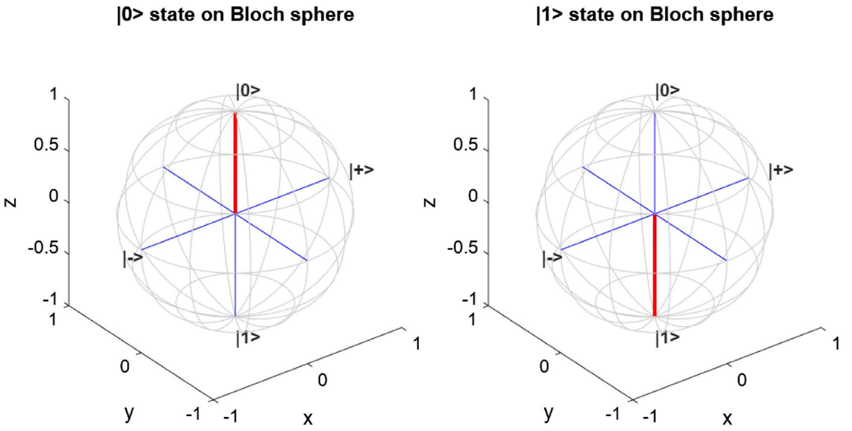

Figure 2. Visualize state of a single qubit in Bloch sphere. By convention, the north pole is the $|0\rangle$ state, the south pole is the $|1\rangle$ state, and the equator is a linear combination of these two states with equal probability of measuring $|0\rangle$ or $|1\rangle$.

Interestingly, many spin qubit implementations use electric fields to control spins by utilizing spin-orbit coupling or electric dipole spin resonance, which makes the standard RF pulse generators and fast voltage modulators become the spin control tools [19]. Since spin qubits are sensitive to magnetic field fluctuations and electric noise, they must be isolated from noise, which demands material engineering using isotopically purified silicon and low-noise cryogenic circuitry to achieve long coherence times [19]. Early experiments were done in GaAs quantum dots, but silicon-based spin qubits have advanced substantially, including MOS quantum dots, Si/SiGe heterostructures, and implanted donor atoms [20]. Due to the improvements in fabrication and control, a "number of spin qubit varieties have attained error rates low enough to be compatible with quantum error correction for single-qubit gates", and two-qubit gate fidelities around 90% - 95% have been achieved in several platforms [21]. In 2022, researchers have notably demonstrated >99% two-qubit fidelity in silicon, which crossed the threshold for error correction in principle. This fidelity level is approximately the minimum required for implementing surface-code-based quantum error correction, where logical error rates can be reduced by increasing system size. Reaching this milestone, therefore, represents a shift from purely experimental demonstrations toward hardware that could realistically support fault-tolerant quantum computation, which was made possible by precise electrical control, low-noise cryogenic electronics, and fast waveform generation. These achievements required refined EE techniques like nanosecond-scale waveform generators to pulse gate voltages that mediate interactions between spins, cryogenic amplification of tiny readout currents, and real-time classical processing to perform feedback or adaptive measurements. One sample case is the use of a charge sensor and a quantum dot adjacent, which will form a tiny transistor whose current is extremely sensitive to the dot's charge state. By monitoring this sensor with a low-noise amplifier, one can detect an electron tunneling out of the dot depending on its spin state, which is read out by spin-to-charge conversion. Since integrating such sensors enables the reading of millions of single-pixel detectors in parallel when scaled up, researchers are also beginning to incorporate control electronics to handle the dozens of gate signals without excessive wiring heat loads. In short, advances in nanofabrication, microwave engineering, and classical electronics have enabled the experimental progress of spin qubits. The ultimate vision is to integrate semiconductor qubits with silicon VLSI technology, allowing the manufacture of quantum processors in chip factories. This is a goal that positions quantum computing as a future extension of electrical engineering.

