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Student review of innovations in quantum technologies. Part 6

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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*—QIT, cryptanalysis, differential equations, quantum materials, quantum radar, tomography, quantum dot, magnetometer, facial expression recognition, quantum sensor, atomic layer deposition**

I. Introduction

Quantum Information Technologies (QIT) are poised to revolutionize multiple domains within Information and Communication Technologies, spanning computing, communication, sensing, and cybersecurity. While current QIT implementations are primarily limited to the Noisy Intermediate-Scale Quantum era, their potential is already prompting significant interest across both academic and industrial spheres. This paper presents the results of a collaborative student research initiative conducted at the Warsaw University of Technology, aimed at exploring the intersections between QIT and the participants' current engineering specializations.

The publication emerged from an editorial workshop accompanying a lecture course on QIT. Participating students, representing diverse areas such as biomedical engineering, cybersecurity, quantum imaging, and software development, were encouraged to investigate how QIT may enhance or redefine existing ICT applications. Each contribution reflects an individual or group effort to align current research or diploma work with the principles, methods, or visions of QIT.

The paper's structure is modular, with each section authored by a student, presenting a focused exploration of QIT relevance within a specific technological or scientific context. While the scope of each section varies—from theoretical feasibility to practical implementation proposals—the overarching aim is to foster interdisciplinary understanding and speculative foresight in applying QIT. The collective effort represents both an academic exercise and a genuine inquiry into the early impact of QIT on engineering education and research.

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II. Quantum Neural Networks: Framework, Experiments, and Transfer Learning

Quantum neural networks (QNNs) leverage variational quantum circuits to encode classical or quantum data into high-dimensional Hilbert spaces and optimize parameters via hybrid classical–quantum loops [1]–[3]. This emerging paradigm promises to surpass classical networks in expressivity and trainability by exploiting quantum phenomena such as superposition and entanglement. In particular, QNNs offer novel routes to mitigate the *barren plateau* problem through favorable Fisher information spectra [1], and can process both classical and intrinsically quantum data within a unified framework [2]. Moreover, hybrid classical–quantum transfer learning enables practical deployment of deep quantum models on noisy, intermediate-scale quantum (NISQ) devices by offloading heavy feature extraction to classical networks [3]. A variational QNN comprises three stages:

- a *feature map* U_x embedding input x into an S-qubit state $\psi_x\rangle$,
- a parameterized circuit G_θ whose d trainable parameters are updated via classical optimizers,
- and a measurement layer yielding readout expectation values that are post-processed into predictions.

Abbas *et al.* introduce the *effective dimension*, derived from the Fisher information matrix, as a data-dependent capacity measure. They prove that QNNs can achieve substantially higher effective dimensions than comparable classical feed-forward networks—implying stronger expressivity and non-vacuous generalization bounds—and relate this to faster convergence in training landscapes less prone to barren plateaus [1]. Farhi and Neven further demonstrate that appropriately designed QNN circuits are *universal classifiers* for Boolean functions, at the cost of circuit depth in worst-case labelings [2]. These theoretical advances set the stage for end-to-end experiments validating QNN performance under realistic NISQ constraints.

To substantiate theoretical claims, Abbas *et al.* train an 8-parameter, 4-qubit QNN on the two-class Iris dataset [1]. In simulation (full-batch ADAM, learning rate 0.1, 100 iterations), the QNN attains a mean training loss of 23.1 %, outperforming a classical counterpart (37.9 %). They then deploy the same depth-2 circuit on IBM's 27-qubit `ibmq_montreal` device, using linear connectivity to reduce CNOT gates and mitigate noise. Despite hardware noise and limited shots (single run, ≈ 33 iterations to convergence), the QNN demonstrates faster loss reduction and stable performance, marking one of the first proofs of practical QNN trainability on NISQ hardware [1].

Farhi & Neven apply their QNN framework to two paradigmatic tasks under classical simulation:

- **Quantum state classification:** Using eight data qubits and one readout qubit, they label random product states prepared by single-qubit rotations according to the sign of a low-degree Ising Hamiltonian. After $\sim 10^3$ samples, a 12-parameter QNN achieves 97 % test accuracy, and scaling to 44 parameters preserves this error rate—evidencing generalization beyond training data [2].
- **Downsampled MNIST digit recognition:** They reduce MNIST images to 4×4 bitstrings, map them to computational basis states on a 17-qubit simulator, and optimize circuit parameters via stochastic gradient descent. Low categorical error on held-out test sets confirms the feasibility of QNNs for real-world pattern recognition [2].

Mari *et al.* extend transfer learning to hybrid architectures by truncating a pretrained ResNet18 (ImageNet) to extract 512 features, projecting them via a linear layer to 4 dimensions, and feeding into a 4-qubit variational "dressed" circuit implemented in PennyLane [3].

- ImageNet Ants vs. Bees - A CQ model, trained for 30 epochs (batch size 4, initial $\eta = 4 \times 10^{-4}$, reduced by $\times 0.1$ every 10 epochs), reaches 96.7 % accuracy in simulation. On real hardware (1024 shots per expectation), `ibmqx4` yields 95 % and Rigetti Aspen-4-4Q-A yields 80 % on the same 153-image test set—validating hybrid QNNs on NISQ devices [3].
- CIFAR-10 Subsets - Applying the same pipeline to CIFAR-10 subsets (cats vs. dogs, planes vs. cars) achieves 97.6 % and 96.05 % simulation accuracy, respectively, with hyperparameters in Table I. These results underscore the robustness and modularity of CQ transfer learning for diverse image domains [3].

