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Student review of innovations in quantum technologies. Part 5

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***Abstract*—The aim of the paper is to show how graduated engineering students in classical ICT view practically the advent of the QIT. The students do their theses in El.Eng. and ICT and were asked how to implement now or in the future the QIT in their current or future work. Most of them have strictly defined research topics and in some cases the realization stage is advanced. Thus, most of the potential QIT application areas are defined and quite narrow. In such a case, the issue to be considered is the incorporation of QIT components and interfaces into the existing ICT infrastructure, software and hardware alike, and propose a solution as a reasonable functional hybrid system. The QIT components or circuits are not standalone in most cases, they should be somehow incorporated into existing environment, with a measurable added value. Not an easy task indeed. We have to excuse the students if the proposed solutions are not ripe enough. The exercise was proposed as an on-purpose publication workshop, related strictly to the fast and fascinating development of the QIT. The paper is a continuation of publishing exercises with previous groups of students participating in QIT lectures**

***Keywords*—quantum technologies, quantum sensors, qantum algorithms**

I. Introduction

QUANTUM Information Science and technologies are potentially influencing, directly or indirectly, the research work performed by the students on their M.Sc. theses. Here, a small group of students doing research in diverse areas including biomedical engineering, software, advanced electronic hardware, communications and cybersecurity participated in a publication workshop. The workshop accompanied a basic lecture on Quantum Information Technologies, and has already been repeated several times with Ph.D. and M.Sc. students groups [1] [2] [3] [4]. The product of the workshop was assumed to be publication of a paper on potential association of the QIT with particular subjects researched by the students for their engineering diplomas. Students were expected to organize on-line or in-person several working editorial meetings related to preparation of the paper. A small editorial team was also defined to polish the final version of the paper and crown it with relevant introduction, conclusions, organized references, etc. The structure of the paper is very simple. Each student was expected to write a concise one-page chapter possibly relating the QIT to personal work performed for the diploma thesis.

These relations were allowed to be loose, even nearing to ones dreams of the type what-if?, yet strongly rooted in the available, published QIT theories and technologies. Students were expected to study a few QIT research papers, strictly of source type, associated with their interests. Strictly original texts of the concise chapters were generated basing on these source papers. Common topical denominators were looked for during the editorial discussions on the final version of the paper. A few general questions were put forward including how to incorporate the new possibilities offered by the three major QIT areas – sensing and timing, computing, transmission and networking into the research done today on quite efficient functional systems.

We are at least one decade away (or more), now as NISQ users, from introducing an error-tolerant (fault tolerant) quantum computer FTQC [5], and perhaps even multilateral (multipartite) quantum communications – initial version of the quantum Internet [6]. Unavoidable coexistence of quite different technological domains in the new generation of the ICT systems with QIT content enforces a substantial change in thinking about the hybrid ICT-QIT system design and applications. The NISQ era of QIT development opens up many possibilities of building hybrid functional systems but still has many limitations. To be able to propose a reasonable hybrid ICT-QIT functionality one has to deeply understand these possibilities and limitations. Therefore, students were asked to base their ideas on the relevant source texts.

II. Quantum Monte Carlo Method

Approximating results of various simulations is a pivotal tool to strategic decision making. In modern world it is pivotal to navigating stock markets, making assumptions about physical phenomena and evaluating investments. Theory of probability provides a method of determining potential outcomes in given system. However they are based on idealistic

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assumptions and to work properly. The expected value can be described with a formula

$$\mathbb{E}(X) = \int_{\Omega} x\, p(x)\, dx$$

or

$$\mathbb{E}(X) = \sum_{\Omega} x_i\, p(x)$$

Where Ω is the set of all possible scenarios in given simulation. $P(x)$ is the probability of specific scenario x occurring and x is the outcome given a specific scenario. This formula theoretically works every time and gives exactly the expected outcome of the system. However, there are several issues that put into question practically of this equation.

Firstly, the set Ω itself for any real world problem is so large that calculating every possible case requires unobtainable processing power. For example to predict value of S&P 500 stock market index one would have to calculate value of every combination of all possible actions taken by 500 largest companies listed on stock exchange and by extension over 29 million employees employed by them. Moreover, expectation formula also requires probabilities of each event happening. Some events are more likely to happen than others and making an educated guess is possible but to get anything more reliable that that in form of actual probability would require knowing the future.

When actual expectation turned out to be impossible to calculate there were attempts to obtain the next best thing. To answer that demand two mathematicans, Stanisław Ulam and John von Newmann in 1946 came up with Monte Carlo method [7]. It assumes that each expected value of a system can be estimated with enough precision by testing values for randomly selected possible scenario and averaging them. The formula they proposed is

$$\mathbb{E}[f(X)] \approx \frac{1}{N} \sum_{i=1}^{N} f(x_i)$$

With this method both problems are solved. The probability of each event is not used so obtaining it is no longer an issue. As for the second issue with size of Ω there is no need to calculate value for every event as this method only gives some approximation. With more iterations this approximation is getting closer to an actual value of $\mathbb{E}(X)$ but sufficiently good approximation of it can be calculated without checking all events. This method doesn't come without drawbacks. Random choice of event can lead to biased data, especially with smaller sample sizes. There is no guarantee that randomly selected events won't be highly improbable events producing outliers when it comes to expected value of a system. The other problem is practical implementation of true randomness which is impossible with classical computers

Since 1940's this approach became popular and is used to this day. But with quantum technologies on the rise it can be further improved upon [8]. With powerful enough hardware there are quantum properties that can be harvested to optimize this process. One of such properties is true randomness [9] obtainable with the usage of quantum computers. With that the risk of biased selection of events by faulty implementation of process is reduced. However the main advantage comes with usage of superposition. This particular property allows computing multiple values at one drastically speeding up the process which allows either to finish estimating faster or calculate more accurate result in the same time frame.