2.3. Other Qubit Platforms and EE Integration

Several other quantum-bit implementations also benefit from EE innovation. For example, Trapped-ion qubits use electromagnetic traps involving RF and DC electrode structures in order to confine ions in a vacuum. Even though stable RF trapping voltages and precise laser controls with acousto-optic and electro-optic modulators are usually an atomic physics approach, they are an essential EE contribution in ion trap experiments. Similarly, topological qubits and Majorana devices rely on semiconductor/superconductor nanowire circuits at the edge of EE nanotechnology. Even the purely photonic quantum computing, which performs computations with single photons in optical circuits, hinges when it comes to integrated photonic chips fabricated with methods akin to electronic chips, and on fast single-photon detectors, which are often superconducting nanowire devices that output electrical pulses for each photon detection. Quantum computing experiments thus demand a merging of quantum physics with RF engineering, microwave electronics, digital control systems, and cryogenic hardware. Krantz's work, "A Quantum Engineer's Guide to Superconducting Qubits", confirms that advances in quantum computing hardware go together with advances in EE techniques [9]. As the research moves toward larger "Noisy Intermediate-Scale Quantum" (NISQ) processors and even beyond, this partnership is only growing. For instance, efforts are being made to design Application-Specific Integrated Circuits (ASICs) that will operate at cryogenic temperatures to integrate qubit control and readout tightly and reduce latency and wiring complexity.

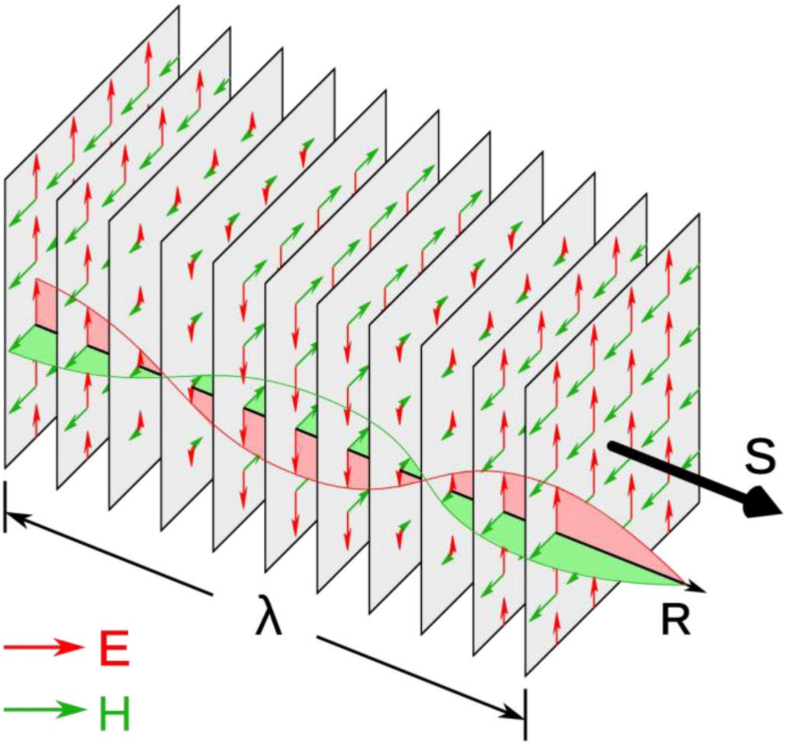

Figure 3. A plane electromagnetic wave showing perpendicular electric filed components (E) and magnetic field components (H) oscillating orthogonally to the direction of propagation. This representation reflects the classical behavior of light and microwave signals used in quantum communication systems.

3. Quantum Communication and Photonic Systems

By enabling fundamentally new protocols like quantum key distribution (QKD) and by suggesting the future possibility of a quantum internet, communications are another field that QM has revolutionized. This involves sending and receiving individual quanta while preserving their quantum states. This is where optical engineering and electronic signal processing work together with quantum physics and electromagnetic wave propagation. A typical electromagnetic wave is shown in **Figure 3** (Courtesy: Wikimedia-Chetvorno). Due to the no-cloning theorem, quantum signals are typically faint and cannot be increased, which makes it a significant challenge where one must engineer extremely sensitive, low-noise links. Researchers have been demonstrating quantum communication over longer distances due to the improved photonic devices and electronics. Fiberoptic QKD (Quantum Key Distribution) has used advanced single photon detectors and ultralow loss fibers to achieve more than hundreds of kilometers of telecom fiber [22]. Experiments have exchanged secret commands over 421 km of optical fiber using QKD protocols and even performed QKD from a satellite to ground across approximately 1200 km in free space [23]. In the discussed demonstrations, the transmitter and receiver hardware made quantum optics work with classical communication tech, where lasers or attenuated laser pulses convert the one-photon signals to electrical pulses and then are processed by standard digital electronics. Micius was the first satellite dedicated to quantum communication, which distributed entangled photon pairs between ground stations that are thousands of kilometers apart. The functioning of this satellite relied on precise optoelectronic engineering, which involved tracking and pointing systems to align ground and satellite telescopes, an ultra-sensitive photon detection module, and custom timing electronics in order to record correlations between the events detected.