TABLE I
CQ TRANSFER LEARNING HYPERPARAMETERS AND TEST ACCURACIES

Dataset	Depth	Epochs	Batch	Accuracy
Ants vs. Bees	6	30	4	0.967
Cats vs. Dogs	5	3	8	0.827
Planes vs. Cars	4	3	8	0.9605

These expanded experiments firmly establish that QNNs can be trained effectively on current NISQ hardware, demonstrating competitive accuracy on classical and quantum tasks, enhanced capacity via effective dimension, and resilience against barren plateaus. Hybrid classical–quantum transfer learning further bridges theory and practice by integrating deep classical feature extractors with low-depth quantum circuits. Looking ahead, scaling to larger datasets, refining data-encoding schemes, and deploying error-mitigation techniques will be crucial steps toward realizing quantum advantage in machine learning.

III. EXPLORING QUANTUM COMPUTING ARCHITECTURES

Quantum computing holds promise to revolutionizing computer science and extending boundaries of what is computable. In 20th century there were numerous algorithms invented harnessing quantum properties to achieve new feats such as Grovers algorithm os Shors algorithm. By using mathematical proofs their inventors shown that quantum supremacy exists and there is a measurable reward to harnessing quantum properties. However, after designing theoretical basics the real challenge turned out to be creating actual hardware capable of performing those operations. Industry pioneers such as IBM, Google and Microsoft, as well as bunch of quantum computing focused innovative startups tried various approaches of creating actual working quantum computer with capabilities needed for the real world applications.

The most popular approach, used in machines invented by Google and IMB was using superconducting materials such as aluminum or niobium. The circuit uses Josephson Junction, which is a this insulator placed between two superconductors, as its core element Such circuits are then put in environment with temperature near absolute zero which in turn nullifies any electrical resistance. In those conditions quantum phenomena can occur and be controlled. This type of qubits uses microwaves applied at precise frequencies to alter qubit state represented by either voltage or current in circuit This approach suffers from short coherence times and high error rates but shows . The most relevant processors using this architecture are Google's Sycamore and IBM's Condor. [4]

As an alternative to superconductors there also exists Trapped Ion Architecture. In this architecture qubits are implemented using singular ions confined in a vacuum chamber by electromagnetic fields. Quantum gates are implemented as laser beams manipulating Zeeman levels levels of individual ions. The main advantage of trapped Ion architecture is cogerence times measured in seconds or even minutes as well as error rates as low as 10^{-4}. It also provides all to all connectivity between individual qubits so their order is irrelevant during operations that require entanglement. However as a drawback it is hard to scale. Basic gate speed is orders of magnitude slower than in superconducting qubits approach and each

additional ion slows this process down even further. [4]
Differenciating itself from matter-based approaches photonic quantum computing is an architecture that uses individual photons—as qubits to process and transmit quantum information. Unlike other systems, photonic qubits are highly resistant to decoherence, allowing them to maintain quantum states over long distances and durations. Information can be encoded in a photon's polarization, path, or time-bin, and manipulated using linear optical elements like beam splitters, phase shifters, and interferometers. One major advantage of this approach is its ability to operate at room temperature, eliminating the need for extreme cooling. However, the architecture faces significant challenges, particularly in implementing reliable two-qubit gates, since photons do not naturally interact. Solutions often involve probabilistic operations or measurement-based quantum computing, where computation occurs through entangled cluster states and selective measurements. Companies like Xanadu and PsiQuantum are leading efforts to overcome these limitations using integrated silicon photonics and continuous-variable techniques. While still in its early stages compared to other platforms, photonic quantum computing holds great promise for scalable, fault-tolerant quantum processing and is particularly well-suited for quantum communication networks and distributed computing systems. [5]
Topological quantum computing is an architecture that encodes qubits in the nonlocal properties of exotic quasiparticles called anyons, specifically Majorana zero modes. These qubits are inherently protected from many types of noise due to their topological nature, where information is stored globally rather than locally. Logical operations are performed by braiding these quasiparticles, resulting in transformations that depend only on the topology of their paths. Although still experimental, companies like Microsoft are investing heavily in this approach. If realized, topological qubits could dramatically reduce error correction overhead and enable scalable quantum computing. [6]
With current state of the art there is no clear right path to take forward. Each approach offers unique advantages and challenges in scalability, error resistance, and physical implementation. Together, they represent diverse pathways toward building practical, reliable, and scalable quantum computers for future technological breakthroughs.

IV. Quantum Facial Expression Recognition

Facial Emotion Recognition (FER) is a rapidly evolving field with significant implications for human-computer interaction, healthcare, and security systems [7]–[9]. Traditional approaches to FER have long relied on computer vision, artificial intelligence (AI), and machine learning (ML) techniques to detect and classify emotions based on facial cues [8]. In recent years, deep learning (DL), particularly Convolutional Neural Networks (CNNs), has achieved remarkable success in automating feature extraction and improving recognition accuracy [8], [10], [11]. However, the increasing complexity of DL models and the computational demands of processing large datasets have motivated the exploration of novel computational paradigms [12]. Quantum Computing (QC), with its potential to solve complex problems more efficiently than classical computers, has emerged as a promising avenue for advancing FER [9], [12], [13].

Quantum computing (QC) presents a transformative approach to FER by leveraging quantum parallelism, superposition, and entanglement to enhance feature extraction, classification accuracy, and computational efficiency [12]. Unlike classical CNNs, which rely on sequential optimization techniques, quantum neural networks (QNNs) can operate in higher-dimensional feature spaces, capturing complex dependencies among facial features more effectively [10]. Quantum algorithms, such as variational quantum circuits, offer faster training times, potentially reducing the computational costs of DL models while improving scalability [14].

Quantum feature extraction (QFE) leverages QC ability to process information in higher-dimensional Hilbert spaces, enabling more expressive feature representations compared to classical methods [13]. Using quantum-exclusive tools like Quantum Feature Approximation (QFA), quantum algorithms can optimize feature selection and transformation, reducing redundancy while preserving discriminative information [14]. Multi-scale feature fusion is enhanced through quantum entanglement, allowing simultaneous extraction and correlation of features across different scales, which is crucial for complex pattern recognition tasks [10]. Quantum data encoding and feature mapping exploit quantum superposition to represent multiple features simultaneously, enabling efficient transformation of classical data into quantum states with richer structural information [10], [12].