All in all quantum Monte Carlo method in its assumptions and use cases doesn't differ from its classical counterpart. It works on the same principles, and produces the same results, but faster. Given how immensely useful this method is and its widespread adoption in financial sector where competing equity funds are fighting to be first to catch an occasion, quantum counterpart has qualities needed to be usefull and adopted as it comes with potential of earning profits.

III. Quantum Technologies in Robotics: Enhancing Swarm Intelligence with Quantum Computing

Human knowledge in various, often completely disconnected fields, develops and expands every year. Interdisciplinary areas can make even greater progress and achieve unimaginable scientific breakthroughs. Robotics is definitely one of these domains. It is based on electronics, mechanics, information technology, physics, AI, and many more. Most of the currently developed robots are made up of three robotics sectors: Hardware, Software, and Simulations. Every one of them is equally important. The advanced combination of these fields is making even the most complicated and complex robotics ideas come true. Quantum technologies could also find usage in this context, not yet as a dominant hardware solution, but as a powerful accelerator for software and simulations. Their theoretical potential makes them suitable for solving optimization and decision-making tasks that are central to modern robotics. Especially in scenarios that involve high computational complexity and parallel processing—such. The increasing demands placed on multi-agent systems lead researchers to seek new methods for optimizing collective behaviors. Swarm robotics, inspired by biology (e.g., the behavior of ants), assumes the cooperation of many simple robots that achieve global goals through local interactions. One of the main challenges of this approach is motion planning and decision-making in challenging environments. In response to these challenges, the authors of the article "Quantum Planning for Swarm Robotics" proposed the use of quantum technologies, specifically quantum circuits, to support the planning process in robot swarms. [10]

In the Quantum Interaction Model approach, the interaction between robots is treated as a quantum process. Each robot is represented by a set of qubits that encode its position (x and y coordinates) and its assessment of proximity to the goal (so-called "reward"). The quantum circuit (Fig. 1 in the source article [10]) simulates decision-making logic: if robot A is close to the goal and assesses its location as precise, it can share this information with other robots. Operations such as Toffoli gates or X gates are used for conditional information processing while preserving the reversibility of the logic.

After processing the information in the quantum circuit, the qubits are measured, resulting in classical output data. Based on this, robots decide whether and where to move. The entire process operates iteratively according to a specific algorithm: first, robots randomly change their positions within a permitted area, then evaluate their paths to the goal and assign themselves a ”success” value. The robot with the highest score becomes the leader, and its input data are used to launch the quantum planning algorithm. The result of the algorithm allows the swarm to determine a new common exploration point. [10]

Grover’s algorithm, a classic example of accelerated search in quantum computing, is used to select the most promising paths in a complex, dynamic environment. It allows for finding solutions with fewer iterations than classical search. Combined with local interactions between robots, this leads to faster and more effective convergence of the swarm toward the goal. [10]

Simulations conducted in the article showed that the quantum-based approach outperforms classical swarm simulations in terms of speed and efficiency of target finding. The ant-inspired model proved effective in search and rescue scenarios. Figure 1 shows an example of a run of the code with 10 robots that was placed in the article ”Quantum Planning for Swarm Robotics”. [10]

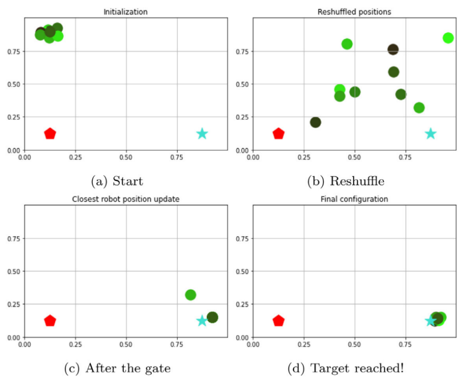

Fig. 1. Results of 10 robots swarm simulation. (Green - robot, Blue - target) [10]

An additional perspective on the intersection of quantum computing and robotics can be found in the article ”Quantum-enhanced Robot Learning”. [11] This work explores how quantum machine learning can enhance optimization in reinforcement learning tasks for robotics. While not focused only on swarm behavior, it demonstrates how quantum algorithms can accelerate the training and adaptability of robotic agents. Such applications, when integrated with swarm strategies, could further improve the coordination and learning of robot systems.

Another relevant contribution is the article ”Modeling and Designing a Robotic Swarm: A Quantum Computing Approach” by Zammuto et al. (2023), which investigates the use of quantum circuits to model local robot interactions in a swarm. [12] This study underlines the importance of information exchange, reversibility, and control logic in the swarm’s internal decision-making process.

The application of quantum computing in swarm robotics opens a new chapter in the design of multi-agent systems. Although quantum computers still have limitations (e.g., noise, number of qubits), simulations already demonstrate the potential of this approach.

IV. TV Solutions Roadmap from Shooting Electrons to Atom Sized Pixels

Display technologies have changed drastically over past decades, undergoing an enormous transformation from heavy and energy-consuming cathode ray tubes to ultra-thin, razor-sharp, quantum-enhanced displays of today. This progression has been driven by advancements in materials science, quantum optics, and semiconductor engineering, each contributing to improvements in color, contrast and brightness, energy efficiency, and compactability.