Integrated quantum photonics is one of the main trends here, which incorporates sources, waveguides, modulators, and quantum light detectors onto a chip, as integrated electronic circuits have given miniaturization and scalability to traditional communications. Wand *et al.* (2020) further state that this field has transitioned from small "few-component" setups to programmable hardware with nearly 1000 on-chip components, including multi-photon entangled state sources [24]. These chips utilize CMOS photonics fabrication methods via materials like silicon nitride or lithium niobate to guide photons within micron-scale waveguides and route them. Electrical engineers assist this with on-chip electro-optic modulator design in order to alter the phase or amplitude of a single photon dynamically. The modulators feature on-chip single-photon sources, e.g., electrically initiated parametric down-conversion sources or quantum dots, and on-chip detectors. Such chips would typically have to be connected to regular electronics for readout and control. One classic example is a reconfigurable photonic circuit in which, at various points of intersection, it may contain thermos-optic or electro-optic phase shifters, each of which would require a stable voltage or current that is basically an array of analog electrical drivers driven by a conventional computer. Besides, picosecond-resolution time-tagged photons are measured with high-speed electronics such that coincidence measurements verify entanglement or perform QKD. Luo *et al.* (2023) work on the "Recent progress in quantum photonic chips for quantum communication and internet" highlights that quantum photonic chips provide scalability, stability, and low cost to miniaturized quantum communication systems [25]. They survey several of the integrated platforms, including silicon photonics, indium phosphide, and silicon carbide, and conclude that such chips enable integration of QKD or even quantum teleportation circuits onto a tiny device [26] [27]. A photonic chip, for example, could generate entangled photon pairs, perform a Bell-state measurement for teleportation, and send the outcome to classical channels all within one chip with electrical control signals directing the tasks. Similarly, free space and fiber-based quantum communication networks are being developed to integrate with existing networks.

Inter-city quantum network testbeds using commercial telecom fiber to carry classical data and quantum signals on multiple wavelengths have been shown by researchers in Europe, China, and the US [22]. This requires accurate engineering of wavelength filters, multiplexers, and synchronization electronics in order to eliminate the classical signals, which are much stronger and will overwhelm the single-photon quantum signals [28] [29]. One of the monumental achievements in engineering history was the development of measurement-device-independent QKD and twin-field QKD protocols, which reduce some detector-side vulnerabilities and have broken the fundamental rate-loss limit of conventional QKD [30] [31]. Such procedures necessitate quantitative interferometric stability for tens of kilometers of fiber, two-station interference between weak quantum signals made feasible by electronics and feedback for phase-locking.

A single-photon detector is yet another extremely crucial component, whose efficiency was significantly improved by EE developments. Engineers improved the efficiency of Semiconductor avalanche photodiodes, which can detect one photon at a specific wavelength by creating a detectable avalanche current pulse, through enhancing their timing resolution and dark count rates by device structure optimization and cooling.