Quantum Facial Expression Recognition (QFER) integrates quantum computing with deep learning to improve recognition efficiency and accuracy [12], [13]. Quantum Convolutional Neural Networks (QCNNs) replace classical convolutional filters with quantum layers, leveraging entanglement and superposition for richer feature extraction [9], [13]. Hybrid quantum-classical models combine quantum feature processing with classical classification, balancing quantum speedups with stability [12], [13]. Quantum Feature Extraction methods, such as quanvolution kernels, reduce complexity to $O(\log(n))$ compared to classical $O(n^2)$ CNNs [13]. Quantum-inspired approaches such as quantum genetic algorithms (QGA) [14] and quantum transfer learning (QTL) [9], [13] further optimize feature selection [14]. Implementations like EQCNNs [13] and QDCNNs [10] demonstrate improved robustness and faster training [9].

QC presents a promising frontier for advancing FER by overcoming the limitations of classical deep learning models. Using quantum parallelism, entanglement, and superposition, QNNs and QCNNs enable more efficient feature extraction, improved classification accuracy, and reduced computational complexity. Hybrid quantum-classical models and quantum-inspired techniques, such as QTL and QGA, further optimize performance while maintaining stability. Despite challenges related to hardware limitations and noise, ongoing research and advancements in quantum algorithms indicate that quantum-enhanced FER could significantly improve real-time emotion recognition applications in the future.

V. Atomic Layer Deposition

Thin film deposition has been a crucial part of advanced technology development for many years, allowing the fabrication of highly specialized materials with specific surface properties. The invention of quantum technologies has revolutionized this field, leading to the emergence of Atomic Layer Deposition (ALD). This deposition technique dramatically improved the precision and control of coating processes at the molecular scale. This opened new possibilities for applications in microelectronics, nanotechnology, and materials science.

Thin film deposition is a process of applying very thin layers ranging from a few nanometers to several micrometers onto a surface. Films can be metals, polymers, semiconductors and other materials which are essential in many high tech applications.

Deposition process is often used in numerous industries: • Aerospace engineering – Deposition of thermal barrier coatings (TBCs) and wear-resistant layers on turbine blades/rocket components for extreme-condition operation. • Jewelry production – Decorative PVD coatings (e.g., TiN for gold-like finishes) or diamond-like carbon (DLC) for scratch resistance. • Electronic components – Precision deposition of conductive (Cu, Al) and insulating (SiO_2, Al_2O_3) thin films for semiconductors [15]. • Optical technologies – Anti-reflective multilayer coatings (e.g., MgF_2/SiO_2 stacks) on lenses and displays.

As we can see this technology have a wide range of use and increases performance of machines and items.

• PVD (Physical Vapor Deposition) – Material is physically vaporized from a target (e.g., via sputtering or evaporation) and condenses on the substrate to form a thin film. • CVD (Chemical Vapor Deposition) – Chemically reactive gases undergo surface reactions on the substrate, depositing a solid film through thermal or catalytic decomposition. • PECVD (Plasma-Enhanced CVD) – Uses plasma to enhance gas-phase reactions, enabling low-temperature deposition (e.g., for temperature-sensitive substrates). • ALD (Atomic Layer Deposition) – Relies on sequential, self-limiting surface reactions for atomic-scale control of film thickness and conformality.

A method of atomic layer deposition that involves alternating sequential reaction of precursors, allowing precise control of layer thickness.

ALD is a more precise method of thin film depositon. Using a specific sequences and deposed materials it can create almost perfect layers that can be exactly as thin as we want (even as thin as single atoms). [16] The process consists of four cyclic steps: • Precursor dosing - Dosing a specific precursor in vaccum conditions until whole space will be covered by atoms. • Purging the leftovers - Precursor only reacts with the base material. That means that if the whole space was covered by atoms of precursor, they don't stick to each other anymore and they can be easily purged. • Co-extant exposure - The first half-layer will be covered with another precursor that atoms react with the first one and stick to them. • Purging the leftovers - After the whole space is covered with co-extant the layer was successfully made. The leftovers are purged and the whole sequence can be repeated to achieve thicker layer.

• Precise control of layer thickness – In ALD, layer thickness can be controlled down to single-atom precision, a resolution unattainable with other deposition technologies. • Uniformity of coverage on complex surfaces – ALD achieves conformal coatings even on 3D or porous structures (e.g., nanopores, high-aspect-ratio channels). • Exceptional layer quality – Produces smoother and more defect-free films compared to PVD/CVD, with superior density and uniformity. • Self-limiting reactions – Surface saturation ensures automatic termination of each deposition cycle, enabling atomic-scale reproducibility.

The ALD technique allowed researchers to achieve deposition precision that was previously unreachable. Its self-limiting, layer-by-layer process ensures exceptional uniformity, conformality, and thickness control, even on complex nanostructures. As a result, ALD has become a key enabling technology in fields such as semiconductors, nanotechnology, and surface engineering, paving the way for more reliable and efficient devices.

VI. Quantum Technologies in Computed Tomography

Tomography is a group of methods that allow to produce cross sectional images of an object using only their projections. The most common of these methods is X-ray computed tomography (CT). It was first introduced as a medical examination tool, later also applied in industrial quality control, scientific research, etc.

The process of conducting a CT scan includes generating X-rays, taking multiple radiographic images of an object with a detector, image processing, reconstructing the three dimensional representation of the investigated object and postprocessing and presentation of volumetric data. Quantum technologies are applicable in some of these fields.