This section will explore each major milestone in the evolution of television display technologies, from the classical to the quantum, providing a perspective on how we arrived at the vibrant, high-performance screens of today.

Cathode Ray Tube displays rely purely on physical interactions between high-energy electrons and phosphorescent materials. Electrons emitted from the cathode are precisely steered by electromagnetic coils to strike specific points on the phosphor-coated screen, exciting atoms and producing visible light. Despite its ingenuity, CRT technology quickly became obsolete due to its large size, high power consumption, and significant weight.

Plasma Display Panel represented a major shift in display technology, enabling the first generation of slim, flat-panel screens. Each pixel consists of tiny cells filled with noble gases such as neon or xenon. When electrically excited, the gas becomes ionized and produces visible light through gas discharge and phosphorescence.

Liquid Crystal Display technology marked a significant step forward by introducing the use of liquid crystals to modulate light. LCDs do not emit light directly; instead, they manipulate light from a continuously glowing backlight. Voltage is applied to liquid crystal molecules placed between polarization filters, adjusting their orientation to control light transmission. This enables thinner, lighter, and more energy-efficient displays. [13]

Organic Light Emitting Diode technology uses organic semiconducting materials that emit light when an electric current passes through them. Each pixel is self-emissive and eliminates the need for a backlight, allowing for ultra-thin and flexible display structures.

Quantum Dot LED integrates quantum dot (QD) films into

LCD architecture. A QDEF layer composed of nanocrystals emits highly pure red and green light when excited by a blue LED backlight, enhancing color gamut and efficiency. [14]

MiniLED enhances contrast and black levels in LCDs by replacing the uniform backlight with thousands of miniaturized LEDs arranged in local dimming zones. This brings LCDs closer to emissive technologies like OLED in performance. [15]

QD-OLED combines the emissive nature of OLEDs with quantum dot color conversion. A blue OLED layer emits light, some of which is converted to red or green by QDCF. This removes the need for color filters, boosting brightness and efficiency. [16]

MicroLED displays use microscopic LEDs as individual pixels. Once considered impractical, advances in fabrication now allow for high brightness, long lifespan, and superior energy efficiency compared to OLED. [17]

Quantum Dot Electroluminescent represents a new frontier, where quantum dots are directly excited by electricity, rather than backlight. Still in prototype stage, QDEL could deliver ultra-sharp, atom-scale emissive displays with unparalleled thinness and pixel precision. [18]

Television displays have come a long way—from the bulky, analog systems of the past to today's sleek, high-resolution screens shaped by advances in quantum and materials science. Each technological leap has brought us closer to displays that are brighter, thinner, and more efficient.

Looking forward, emerging quantum solutions may lead to displays built from structures just atoms across, enabling levels of sharpness and flexibility once thought impossible. As research continues to push these frontiers, the future of television promises to be more vivid, immersive, and extraordinary than ever before.

V. Quantum Sensors in Space: Present Capabilities and Future Prospects (AT)

Humanity is currently on the verge of a quantum revolution - one that promises great transformative advances not only in fields such as computing, medicine, and materials science, but also in space technologies. Rapid innovation in the world of quantum sensing is increasingly finding its way into space research and exploration. The application of ultra-precise quantum sensors, which exploit the principles of quantum physics such as interference, spin, superposition and entanglement, can pave the way for the enhancement of critical systems aboard spacecrafts. For instance, Attitude and Orbit Control Systems (AOCS), which are essential to the success of almost every space mission, can benefit from quantum gyroscopes, magnetometers and accelerometers that are nearly immune to signal loss. In navigation, quantum sensors could enable fully autonomous deep-space travel by providing highly accurate positioning in environments where traditional methods fail. Moreover, they can boost data quality in planetary observations, gravitational field mapping, and other scientific space experiments. As these technologies progress, quantum sensing is rapidly becoming a cornerstone of next-generation space missions - enabling new scientific discoveries, increasing mission reliability, and supporting long-term exploration beyond Earth orbit.

Atomic and Optical Clocks: The most prominent current use of quantum sensors in the space environment comes in the form of atomic clocks. These are the devices which form the backbone of Global Navigation Satellite Systems (GNSS), such as GPS (USA), Galileo (EU), GLONASS (Russia) and BeiDou (China). Atomic clocks exploit the stable frequency of atomic energy transitions - typically using cesium (Cs) or rubidium (Rb) - to maintain extraordinarily precise timekeeping. An atomic second corresponds to exactly 9 192 631 700 cycles of the radiation associated with the transition between two hyperfine energy levels of the cesium-133 isotope when exposed to excitement. This technology allows for highly accurate timekeeping, which translates into Galileo's High Accuracy Service (HAS) achieving the positional accuracy of up to 20 cm horizontally and 40 cm vertically. Although currently used atomic clocks are already very precise, scientists are working on improvements in the form of optical clocks, which were successfully tested aboard a naval vessel in 2022. Optical clocks operate by locking a laser to the frequency of light absorbed or emitted by electrons transitioning between energy levels in atoms such as strontium (Sr) or ytterbium (Yb). Optical frequencies are much higher than the microwave ones used in traditional atomic clocks, which offers significantly better stability and resolution. The implementation of optical clocks in GNSS satellites could potentially increase positional accuracy to within 1 millimeter [19].