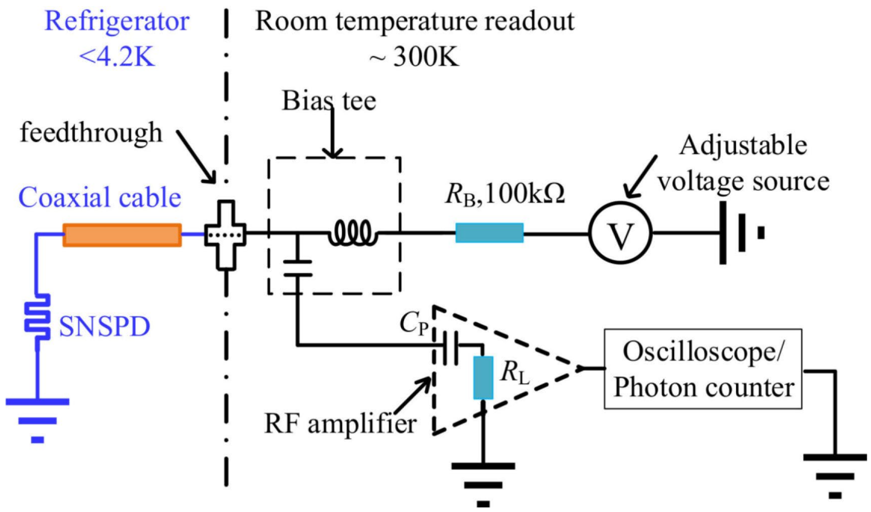

Figure 4. Conceptual diagram of a superconducting nanowire single-photon detector (SNSPD) adopted from [32]. A photon generates a resistive hotspot in the superconducting nanowire, causing a redistribution of current and creating a voltage pulse used for single-photon detection.

Superconducting nanowire single-photon detectors (SNSPDs) have recently been the gold standard. As shown in **Figure 4** (adopted from [32]), wherein Niu *et al.* have provided the SNSPD readout scheme. These are nanolithographed superconducting wires biased near their critical current, where a local normal state transition is triggered by an absorbed photon to generate a short voltage pulse. These detectors provide a very low timing jitter of almost <50 ps and have a high detection efficiency with almost zero dark counts, but require cryogenic refrigeration with a temperature of almost 2 - 4 K. EE plays an important role in integrating SNSPDs into systems since one is needed to amplify and time discriminate their pulses, which is often done by using microwave amplifiers and time-to-digital converters, and correlate the detection stances in real time. Custom cryogenic microwave multiplexers help in reading many SNSPD channels with very minimal wiring. All of these are achievements of precise electronic design under unusual constraints like low temperature and high speed. Making quantum communication practical, therefore, involves integrating optics, analog, and digital electronics and communication engineering, which results in systems where quantum mechanical bits function alongside classical signals in order to open new secure communication possibilities. The field of quantum communications is not only about physics, but also works with interoperability with existing infrastructure and networking protocols. This can be seen in the case of China's Quantum Experiments at Space Scale (QUESS) project, where a quantum satellite QKD link was combined with a classical network, and a secure intercontinental video conference was achieved by augmenting classical cryptography with quantum-generated keys [33] [34]. The research papers about this field often appear in physics journals and engineering venues, which shows its multidisciplinary nature. As efforts continue toward a "quantum internet" in the future, a stronger integration of quantum devices like quantum memories or repeaters with classical networking and possibly a greater role for electrical and computer engineers in designing architectures that distribute entanglement can be expected [35].

4. Quantum Sensing and Metrology

In this field, quantum phenomena are exploited to measure physical quantities with extreme sensitivity and precision [36]. SQUID magnetometers, atomic vapors, and atomic clocks are a few of the historical examples of quantum sensors that were designed by physicists using electrical circuits to interrogate quantum systems [36]. A SQUID is a flux-to-voltage transducer that consists of a superconducting loop with one or two Josephson junctions that can detect minute magnetic flux changes by converting them into voltage oscillations through the Josephson effect. Diagram of a SQUID is shown in **Figure 5** (Courtesy: Wikimedia-Miraceti). Exquisite low noise electronics and cryogenics were required for its development in the 1960s to 1970s, and it remains as a prime example of an engineered device whose sensitivity is fundamentally quantum limited. On the other hand, atomic magnetometers use ensembles of atomic spins, which are often vapor cells of alkali atoms that are processed in a magnetic field, which can be inferred by optically pumping and detecting their quantum spin precession. Since the optical rotation signals are small, low-noise optical detectors and amplifiers are a critical EE contribution. Atomic clocks, however, use a microwave or optical oscillator that is phase-locked to a stable atomic transition frequency. In order to build one, one requires a combination of engineering, since one needs RF/microwave synthesizers, stabilized lasers, vacuums, and cryogenic systems sometimes.