The first area in which quantum technology has already been applied is imaging detectors. In both medical and industrial/scientific scanners, images are obtained mostly with detectors with indirect conversion. They consist of a layer of X-ray to visible light converter called scintillator, array of photodiodes and readout electronics. The brightness of each pixel of an image depends on the amount of light generated in the scintillator, further converted to electrical signal and integrated over a period. In 2022 the first medical CT system with photon-counting detector has been introduced [**?**], which can be classified as a quantum device. The detector of this type consists of a layer of cadmium telluride semiconductor in which electrical signal is produced directly by incident X-ray photons. The generated charge is collected by the pixelated anode generating short pulse which allows to detect single photon as well as record its energy. This method improves X-rays detection efficiency what allows to reduce dose received by the patient during the examination keeping the same image quality, increases spatial resolution as there is no optical cross-talk between pixels in the scintillator and also make possible multi-spectral scans as detected photons' energy is known. The impact of introducing photon counting detectors on scans' quality has been reported for example in [17] [18], [19].

The most time consuming part of CT scan is reconstruction. Quantum computing has a potential to accelerate that process. The first approach to that problem is to adapt classical reconstruction algorithms to quantum computers. The second one is to create dedicated algorithms. One group of classical algorithms include algebraic technique. Projections are described as a linear system of equations and reconstruction of the image consists in solving it. For example use of Harrow–Hassidim–Lloyd (HHL) [20] quantum algorithm might accelerate this process. Another classical reconstruction approach is based on analytical method that utilises inverse Radon transform and its implementation is a filtered back-projection algorithm. Important part of it is applying filtering that requires Fourier transform. As quantum Fourier transform might give faster results than then the one based on the classical computers a hybrid approach might be applied in which only Fourier transform is calculated on quantum machine and back projection using classical methods. Kyungtaek Jun proposed [21] a dedicated quantum optimisation algorithm that uses sinograms for the reconstruction. This approach, among other advantages, show resistance to artifacts (errors) in the projection images. However, any reconstruction method requires encoding a vast amount of acquisition data on quantum computer which may outbalance the profits of this approach.

VII. Application of Quantum Dots in Lithium-Ion and Lithium–Sulfur Batteries

Quantum dots (QDs) are semiconductor nanoparticles smaller than 10nm, whose discrete electronic states yield unique interfacial and charge transport properties. These features render QDs promising for next-generation lithium-based storage: by buffering volume changes, facilitating Li^+ transfer, and stabilizing electrode/electrolyte interfaces.

Si QDs with sizes below 10nm exhibit quantum confinement effects and abundant surface sites, which primarily buffer the volumetric changes of Si during lithiation/delithiation cycles and mitigate particle cracking. In the graphite-embedded architecture, the graphite layers undergo a slight expansion to form nano-channels that preferentially admit desolvated Li^+ while hindering solvent molecules. Consequently, a stable SEI forms predominantly on the graphite surfaces, protecting both the graphite and the Si QDs from continuous degradation [22].

These confinement and surface phenomena lay the foundation for the SiQD–in–MG architecture described below.

Silicon's high theoretical capacity ($\sim 3\,579\,\mathrm{mAh\,g^{-1}}$) suffers from $\sim$ 300% volume expansion upon full lithiation, causing particle fracture and unstable SEI formation. Li & Buckingham (2022) proposed embedding Si QDs (¡10nm) within a MG matrix to combine the high capacity of Si with the structural stability of graphite. In this SiQD–in–MG architecture [22]: • Si QDs undergo greatly reduced volumetric expansion, avoiding particle cracking. • Graphite interlayer spacing expands slightly (from $\sim 0.34\,nm$), forming nano-channels that preferentially admit desolvated Li^+ while blocking solvent molecules. • SEI growth localizes on graphite surfaces, suppressing continuous electrolyte decomposition on Si and limiting gas evolution.

This design is expected to deliver high reversible capacity and coulombic efficiency in fast-charging pouch cells when paired with NMC cathodes.

Brahma et al. (2025) report crystalline SiO_2 QDs (3–5nm) synthesized directly within reduced graphene oxide (rGO) laminates, wherein SiO_2 QDs serve as rigid frameworks for lithiation products and rGO provides a conductive network. Key metrics include [23]: • Initial discharge capacity of $\sim 865\,mAh\,g^{-1}$ at $51\,mA\,g^{-1}$. • Capacity retention of $\sim 286\,mAh\,g^{-1}$ after 60 cycles (coulombic efficiency $\sim 96\%$). • Rate capability of $\sim 214\,mAh\,g^{-1}$ at $1\,A\,g^{-1}$.

Lithium–sulfur systems offer ultrahigh theoretical energy densities ($\sim 2\,600\,\mathrm{Wh\,kg^{-1}}$) but face challenges of poor conductivity, large volume swings, and polysulfide shuttling. Inorganic QDs address these by multiple synergistic roles [24]: • Polysulfide adsorption: Polar metal-oxide/sulfide QDs chemisorb Li_2S_n intermediates, immobilizing them and mitigating shuttle effects. • Electrocatalysis: High-surface-area QDs lower activation barriers for sulfur redox (e.g., $Li_2S_6 \rightarrow Li_2S_2$), boosting kinetics. • Lithiophilic nucleation sites: Functionalized carbon QDs furnish uniform Li^+ deposition centers on Li-metal, reducing dendrite growth. • Mechanical buffering: Embedding QDs in 3D carbon matrices accommodates volumetric changes of sulfur and Li-metal, preserving electrode integrity.

Quantum dots bridge nanoscale reactivity and macroscopic stability, enabling high-capacity, fast-charging Li-ion anodes and long-lived Li–S cathodes. Future directions include: • Tailored QD compositions: Optimizing stoichiometry, defect concentration, and heterostructures to tune binding energies across redox couples. • Multifunctional architectures: Designing mixed-anion or high-entropy QDs for simultaneous catalytic and adsorption functions. • Scalable syntheses: Developing low-temperature, one-pot routes compatible with roll-to-roll manufacturing. • Interface engineering: Controlling QD-carbon and QD-electrolyte interfaces to fine-tune SEI chemistry and durability.