Nitrogen-Vacancy (NV) centers in Diamond quantum sensors: Sensors using Nitrogen-Vacancy (NV) centers in diamond are other devices with a huge potential to revolutionize the space sector. At the core of the technology of these sensors lies the NV center which is a defect found in the diamond lattice. This configuration creates a system with spin – dependent photoluminescence properties. The readout of spin states with the usage of laser light enables extremely precise readings even at room temperature. The technology is highly sensitive to the changes in electric or magnetic fields and temperature. This unlocks the possibility of creating super precise magnetometers which are crucial in magnetic field mapping. Robustness and sensitivity of NV Diamond sensors make them suitable for deployment in harsh space environments, where traditional sensors may not perform as needed. A project from Hasselt University OSCAR-QUBE (Optical Sensors Based on CARbon materials Quantum Belgium) [20] already demonstrated that NV center based magnetometers are feasible in space environments when it comes to magnetic field mapping. Furthermore, NV centers' ability to operate without the robust cryogenic cooling simplifies their integration into spacecraft systems. These advancements show that NV center in diamond quantum sensors could play a significant role in future space missions, providing super-precise measurements of magnetic fields, gravitational anomalies and other geophysical parameters.

Atom Interferometers: Atom interferometers are based on the wave-like nature of ultra-cold atoms to measure inertial forces with extraordinary precision. Manipulation of these near 0 K atoms using laser pulses allows interferometers to detect minute changes in acceleration and rotation which makes them invaluable for applications like gravity field mapping and inertial navigation. The European Space Agency (ESA) is spearheading the application of atom interferometers by preparations of the CARIOQA (Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry) Pathfinder mission [21]. This mission aims to demonstrate the operation of a highly precise quantum interferometer in space environment. The CARIOQA Pathfinder plans on testing a single-axis atom interferometer onboard a satellite in an orbit at an altitude of 600 km. The mission's objectives include validating the performance of quantum sensors in space conditions and assessing their potential in future applications, which paves the way for great improvements in the fields of AOCS, observations and inertial navigation.

As quantum revolution accelerates, quantum sensors are dynamically emerging as transformative tools in space technologies. Precise timing enabled by atomic and optical clocks, exceptional magnetic field mapping capabilities offered by sensors based on NV centers in Diamonds and the potential inertial accuracy of atom interferometer all redefine what is possible in space. All of those highly precise qualities will become valuable as humanity expands the exploration of other planets and deep-space. With initiatives like ESA's CARIOQA Pathfinder and Hasselt University's OSCAR-QUBE demonstrating the feasibility of quantum sensors in space, we can safely assume that the new era for more accurate AOCS, navigation systems and other instruments is ahead of us. However, we still require more insight into the capabilities and that requires more space programs focused on the research of quantum technologies in space.

VI. Quantum techniques for solving differential equations

Differential equations play a foundational role in modeling dynamic systems across numerous scientific and engineering disciplines, such as physics, chemistry, fluid dynamics, control theory, and systems biology. These equations encapsulate the behavior of systems evolving over time or space, making them indispensable in both theoretical and applied research. While the way they can describe physics in an elegant manner is very compelling, solving differential equations efficiently–particularly in high-dimensional regimes–remains a serious challenge for classical methods. The exponential growth of resources needed with increasing system complexity is often a serious limiting factor, requiring ever more powerful computers and ingenuity.

As quantum information technology advances, it offers a new computational paradigm that has the potential to overcome some of the intrinsic limitations of classical numerical methods. Quantum algorithms can exploit entanglement and quantum parallelism to address specific types of differential equations in a more efficient way, especially when these equations exhibit suitable properties.

Some differential equations may be formulated as linear algebra problems, which are more approachable for quantum algorithms. Especially interesting problems suitable for such treatment are linear ordinary and partial differential equations arising from physical systems. One of the earliest and most well-known approaches, the Harrow-Hassidim-Lloyd (HHL) algorithm [22], provides exponential speedup when used for solving sparse, well-conditioned linear systems under certain conditions. Extensions of HHL and related linear system solvers form the foundation for solving discretized forms of differential equations, particularly in areas such as quantum mechanics, electrodynamics, and systems biology [23].

Quantum simulation algorithms, a key area in quantum information science, are naturally well suited for handling time-evolution problems described by differential equations. Hamiltonian simulation techniques [24], [25] enable efficient modeling of unitary dynamics governed by both time-dependent and time-independent differential equations. They are particularly impactful in domains like condensed matter physics, quantum field theory, and quantum thermodynamics, where the underlying physics is governed by complex differential operators and where conventional simulations are often intractable.

The current technology is labeled as noisy intermediate-scale quantum (NISQ) devices. Because of that, fully fault-tolerant implementations of quantum differential equation solvers remain out of reach. Thankfully, for near-term applications, variational quantum algorithms (VQAs) provide a viable and adaptable framework. The Variational Quantum Linear Solver (VQLS) [26], [27] utilizes parameterized quantum circuits to approximate solutions, usually with assistance from classical optimization routines. Such hybrid quantum-classical strategies are compatible with existing quantum hardware and offer a valuable benchmark for exploring quantum enhancements to differential equation solvers under realistic noise conditions.