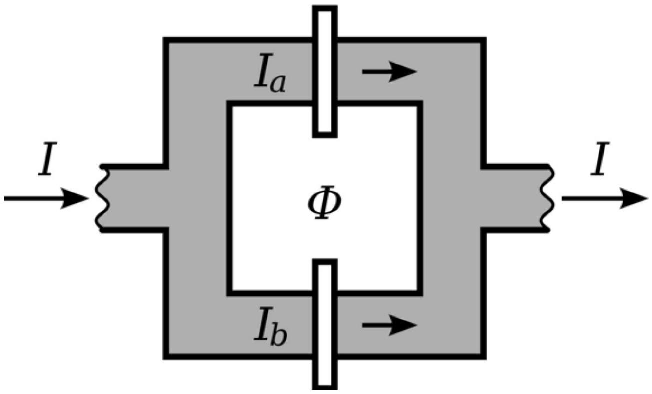

Figure 5. Diagram of a DC Superconducting Quantum Interference Device (SQUID), consisting of a superconducting loop interrupted by two Josephson junctions. External magnetic flux modulates the phase difference across the junctions, producing interference patterns that allow the detection of extremely small magnetic fields.

A research work by Degen *et al.* in 2017 about quantum sensing describes that quantum sensing has become a distinct and rapidly growing branch of research with common platforms including spin qubits, trapped ions, and flux qubits [36]. The attraction of quantum sensors is that they can surpass classical limits like thermal or shot noise by utilizing quantum resources. The NV (Nitrogen Vacancy) center diamond magnetometers use the quantum spin of a nitrogen vacancy defect in diamond as an atomic-scale sensor for magnetic fields. This spin can be initiated and read out visually and manipulated by microwave pulses. This single defect can detect magnetic fields from single electrons or even molecules, considering it is monitored with a photodiode and controlled by a microwave synthesizer. NV magnetometry has given a chance for magnetic imaging of single neuron signals and nanoscale NMR of single proteins in research settings by utilizing both optical engineering and microwave control.

Another area where EE works with quantum metrology is quantum optics and interferometry, which involves the detection of gravitational waves by quantum squeezed light to enhance sensitivity. Squeezed light is where the quantum noise in one quadrature is reduced at the expense of the other, and this was injected into the interferometer to beat the shot noise limit. Generating and controlling this involves nonlinear optics and precise phase control, where the latter is achieved by electro-optic modulators and feedback loops that an electrical engineer might design. Using a network of photodetectors and servo electronics, the squeezed vacuum had to be phase-locked to the interferometer signal with high stability [37]. Therefore, even though the phenomenon of squeezing is quantum, its functioning in an experiment is highly dependent on classical control circuits.

Quantum-limited amplification and noise thermometry are two notable techniques in the RF domain. Josephson parametric amplifiers (JPAs) and the latest travelling-wave parametric amplifiers use superconducting circuits to increase the microwave signals with noise approaching the quantum limit. These devices require pumping by a string microwave tone and careful biasing, which is a task for RF engineering. Their development, as cited by Krantz *et al.* [9], has significantly improved the ability to measure quantum signals without obscuring them with thermal noise.

If the topic is about systematic improvement, entangled and correlated states are being explored in order to improve the efficiency of sensors. Performing this usually involves using one quantum system to sense and another to read out or exchanging quantum information between different physical carriers. This requires complex control sequences like timing electronics and multichannel pulse generation.

Degen's work on Quantum Sensing highlights that quantum sensing's most common platforms, like spins, ions, superconducting circuits, etc., require substantial apparatus and know-how to operate [36]. It also emphasizes an "experimentalist's" viewpoint [38], which is just acknowledging that successful quantum sensors arise from a structure of experiments, which often means electronics, data acquisition, and signal processing, along with creative quantum ideas, of course. This can be seen in flux qubits, which have been used as sensitive magnetometers to detect tiny magnetic moments. The flux's qubit state, be it direction or current, might shift when a small external flux is applied. To read this, one couples the qubit to a SQUID or resonator, and the presence of the external flux then changes a measurable resonance frequency or switching probability, reading out that minimal change might involve averaging thousands of cycles with fast electronics and possibly actively stabilizing the qubit's environment by using feedback coils driven by PID (Proportional-Integral-Derivative) controllers. Therefore, each piece is an engineering solution that enables the fundamental sensitivity of the qubit to be harnessed.