By harnessing size-dependent and surface-driven properties of QDs, next-generation lithium-based batteries can attain the key trifecta of high energy density, rapid charging, and prolonged cycle life.

VIII. Quantum magnetometers

Quantum magnetometers stand out among modern sensing tools for their exceptional accuracy in detecting magnetic fields. These instruments rely on quantum phenomena—particularly interactions involving spin states or superconducting circuits—to achieve detection thresholds reaching even a few femtotesla. Leading technologies in this area include devices based on optically manipulated atomic vapors (OPMs) and solid-state sensors utilizing Nitrogen-Vacancy (NV) centers embedded in diamond. Both offer distinct strengths and are suited to different application scenarios, although they also come with unique engineering challenges.

Nitrogen-Vacancy (NV) centers are point defects in diamond crystals that form when a nitrogen atom occupies a position adjacent to a missing carbon atom in the lattice. These imperfections enable the use of diamonds as quantum sensors under standard environmental conditions. The electron spin states associated with NV centers can be manipulated and observed using light, particularly through photoluminescence techniques. The energy levels of these spin states are highly responsive to changes in nearby magnetic fields, which allows for precise, vector-resolved magnetic measurements at the nanometer scale.

One of the main benefits of NV-based magnetometry lies in its ability to provide high-resolution spatial mapping, often reaching below the micrometer level. This makes it suitable for advanced applications such as studying neuronal signals in living organisms, detecting magnetic properties at the level of individual cells, and conducting nanoscale imaging using scanning probes. Importantly, these sensors function effectively at room temperature and can be incorporated into biological or microfluidic systems, increasing their potential in biomedical and lab-on-chip technologies.

OPMs use alkali metal vapors (e.g., rubidium or cesium) enclosed in glass cells, where the atomic spin population is optically aligned using laser light. Changes in external magnetic fields cause precession of these spin populations, which is then detected optically through Faraday rotation or absorption spectroscopy. One key advantage of OPMs is their lack of cryogenic requirements—they operate effectively at or near room temperature.

OPM sensors are currently being miniaturized and implemented in multi-channel systems for applications such as magnetoencephalography (MEG). They offer sensitivity comparable to SQUIDs, but with lower power and infrastructure requirements. Their main drawback remains susceptibility to magnetic noise, making them dependent on magnetic shielding or active compensation systems.

Quantum magnetometers are rapidly gaining traction in various scientific and industrial domains due to their extreme sensitivity and versatility. Key application areas include: • Biomedical diagnostics: Optically Pumped Magnetometers (OPMs) are used in magnetoencephalography (MEG) to non-invasively record brain activity. NV-center-based sensors enable real-time cardiac field detection and potential single-neuron resolution imaging. • Geosciences and archaeology: Quantum magnetometers can detect subsurface magnetic anomalies with high spatial resolution, supporting archaeological site mapping, tectonic activity monitoring, and resource exploration. • Navigation and defense: Magnetic field maps obtained via quantum sensors allow for GPS-independent navigation in submarines, drones, and aircraft. Their high precision also enables the detection of hidden or shielded objects. • Space and planetary missions: Compact, low-power magnetometers are under consideration for measuring magnetic environments of celestial bodies, enhancing planetary science missions. • Fundamental physics and materials science: NV sensors are used to probe exotic quantum phases in condensed matter systems, investigate topological defects, or map current distributions in superconductors.

While both NV-based and OPM sensors have demonstrated impressive sensitivity, their broader adoption hinges on several challenges. For NV sensors, increasing the density of addressable centers without degrading coherence times remains a technical barrier. Additionally, robust integration with CMOS and fiber systems is needed for scalable applications. In OPM technology, further progress is required in miniaturization, magnetic shielding, and array calibration.

Emerging hybrid systems that combine quantum sensors with machine learning algorithms may further enhance sensitivity and resilience to environmental noise. Moreover, integrated quantum magnetometry is becoming increasingly important in the development of compact biomagnetic devices, quantum imaging systems, and next-generation navigation platforms.

IX. Quantum Cryptanalysis

Cryptography and cryptanalysis are two complementary pillars of information security. While cryptography focuses on the development of secure communication protocols, cryptanalysis seeks to evaluate and potentially compromise these systems. With the emergence of quantum computing, cryptanalysis has taken on a new dimension—quantum cryptanalysis—raising concerns about the long-term security of classical cryptographic schemes.

Cryptanalysis involves the study and implementation of techniques for decrypting or compromising encrypted data without prior access to the secret key. As computational capabilities evolve, cryptographic schemes that were once considered secure may become vulnerable. This raises critical questions about the durability of cryptographic systems: Will RSA or elliptic-curve-based protocols remain secure in the next 5, 15, or 30 years? The increasing plausibility of scalable quantum computers suggests that these systems may be fundamentally insecure in the foreseeable future.

Quantum computers leverage principles from quantum mechanics [25] to perform computations that are infeasible for classical machines. The fundamental unit of quantum computation is the *qubit*, which can exist in a superposition of classical states ($|0\rangle$ and $|1\rangle$). A register of n qubits can represent 2^n states simultaneously, enabling quantum parallelism.

Quantum operations are implemented via *quantum gates*, which manipulate qubit states through unitary transformations. Computation typically proceeds by initializing qubits in a known state, applying a series of quantum gates to perform transformations, and then measuring the outcome to obtain classical results. This paradigm facilitates the development of algorithms that outperform their classical counterparts for specific problems, including those underpinning modern cryptography.

Proposed by Peter Shor in 1994, *Shor's algorithm* [26] provides an efficient quantum method for solving the problems of *integer factorization* and *discrete logarithms*. These problems form the security basis for widely used public-key cryptosystems, such as RSA and Diffie-Hellman (including elliptic-curve variants).