The application of machine learning in the context of quantum computing has resulted in the development of quantum machine learning (QML) approaches designed for scientific computing tasks [28]. Quantum neural networks are being researched as they appear as promising means for approximating solution functions to differential equations. QML may prove especially advantageous in problems where the equations are only partially known or where data-driven models are preferred. It is particularly well-suited for high-dimensional PDEs arising in financial modeling, fluid dynamics, and climate science, where conventional numerical methods may falter due to the curse of dimensionality.

The integration of quantum algorithms for differential equations with classical methods–such as optimization techniques, spectral methods, adaptive mesh refinement, and multigrid solvers–could be the pioneering hybrid architectures that prove to be scalable and robust. Also, as quantum error correction protocols improve and more resource-efficient algorithms are developed, the long-term potential of quantum computing in scientific modeling will likely include not only speedups but also fundamentally new capabilities in representing and manipulating complex solution spaces.

Quantum computing presents a rapidly evolving set of techniques for the solution of differential equations, which may help in solving some of the most pressing computational difficulties encountered in this realm. Persistent progress in both algorithm and quantum hardware design hints at a promising future for quantum-enhanced differential equation solvers, which–if it were to happen–is likely to have a monumental effect on science and mathematics.

VII. Quantum Ion Traps: Realization of Qubits Using Trapped Ions

Quantum computation requires information carriers—qubits—that exhibit fundamental quantum properties such as entanglement and superposition. Various physical realizations of qubits exist, including photonic, superconducting, topological, and quantum dot qubits, each characterized by specific properties and applications. In this part of the paper, qubits represented by ions are discussed, along with methods of trapping and controlling them in quantum ion traps.

An ion is an atom that has lost one or more electrons, thereby disrupting the balance between the positive charge of the nucleus and the negative charge of the orbiting electrons, resulting in a net positive charge. Charged particles can be manipulated using electric fields—causing electrostatic forces—and magnetic fields—causing Lorentz forces. By appropriately shaping and modulating these fields, it is possible to trap ions within a confined space and perform computations on them.

In ion trapping technology, two primary types of traps are distinguished: the Penning trap and the Paul trap. The Penning trap utilizes both a static magnetic field and a static electric field. The electric field, created between the top and bottom electrodes, immobilizes the ion along the vertical axis (z-axis), while the strong magnetic field, reaching intensities of 2–3 Tesla, maintains the ion's confinement in the horizontal plane (xy) via the Lorentz force, causing the ion to move along small circular orbits. In contrast, the Paul trap relies solely on a time-varying electric field [29]. In this case, the ion is stabilized along the z-axis by appropriately polarized top and bottom electrodes, while in the xy-plane, stability is ensured by dynamically alternating the polarization of side electrode pairs, generating a time-dependent electric field.

After trapping, ions must be cooled to limit their intrinsic vibrations, which affects the stability of quantum states and the coherence time. Laser cooling techniques are used, employing a laser beam with a frequency slightly lower than the ion's minimum photon absorption frequency, exploiting the Doppler effect. An ion moving toward the laser source absorbs photons, which, according to the law of conservation of momentum, leads to a loss of its own momentum. The absorbed energy is then re-emitted through spontaneous emission. Due to the random nature of the emission process, the resultant momentum vectors of emitted photons sum approximately to zero, preventing additional excitation of the ion's motion.

Encoding logical states 0 and 1 in ion-based systems can be realized in two ways, depending on the properties of the particle that exhibit superposition. The first approach assigns logical values to specific electronic energy levels within the atom, with a higher energy state representing a logical "1" and a lower one representing a "0". Alternatively, electron spin can be used, where, for instance, a positive spin state corresponds to "1" and a negative spin state to "0".

Cooled ions trapped in an ion trap are entangled using laser pulses. These pulses simultaneously introduce the ions into a superposition state, and due to the close proximity of the ions, their quantum states become interdependent. The ability to entangle multiple ions can be analogized to the formation of conduction and valence bands in solid-state systems, where the close arrangement of atoms in a lattice leads to overlapping and splitting of discrete energy levels, forming bands.

The ability to induce entanglement and superposition in ion qubits enables the performance of quantum operations. After computations are completed, it is necessary to read out the system's state. This process also uses laser radiation, with the readout method depending on the type of qubit encoding. In the case of energy level encoding, the ion's response to the laser pulse manifests as either the presence or absence of photon emission. For spin-based encoding, the ion's response is reflected in characteristic changes in vibrational modes [30].

Ion trap technology is considered one of the most promising approaches in the field of quantum computing. This is due to its high scalability [31], the potential for realizing planar ion trap structures [32], and relatively long coherence times compared to other technologies. Quantum ion traps combine high controllability of quantum states, precise techniques for manipulating individual particles, and effective cooling methods. The ability to induce superposition and entanglement in trapped ions, alongside efficient quantum state readout, opens the path toward the realization of increasingly complex quantum operations and the construction of scalable next-generation quantum computing architectures.

VIII. Diamond Quantum Sensors: A Revolution in Precision Measurement

Diamond quantum sensors, based on nitrogen-vacancy (NV) centers embedded in the crystalline structure of diamond, represent a cutting-edge innovation at the intersection of quantum physics, advanced nanotechnology, and precision materials engineering [33]. These unique sensing systems derive their exceptional capabilities from the quantum properties of NV defects, which enable the measurement of fundamental physical quantities—such as magnetic fields, temperature, mechanical stress, and electric fields—with unprecedented accuracy and resolution at the nanometer scale. Crucially, these sensors operate at room temperature, eliminating the need for complex and expensive cryogenic systems, and positioning themselves as a revolutionary alternative to conventional measurement technologies.