5. Quantum Control Engineering

Controlling quantum systems is where one makes them do desired transformations or stabilize fragile states. This is an area where classical control theory and signal engineering intersect strongly with quantum mechanics. Control theory usually deals with how to drive a system's outputs using inputs in the presence of disturbances and uncertainties in classical EE. Quantum control is similar in spirit but complicated by measurement back-action and the complexity of quantum state spaces. Nevertheless, many control engineering techniques have been successfully adapted to the quantum realm [39] [40]. In contrast, quantum control problems have inspired new theoretical and experimental developments that broaden the concept of control theory. A Royal Society meeting issue in 2013 on "Principles and applications of quantum control engineering" discussed how quantum control has become vital in quantum technology and how concepts like controllability, observability, and feedback must be reinterpreted for quantum systems [41] [42]. While the dynamics of quantum states obey Schrodinger's equation, applying control inputs can be seen as steering a system through a space of unitary transformations, which is a problem quite similar to steering a classical nonlinear system.

The open-loop quantum control has been experimentally used broadly since it shapes control pulses to achieve a desired quantum gate or transfer of state with constancy. This is similar to waveform engineering in the field of communications. For example, engineers designed amplitude and phase modulated microwave pulses that implement precise rotations while minimizing the undesired transitions in NMR and superconducting qubit control. There is an entire subfield of quantum optimal control where computational algorithms are used to find the ideal pulse shapes that achieve a quantum task in minimal time or with maximum robustness. These algorithms often use optimal control theory, like Pontryagin's principle or gradient ascent, and are implemented with heavy classical computing. Julian Berberich, Robert L. Kosut, and Thomas Schulte-Herbrüggen's work "Bringing Quantum Systems under Control" explains about pulses that suppress certain types of noise and create so-called dynamical decoupling sequences, which was an idea originating from NMR spin echo and is now formulated in control terms. They also discuss pulses that implement a quantum logic gate while avoiding crosstalk on neighboring qubits [41] [42].

In practice, these optimal control strategies must operate under significant hardware constraints introduced earlier in the paper. For example, control pulses optimized using Pontryagin's principle are limited by the available bandwidth of room temperature and cryogenic electronics, while the number of control lines is restricted by wiring heat loads at millikelvin temperatures. Therefore, control solutions must balance theoretical optimality with practical limitations such as pulse complexity, power dissipation, and latency, supporting the close connection between control theory and electrical engineering design choices.

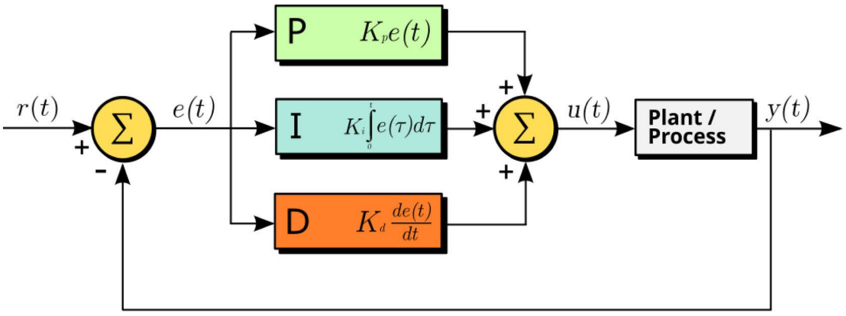

Figure 6. Block diagram of a Proportional-Integral-Derivative (PID) controller showing the three control pathways acting on the error signal: proportional response, integral accumulation, and derivative prediction. The three components combine to generate the control output used in stabilization and feedback systems.

Feedback control on quantum systems is another critical aspect where EE plays a significant role because feedback involves measurement and real-time processing. Traditional control systems like PID controllers and state observers measure a system's output and adjust inputs accordingly. The block diagram of a typical PID controller is shown in **Figure 6** (Courtesy: Wikipedia-Arturo Urquizo). Since measurement affects the state in quantum systems, feedback control must be more subtle, which often requires theoretical frameworks like quantum trajectories or stochastic master equations. Nevertheless, experiments have demonstrated quantum feedback control in many cases. For example, in cavity QED, researchers stabilized a fixed photon number in a microwave cavity by continuously monitoring it with Rydberg atoms and feeding back to a source that injects or removes photons and implements a quantum version of a PID loop. Using fast electronic logic to process the detection signals and apply corrections before the state decayed was the only way this could be possible. As noted by Berberic *et al.* (2023), "experimental realizations of quantum devices require the development of specialized techniques for controlling quantum mechanical systems", and systems and control theory are crucial while tackling noise and scalability challenges [43]. They also highlight that many challenges in quantum computing are "closely connected to control-theoretic concepts" [44]. Decoherence is one of the major issues, where uncontrolled environmental coupling is causing loss of quantum information. In terms of control, it can be seen as a disturbance that one might counteract through feedback or filtering. There is indeed a growing body of research on applying robust control methods to quantum systems [45] [46]. *C* Filtering or Lyapunov control techniques are two that have been adapted for simple quantum models in order to suppress the effect of noise. Berberich *et al.* mention using set-membership uncertainty and modified averaging transformations to handle model uncertainties in quantum control systems, which helps yield performance tradeoffs analogous to classical robust control [47] [48].