Shor's algorithm operates in two phases: • Reduction of the cryptographic problem to the task of finding the *order* of an element. • Application of the *Quantum Fourier Transform (QFT)* to determine this order efficiently on a quantum computer.

The implications are severe: • RSA, which relies on the hardness of factoring large semiprimes, would be efficiently broken. • Elliptic-curve cryptography and discrete logarithm-based systems would also be compromised. • Protocols such as *TLS* (Transport Layer Security) would no longer provide reliable protection against eavesdropping.

This renders all current public-key infrastructures (PKIs) insecure in a post-quantum scenario.

Grover's algorithm [27] addresses the problem of searching an unstructured database of size N in $O(\sqrt{N})$ time, offering a quadratic speedup over classical brute-force search. While Grover's algorithm does not achieve exponential speedup, its implications for symmetric cryptography are nonetheless important.

Applications in cryptographic contexts include: • Key search: Breaking a k-bit symmetric key (e.g., AES) in $O(2^{k/2})$ operations. • Hash inversion: Finding a pre-image for a k-bit hash output in $O(2^{k/2})$ time. • Collision search: Locating two inputs with the same n-bit hash output in $O(2^{n/3})$ time.

Although the algorithm requires substantial quantum memory and gate operations, its impact necessitates adjustments to security parameters. Specifically: • Symmetric key lengths must be *doubled* to maintain classical security levels. • Hash output lengths must also be increased accordingly.

Despite these adjustments, symmetric-key cryptography remains more resilient to quantum attacks than public-key systems.

Recognizing the existential threat quantum computing poses to existing cryptographic infrastructures, the *National Institute of Standards and Technology (NIST)* initiated the *Post-Quantum Cryptography (PQC) Standardization Project* [28]. The goal is to identify and endorse cryptographic algorithms that are secure against both classical and quantum adversaries.

As of 2025, the competition has entered its fourth round, focusing on the selection and refinement of algorithms for standardization. Categories under consideration include: • Key Encapsulation Mechanisms (KEMs) • Digital Signature Schemes

The leading candidate algorithms are based on mathematical problems believed to be resistant to quantum attacks, such as: • Lattice-based constructions • Code-based encryption • Multivariate polynomial systems • Hash-based signature schemes

The competition's outcomes will shape the future of cryptographic standards and ensure continuity of secure communications in a quantum-enabled world.

X. Quantum solving methods of differential equations

Quantum computing offers promising new approaches to solving differential equations, a key challenge in many areas of science and engineering. While classical methods become costly in high dimensions, quantum algorithms may provide speedups under certain conditions. As shown by Childs et al. (2022), quantum approaches such as amplitude estimation can offer at most a quadratic improvement for solving the heat equation, with performance depending heavily on problem parameters. Despite these limits, quantum techniques remain a valuable area of research, especially as hardware continues to improve.

Building on theoretical foundations, recent work has demonstrated that quantum algorithms can go beyond conceptual frameworks and be realized experimentally. In particular, Cao et al. (2019) developed a quantum algorithm tailored for linear ordinary differential equations (ODEs) and successfully implemented it on a four-qubit NMR quantum processor. Their approach reformulates the ODE as a linear system, allowing the use of the Harrow-Hassidim-Lloyd (HHL) algorithm. Notably, their results confirm that the method can efficiently simulate time evolution for certain systems with an exponential speedup under ideal conditions. This experimental proof-of-concept marks an important step toward practical quantum solvers for differential equations, showing that quantum hardware—despite its current limitations—can already tackle meaningful instances of scientific problems.

Despite promising theoretical and experimental progress, quantum methods for solving differential equations face several critical challenges. Current quantum algorithms often rely on idealized assumptions, such as access to well-conditioned matrices, efficient state preparation, and fault-tolerant quantum hardware. As highlighted by both Childs et al. (2022) and Cao et al. (2019), the efficiency of quantum solvers is strongly dependent on problem-specific parameters, including sparsity, matrix condition number, and the encoding of initial conditions. Moreover, most practical implementations are limited to small-scale systems due to decoherence, gate noise, and qubit count limitations. These factors constrain real-world applications and motivate further research into algorithmic robustness, error mitigation, and hybrid quantum-classical approaches that can bridge the gap between theory and hardware capabilities.

Childs et al. (2022) highlight that quantum algorithms often provide only limited practical speedups. For the heat equation, even advanced techniques like quantum walks with amplitude estimation offer at most a quadratic gain in accuracy, falling short of earlier expectations. Moreover, their effectiveness declines with increasing spatial dimensions due to the curse of dimensionality. This shows that quantum advantages are conditional and highly problem-dependent.

To successfully apply quantum algorithms to differential equations, several technical and mathematical conditions must be met. These requirements are crucial for ensuring theoretical speedups translate into real performance gains: • Problem Linearity: Most quantum solvers, including those based on the HHL algorithm, are currently limited to linear differential equations. Nonlinear problems require alternative or hybrid approaches. • Matrix Sparsity and Structure: The discretized system matrix must be sparse or have a structure that allows for efficient simulation on quantum hardware. Dense or unstructured matrices can negate quantum speedups. • Low Condition Number: Quantum algorithms become inefficient when dealing with ill-conditioned matrices. A low condition number ensures numerical stability and shorter quantum circuit depths. • Efficient State Preparation: Preparing the right-hand side of the system and initial conditions as quantum states must be computationally feasible. Otherwise, the overhead cancels out the algorithmic advantage.

Each of these points represents not just a technical hurdle, but a design constraint shaping which differential problems are truly suitable for quantum treatment.

Quantum algorithms for differential equations represent a promising but still maturing area of research. While early works, such as those by Cao et al. (2019), have shown that quantum solvers can be implemented experimentally, their performance remains constrained by key factors including matrix sparsity, condition number, and the complexity of state preparation. Childs et al. (2022) further emphasize that quantum speedups are often modest—typically quadratic—and strongly dependent on the structure and dimensionality of the problem.