At the heart of these advanced sensors lies the NV center—a defect in the diamond lattice formed when a carbon atom is replaced by a nitrogen atom and an adjacent vacancy (missing carbon atom) is created. This atomic configuration gives rise to a unique electron spin state characterized by quantum phenomena such as superposition and entanglement. Importantly, this spin state can be precisely manipulated and read out using laser light, forming the basis for their function as highly sensitive sensors.

The principle behind NV center-based detection is rooted in the emission of fluorescence triggered by light excitation [34]. When exposed to green laser light, the NV center emits red photons, and the intensity of this luminescence reflects the electronic spin configuration of the defect. Variations in environmental conditions—such as magnetic field strength or temperature—can shift the spin state, which modifies the amount of emitted light. This mechanism forms the foundation for detecting minute physical changes with high precision.

A widely applied technique in this context is Optically Detected Magnetic Resonance (ODMR). It involves subjecting the NV center to a microwave field while simultaneously tracking its fluorescent response. As the microwave frequency aligns with specific spin transitions, changes in fluorescence intensity occur due to altered spin populations. Mapping these responses across a frequency spectrum yields detailed information about the surrounding magnetic environment. Shifts in the resonance frequency—caused by external magnetic fields via the Zeeman effect—can be accurately measured, enabling magnetic imaging at the nanometer scale. Such capabilities are instrumental in cutting-edge research and nanoscale diagnostics.

The range of applications for diamond quantum sensors is vast and rapidly expanding. In biology and medicine, they offer unique capabilities for studying processes at the level of single cells. They can be used to image neuronal activity with high spatial and temporal resolution, monitor microscopic temperature changes within cells, track metabolite flow, and detect single ions or biomolecules. Their ability to operate in aqueous environments and at physiological temperatures makes them highly promising tools for in vivo studies, both in preclinical models and potentially in future clinical diagnostics—for example, in early cancer detection or therapy monitoring. Intensive research is underway to integrate NV sensors with miniature micro-optical systems and implants, potentially leading to a new generation of smart biomedical systems for real-time health monitoring.

In geophysics and materials science, NV sensors are used for non-invasive detection of local stress in crystalline structures. Thanks to their sensitivity to environmental changes, they can identify defects, microcracks, and other irregularities in materials—crucial for quality control and durability assessment. They are also employed in the study of paleomagnetism in meteorites and rocks, offering valuable insights into the history of Earth's and other celestial bodies' magnetic fields. In microelectronics, NV sensors pave the way for nanoscale diagnostics of integrated circuits, enabling the analysis of voltage and current distributions in transistors—critical for the development of smaller and more efficient electronic devices. There is growing interest in their potential role in spintronics, an emerging field that uses electron spin as an information carrier, offering faster and more energy-efficient devices.

Despite their immense potential, the development of this groundbreaking technology presents significant challenges. Producing synthetic diamonds with high purity and precisely controlled NV center density and placement requires advanced and costly processes, such as chemical vapor deposition (CVD) and precision ion implantation. Another major hurdle is the effective integration of NV sensors with miniature microwave, optical, and detection components while maintaining low energy consumption and compact form factors. However, rapid progress in nanofabrication, integrated optics, and quantum electronics is gradually overcoming these challenges, paving the way for the commercialization of this technology [35].

The technological potential of NV-based quantum sensors is widely recognized. Their ability to function effectively without the need for cryogenic cooling, combined with outstanding mechanical durability, chemical inertness, and resistance to physical degradation, positions them as promising tools in next-generation measurement platforms. Furthermore, their compatibility with emerging technologies—such as artificial intelligence (AI), Internet of Things (IoT), and wearable electronics—enhances their versatility across diverse applications. As these sensors continue to evolve, they are expected to significantly impact various fields including medical diagnostics, environmental sensing, material science, and high-resolution biological imaging, paving the way for transformative advancements in both science and industry.

IX. The Deutsch–Jozsa Algorithm: the first algorithm to outperform a classical computer

Since the beginning of quantum computation research, tenths of quantum algorithms have been developed. Their potential applications lie in a wide range of domains, from the possibly most widely acknowledged ones, such as cryptography, to those a bit less commonly acknowledged, like quantum system simulation. The validity of the concept of quantum superiority was proven in 1992 with the introduction of the Deutsch–Jozsa algorithm. Although the problem that it solves is not directly practical, it is the first algorithm to outperform its classical counterpart.

The problem solved by this algorithm can be stated as follows. For a given function f: $\{0,1\}^n - > \{0,1\}$ find out which of the following statements is true:

- f is not a constant function (one that returns always 0 or 1 regardless of input)
- f does not return 0 for exactly half of all possible input 0's and 1's combinations, and 1 for the other half

In the case where both statements mentioned above are true, the algorithm may not give a correct answear. [36] Therefore, it is assumed that the chosen function only meets the conditions of one of these statements.

As for the performance and computational complexity criteria, a classical algorithm for this problem would, in the worst case, require $2^{n-1}+1$ evaluations of f to determine the answer. The Deutsch–Jozsa algorithm requires only a single evaluation of f. [37]

For the purpose of further algorithm explanation, basic notation needs to be explained. The qubit can be identified as a vector ψ in the two-dimensional Hilbert space defined as follows:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \alpha\begin{pmatrix}1\\0\end{pmatrix} + \beta\begin{pmatrix}0\\1\end{pmatrix} \tag{1}$$

where the scalars α and β are complex numbers, normalized so that $|\alpha|^2 + |\beta|^2 = 1$. Their values represent the probability amplitudes of states $|0\rangle$ and $|1\rangle$ respectively.