From an experimental point of view, a recent achievement was the use of feedback control to correct quantum errors on the fly in small quantum processors. This requires ultra-fast detection and processing, which is essentially building a classical coprocessor that sits alongside the quantum device. This can be seen in the case of superconducting units, where Google and IBM have implemented rudimentary quantum error correction, where a central classical FPGA reads out multiple qubits and computes which error occurred and feeds back a corrective pulse to certain qubits within a few microseconds. This is an ultimate interaction of classical and quantum computing where the quantum chips provide syndrome data, and the classical logic decides on a correction, and then the pulse generators apply it. This entire cycle must be completed very fast. Unlike how a chemical plant has a digital control system, the quantum computer comes with an attached real-time control system to keep it stable. Engineers played a major role in this by optimizing gate and measurement times and inventing fast cryogenic interconnects to make such feedback feasible. Overall, quantum feedback control closely resembles a classical engineering systems problem, where sensing, signal processing, and actuation must all happen within tight timing and thermal constraints. This makes feedback control a key area where electrical engineering directly enables the stabilization and scalability of real quantum hardware.

6. Conclusions

All the literature reviewed makes it clear that EE plays a major role in the advancement of quantum mechanics research and the development of quantum technologies. EE techniques have helped scientists to create, manipulate, and detect quantum states with increasing efficiency since day one. In experimental quantum mechanics, it is the EE techniques of precise instrumentation, circuit design, signal processing, and control algorithms that turn theory into real experiments. Superconducting qubits and semiconductor spin qubits are two of the leading quantum computing platforms that were born from utilizing microfabrication and microwave engineering to trap and control individual quantum two-level systems [9] [49]. Achievements in the field of quantum communications, such as long-distance QKD and satellite-based entanglement distribution, helped advanced optics and classical telecommunication engineering work hand in hand [22] [24]. Quantum sensors like SQUIDs, atomic clocks, and NV centers demonstrate how precisely engineering devices can measure the obstacles imposed by quantum theory [36]. A common theme across these examples that can be observed is that progress was driven by improvements in hardware and control, like faster electronics, lower noise measurements, and better fabrication, as much as by new theory-based physics ideas.

One can also see that the flow of knowledge was bidirectional, where not only EE techniques help achieve quantum research goals, but quantum discoveries are also helping back into the field of engineering. This can be seen in the case of understanding and managing quantum tunneling and quantization, which is now essential for designing nanometer-level transistors [1] [50]. This bidirectional pollination is now giving rise to a new discipline that "bridges quantum science and conventional engineering" to build useful quantum devices and systems. Daniel Ackerman mentions in his article on Quantum Engineering that just as the 20th century had electrical engineers harnessing electromagnetism for technology, the 21st century will see quantum engineers harnessing the counterintuitive properties of quantum mechanics for next-generation technologies [10] [51]. The difference between a "pure" quantum physicist and an "applied" electrical engineer is fading since successful quantum research teams are often inherently interdisciplinary.

As for future advancements, the challenges of scaling up quantum technologies to larger qubit numbers, global quantum networks, etc., will only increase the dependence on innovative engineering. Issues like heat dissipation, integration density, error rates, and manageability of complex systems require the techniques of engineering to be solved. Building a million-qubit quantum computer will require new cryogenic interconnects, chip architectures, and even breakthroughs like quantum-compatible error correction chips, which is a task that requires clever

EE solutions at every level of development. Similarly, a future quantum internet will need quantum repeaters, wavelength converters, and hybrid quantum-classical routers, which are again blending optics, electronics, and quantum memory devices. As Preskill, a leading quantum information scientist at the California Institute of Technology, remarked, our current technologies "have only scratched the surface of how quantum theory has modified our view of what's possible in the universe" [52] and realizing that the rest will depend on concerted engineering efforts.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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