More recent advancements, like the algorithm proposed by Lin and Tong (2023), aim to overcome some of these limitations through more sophisticated mathematical tools, such as wavelet-based representations and efficient preconditioning. These techniques indicate that future progress will depend not only on improved quantum hardware, but also on deeper integration of algorithm design with numerical analysis.

In conclusion, while quantum methods are not yet ready to replace classical solvers in general-purpose settings, they continue to open new possibilities for tackling high-dimensional or computationally intensive differential problems under the right conditions.

XI. Quantum materials

Quantum computing is a topic that gathers attention of both scientists and investors due to its potential of surpassing classical computing methods. It is not the only field of research which involves quantum mechanics, as quantum sensing and quantum communication are also modestly advancing. There are many more fields that could benefit from incorporating quantum mechanics in their solutions. All in all at the core of all these technologies lie quantum materials.

Quantum materials is a broad therm used to describe a category of materials that posses properties grounded in quantum mechanics. Crucial of them, that make quantum material suitable for use in quantum systems, are: superposition - ability to exist in multiple states simultaneously. It allows to create qbits (quantum equivalent of bits). entanglement - enables correlation between qbits regardless of distance. Thanks to it, knowing the state of one qbit, it is possible to determine state of the qbit entangled with it. coherence - it describes stability of the state of superposition. Qbits are not able to last in the state of superposition indefinitely, because an environmental element interacts with it , causing its state to define. The better coherence of the material is, the longer qbit is able to stay in superposition, providing more time for conducting operations on it.

There are many quantum materials being studied. They can be based on superconductors, trapped ions, color centers in crystal lattice, quantum dots and so on [29]. Selection covered in this article is narrowed down to few interesting examples.

Nitrogen Vacancy in diamond One of the quantum materials that is being heavily researched is nitrogen vacancy (NV) center in diamond. Such centers consist of a nitrogen atom that substitutes carbon in the crystal lattice, which sites next to a mono-vacancy [30]. They are a promising material for solid state qbits due to their unique properties, and also have applications in quantum sensing, as their quantum state is sensitive to magnetic and electric field, temperature and mechanical strain. Thus enabling measurements of these parameters. There are works being conducted to improver reading out state of NV in diamond [31].

Nitrogen Vacancy in silicon carbide NV in diamond, although very promising, have their drawbacks such as compatibility with microelectronics. This can be overcome by NV in silicon carbide (SiC), as it is widely used in microelectronic semiconductor power devices. Substrates of size 300 mm are commercially available [32]. Research is being done to fully characterize NV in SiC as they could be strong alternative to NV in diamond in the future [33].

Quantum dots Quantum dot (qdot) is a 3-dimensional quantum well, which thanks to its small size is capable of confining one electron inside it. Under electric bias it emits light which wavelength is determined by size of the qdot and materials used during fabrication process. This material found its applications in RTV industry as it is used to produce qLED screens. However it has potential to be used in quantum computing as a qbit [34], but also can be use to create single photon emitter that is a required element for photon based quantum computing and quantum communication. To achieve single photon emission using quantum dots fabricated from common semiconductor materials as Silicon or Germanium, it is required to supercool these materials to temperatures near absolute zero. Qdots based on GaN nano-wires are being developed which are capable of single photon emission without extreme cooling being required. [35], making this material easier to apply in quantum systems as it wouldn't require cooling to operate.

There is plenty of quantum materials and many are yet to be discovered. Time will tell which of them are going to become base for quantum technologies of the future that will change the world the same way as silicon based classical computing led to the world we know today.

XII. Quantum sensors for impedance pneumography

Impedance measurement is highly significant, especially in medicine. Lung diseases are becoming an increasing problem in the modern world. Chronic lung diseases accounted for 7% of deaths worldwide in 2017. From 1990 to 2017, the number of deaths caused by these diseases increased by 18%. The most common respiratory diseases include chronic obstructive pulmonary disease, asthma, and pulmonary sarcoidosis. [36]

Proper diagnosis plays a crucial role in the treatment of respiratory diseases, including tests such as radiography, computed tomography, and spirometry. Another test that allows measuring the mechanical activity of the respiratory system is impedance pneumography. The method is based on the measurement of electrical impedance as a tissue biomarker. Impedance is a physical quantity that describes the relationship between current and voltage in alternating current circuits. This method involves measuring changes in the electrical impedance of the subject's chest. These changes depend on the depth and frequency of breath. [36]

To measure impedance, various types of sensors can be used, including quantum sensors. Quantum sensors are devices that utilize quantum states, and quantum states and their behavior under the influence of external fields and interactions enable extremely precise measurements. Ion qubits interact with electrical fields, while spin qubits interact with magnetic fields. [37]

Small changes in circuit parameters (e.g. voltage, current, signal phase) can cause changes in the quantum state of the sensor. This allows for highly accurate detection of these changes, which is especially important for analyzing systems with very low signal levels. A crucial aspect is the conversion of information about impedance changes into changes in the quantum state.

SQUID - Superconducting Quantum Interference Device is simultaneously one of the oldest and most sensitive type of sensors. These devices measure magnetic fields with very high sensitivity. From a commercial perspective, SQUIDs can be considered the most advanced type of quantum sensors - they are used for purposes ranging from material characterization in solid-state physics to clinical magnetoecephalography systems, which measure small magnetic fields distributed by electric currents in the brain. [38]

A SQUID can be used to measure impedance by employing it as an ultrasensitive amplifier of signals resulting from small current changes in the circuit containing the tested element. Impedance changes of the tested element would be translated into magnetic changes that the SQUID can detect.