Multiple qubits $|i_1\rangle|i_2\rangle\ldots|i_n\rangle$ can be represented as $|i_1 i_2 \ldots i_n\rangle$, where the vector e.g. $|01\rangle$ can be written as $|0\rangle \otimes |1\rangle$, which is the tensor product of $|0\rangle$ and $|1\rangle$:

$$|01\rangle = |0\rangle \otimes |1\rangle = \begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}0\\1\\0\\0\end{pmatrix}$$

[38] To perform operations on qubits, they are passed through quantum gates, which, similarly to traditional electric gates, transform the values (qubits in this case) that go into them. The mathematical notation of these operations can be done using a matrix representation of the gate and left-multiplying the input value by the gate's transformation matrix. An example of a very commonly used quantum gate is the Hadamard gate. For just one qubit as an input, the matrix notation of the gate is as follows:

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\1 & -1\end{pmatrix}$$

For longer inputs, the Hadamard gate 'grows' as follows:

$$H^{\otimes(n+1)} = H^{\otimes n} \otimes H \tag{2}$$

The principals behind the algorithm can be stated as follows. The quantum system starts in initializing n qubits to 0's and one qubit to a 1.

$$|\psi_0\rangle = |0\rangle^{\otimes n} \otimes |1\rangle \tag{3}$$

Then, the Hadamard transform is applied to each qubit of $|\psi_0\rangle$.

$$|\psi_1\rangle = \otimes_{i=0}^{n-1} H\,|0\rangle \otimes H\,|1\rangle =$$
$$= \left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right)^{\otimes n} \otimes \left(\frac{1}{\sqrt{2}}|0\rangle - \frac{1}{\sqrt{2}}|1\rangle\right) =$$
$$= \frac{1}{\sqrt{2^{n+1}}}\sum_{x=0}^{2^n-1}|x\rangle(|0\rangle - |1\rangle)$$

Next the f operation is performed using a quantum oracle that converts the input state $|x\rangle|y\rangle$ to $|x\rangle|y \oplus f(x)\rangle$ ($\oplus$ representing addition in modulo 2 arithmetic).

$$|\psi_2\rangle = \frac{1}{\sqrt{2^{n+1}}}\sum_{x=0}^{2^n-1}|x\rangle(|f(x)\rangle - |1 \oplus f(x)\rangle) =$$
$$= \frac{1}{\sqrt{2^{n+1}}}\sum_{x=0}^{2^n-1}(-1)^{f(x)}|x\rangle(|0\rangle - |1\rangle)$$

As the last step, we perform the Hadamard transform only on the first n qubits of $|\psi_2\rangle$, so we ignore the last qubit $\frac{|0\rangle - |1\rangle}{\sqrt{2}}$.

$$H^{\otimes n}|x\rangle = \frac{1}{\sqrt{2^n}}\sum_{z=0}^{2^n-1}(-1)^{x\cdot z}|z\rangle$$

$$\frac{1}{\sqrt{2^n}}\sum_{x=0}^{2^n-1}(-1)^{f(x)}\left(H^{\otimes n}|x\rangle\right) =$$
$$= \frac{1}{\sqrt{2^n}}\sum_{x=0}^{2^n-1}(-1)^{f(x)}\left(\frac{1}{\sqrt{2^n}}\sum_{z=0}^{2^n-1}(-1)^{x\cdot z}|z\rangle\right) =$$
$$= \frac{1}{2^n}\sum_{z=0}^{2^n-1}\left(\sum_{x=0}^{2^n-1}(-1)^{f(x)}(-1)^{x\cdot z}\right)|z\rangle$$

The probability of measuring all output qubits being in the $|0\rangle$ state is equal to:

$$\left|\frac{1}{2^n}\sum_{x=0}^{2^n-1}(-1)^{f(x)}\right|^2 \tag{4}$$

It can be noticed that the above equation is always equal to 1 if f is constant and is always equal to 0 if it is balanced (returns 0 for exactly half of the possible input values). Therefore, if all output qubits are measured as zeros, it means f is constant. Any other output means that f is balanced. [38]

X. Quantum technologies in Control Systems: optimizing controller parameters and quantum sensing

Quantum technologies are increasingly influencing control systems engineering, offering novel approaches to system modeling, controller optimization, and sensing capabilities. These advancements are particularly pertinent in scenarios where traditional methods face limitations due to safety concerns or the complexity of the systems involved.

In control systems engineering, tuning controllers such as Proportional-Integral-Derivative (PID) regulators necessitates accurate modeling of the target system. Direct experimentation on physical systems is often impractical or hazardous, especially when dealing with critical infrastructure or systems sensitive to instability. Consequently, digital simulations have become integral to the design and tuning process. These simulations typically involve solving differential equations that represent the system's dynamics. Numerical methods approximate these solutions, with the accuracy dependent on factors like machine precision and integration step size. Smaller step sizes generally yield more accurate results but at the cost of increased computational resources.

Quantum computing is emerging as a powerful tool for solving differential equations. Classical methods often struggle with high-dimensional or stiff systems, especially when real-time or large-scale simulations are required. Quantum algorithms offer potential speedups by reformulating these problems into forms suitable for quantum processing. A key example is the Quantum Linear Systems Algorithm (QLSA) to solve systems of linear differential equations. [22] This method encode the solution into a quantum state, providing exponential or polynomial efficiency gains under specific conditions. [39]

For nonlinear systems (common in real life applications) variational quantum computing has shown promise. This technique utilizes multiple copies of variational quantum states to treat nonlinearities. [27]Their effectiveness on nonlinear oscillators and reaction-diffusion systems poses great values relevant to control dynamics.

Once a reliable model is established, simulations can be used to assess the performance of various controller parameters. Optimization algorithms, such as genetic algorithms or particle swarm optimization, are employed to identify parameter sets that minimize performance criteria like overshoot, settling time, and steady-state error. This iterative process enhances the efficiency and effectiveness of controller tuning.

Quantum computing introduces new paradigms for optimization problems in control systems. Quantum algorithms leverage principles like superposition and entanglement to explore multiple solutions simultaneously, potentially accelerating convergence to optimal solutions. An illustrative example is the application of an improved quantum genetic algorithm (IQGA) for tuning PID controllers in Permanent Magnet Synchronous Motors (PMSMs). This approach integrates quantum-inspired operations, such as Hadamard gates and adaptive weight changes, to enhance the global search capability and avoid local optima. In the simulation, IQGA can achieve the required speed faster than classic genetic algorithm, and there is no overshoot or oscillation compared to particle swarm optimization, and the speed is more stable. [40]

Improved process of tuning is one side of a coin there are also ways to enhance executive devices. Let's look into how quantum sensors exploit quantum phenomena to achieve high sensitivity and precision in measurements, which is invaluable for control systems requiring accurate state estimations. These sensors can detect barely noticeable changes in physical quantities, enhancing the feedback quality for control loops. Applications include precision navigation, structural health monitoring, and environmental sensing. Quantum radar and LiDAR systems utilize quantum entanglement and superposition to detect objects with higher resolution and sensitivity than classical systems. These technologies are particularly beneficial in scenarios with low signal-to-noise ratios or where stealth detection is required. Advancements in quantum illumination protocols have shown promise in enhancing target detection and range estimation capabilities. [41]

The integration of quantum technologies into control systems holds significant potential for enhancing performance, reliability, and adaptability. Quantum algorithms can optimize controller parameters more efficiently, while quantum sensors and detection systems provide superior measurement capabilities. As research progresses, these technologies are expected to become more accessible and widely adopted in various control applications.

XI. Quantum Sensor Networks: Advances and Applications

Quantum sensor networks (QSNs) leverage distributed quantum systems to achieve unprecedented precision in measuring physical phenomena. Recent research demonstrates their potential in dark matter detection, transmitter localization, and environmental noise suppression, with advancements in both theoretical frameworks and experimental implementations.

A landmark study employed a network of 15 atomic magnetometers to search for dark-photon dark matter, achieving enhanced sensitivity through cross-correlation analysis of synchronized sensors [42]. This approach mitigated local noise, distinguishing true signals by exploiting the expected global correlation of dark matter interactions. The network's sensitivity scaled with the number of sensors, yielding a 15 fT/Hz resolution across a 1–500 Hz bandwidth, corresponding to dark photon masses of 4.1 feV–2.1 peV [42]. Such configurations outperform single-detector setups by orders of magnitude, particularly in shielded environments where signal attenuation limits conventional methods [42].

For transmitter localization, QSNs have been modeled as quantum state discrimination (QSD) problems, where entangled sensor states improve detection probabilities [43], [44]. A two-level localization strategy-coarse-grained region identification followed by fine-grained resolution-reduces error rates inherent to high-dimensional QSD [43]. Hybrid quantum-classical circuits further optimize measurements by training parameterized operations on sensor data, enabling accurate RF signal source tracking despite environmental decoherence [43]. Theoretical work confirms that while entanglement enhances detection in small networks, this advantage diminishes with larger sensor arrays due to increased complexity [44].

Correlation spectroscopy has emerged as a powerful technique for noise suppression in QSNs. By analyzing simultaneous state changes across 91 sensor qubits, researchers achieved sub-nanometer precision in magnetic field measurements and inter-sensor distance calculations [45]. Notably, the method's precision improved linearly with the number of sensors, outperforming entanglement-based strategies under realistic conditions [45]. This scalability highlights the viability of QSNs for applications requiring distributed sensing, such as gravitational wave detection or mineral exploration.

Fundamental limitations of QSNs have also been explored. Networks measuring single parameters (e.g., a uniform magnetic field) derive no significant advantage from inter-sensor correlations, as classical statistical methods match quantum-enhanced precision [46]. However, for multi-parameter estimation or linear functionals (e.g., spatial field gradients), quantum correlations enable superlinear scaling in accuracy, a feature critical for large-scale sensor arrays [46]. These insights guide the design of task-specific QSN architectures, balancing entanglement generation costs against performance gains.

XII. Conclusions

The broad spectrum of quantum technologies explored in this review — from Monte Carlo simulations and quantum robotics to ion traps, diamond sensors, and quantum neural networks — highlights the potential of this rapidly evolving field. Despite their diversity, these technologies share a common theme: promise of improvement paired with developmental challenges. While theoretical models and algorithms show great potential, real-world implementation remains hindered by hardware limitations and the early stage of technological maturity. Continued research, investment, and interdisciplinary collaboration will be key to transforming quantum technologies from laboratory concepts into practical, scalable solutions.

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