Optically Pumped Magnetometers (OPM) are a type of quantum sensors used to detect very weak magnetic fields. Quantum technology in OPM sensors is based on phenomena such as optical pumping and measuring spin states of individual atoms or defects. These sensors operate by optically exciting atoms in specially prepared chambers, where laser light aligns with their spin state. Subsequently, changes in the external magnetic field affect these states, enabling very precise measurements. [39]

The advantage of OPM sensors is that they can operate in room temperature and have a big potential for miniaturisation.The minor disadvantage of these sensors is that they are very complex technology-wise. The are also extremely sensitive to magnetic field changes and so they are sensitive to noise and other environmental disturbances. The mechanism to measure impedance using OPM sensors could be exactly the same as the one mentioned in previous section.

To summarize, SQUID sensors are very sensitive and have the advantage of being well studied and established. However, their primary drawback is the requirement for cooling, making the infrastructure needed for their use costly and often problematic. On the other hand, OPM sensors are also highly sensitive but still requires extensive research. It is worth noting that none of the discussed sensors allow for direct impedance measurement. Therefore, to use these sensors for impedance measurements, they would need to be equipped with an appropriate interface.

XIII. Quantum Radars

With the rise of quantum technologies a new interesting device was proposed, the Quantum radar (QR). It is type of radar that utilizes the principles of quantum mechanics to improve radar performance [40]. Conventional radar rely on microwaves signal to detects objects. Quantum radars working principle involves creating and manipulating entangled photons. These photons are linked so that they can be correlated at any time, regardless of the distance between them [40]. With current state of quantum technologies that may be hard to achieve, but with the research being done on other branches of quantum technologies it may be achievable in the future.

Quantum radar is a quite novel concept. First articles describing it were published around 2008, although the first analysis date back to 2003 [41]. First patent and articles stated that Quantum Illumination (QI) may be used in quantum radars but in its microwave implementation, which exploits quantum coherence properties of non-classical states of light. Which variation of will be described further in this paper.

Quantum Radar research can be briefly described by dividing it into four periods as stated in [41]: • Proposals era (2008-2011) • Early article production (2011-2017) • Mass article production (2018-2022) • Disillusionment and endurance (2022-2025)

As previously mentioned, Quantum Radars are usually based on Quantum Illumination concept because this approach may yield better results than for example interferometric quantum radar [42].

Quantum illumination works on the basics of quantum entanglement, which is purely quantum phenomenon with no equivalent in classical applications, thus its use is limited only to the Quantum Radars [40]. One can call two particles, for example photons, entangled if they can be described by the single quantum state. It implies that said particles are correlated at the quantum level, and they can be labelled as entangled if they have interrelated properties without dependence on distance [40], [43].

Thus Quantum Radar working on Quantum Illumination principles may be compared to the conventional. Basic idea of Quantum Radar operation is as follows [43]: • Generate a pair of entangled electromagnetic signals. • Send one signal to the target while saving the second signal as a reference. • Receive signal. • Perform quantum joint measurement between the free space and the reference signal. If the measurement indicates entanglement of two signals detection of an object can be declared.

This may be compared to the measurement principle of the noise radar (NR) or other radar types [43], [44]. Main difference is that the reference signal is an entangled twin, not a copy of transmit signal. Also quantum joint measurement is performed instead of conventional cross-correlation [43].

Working *Quantum Two-Mode Squeezing radar* (QMTS radar) prototype was constructed. It is not a fully "Quantum" radar, but may be claimed as one as the authors of the paper [42] justify. This device is based on variation of quantum illumination concept [42]. It works in the microwave regime by generating two entangled beams of microwaves. And as in the conventional radars, one is transmitted and the second is saved for further processing.

It is described as *Quantum Two-Mode Squeezing radar*, because the entangled signals are known as *Two-Mode Squeezed Vacuum* (TMSV). They are similar to the noise generated in the conventional noise radar [42].

Signal generator used in QMTS radar is known as Josephson parametric amplifier (JPA), which is also the only quantum component of this type of radar. It generates a pair of entangled microwave signals with frequencies of 6.1445 GHz and 7.5376 GHz. Both of them are passed through the set of amplifiers and are split in two signal paths. The signal with frequency of 6.1445 GHz is measured and digitized to be saved for later comparison with received signal. Other signal with frequency of 7.5376 GHz is transmitted and received [42].

In experiment conducted with QTMS radar in the paper [42] it was concluded that creating quantum enhanced radar is no longer impossible. But it is important to mention that created prototype was tested in only one way propagation scenario, which means that signal was not reflected from any object, but sent from transmit antenna to receive antenna without any reflections. Also authors mentioned that extracting signals from the JPA source placed in the refrigerator break the entanglement and that may create an objection that the experiment results may be reproduced without a reference to quantum physics.

Quantum radars require a lot of work to be put into research and development before they will reach an operational level. While time horizon for quantum computer is set for around year 2030 with technology readiness level (TRL) between 4 and 5, quantum radar does not have one with TRL level of only 1 to 2 [41].

Quantum enhanced radars prototypes do exist and work as it was previously mentioned in this paper, but there are still many limitations in its use and performance. For example, dilution refrigerator which is used to create temperature adequate for operation of JPA require approximately 15 kW of power [41]. With the current state of quantum technology it may be difficult to achieve fully quantum radar, thus there is much experimental work remains to be done before the creation of fully quantum radar is possible [42].

XIV. Conclusions

Quantum technologies are swiftly transitioning from experimental demonstrations to practical deployments. Quantum-enhanced neural networks are poised to deliver superior facial recognition accuracy and efficiency, provided challenges in noise mitigation and scalable architectures are addressed. Ultra-precise sensors—including atomic and optical clocks, NV-center magnetometers, and atom interferometers—are redefining navigation, geological surveying, and fundamental physics experiments, even as efforts continue to shrink device footprints and improve environmental robustness.

In materials and energy, Atomic Layer Deposition offers unmatched atomic-scale control for advanced electronics and photonics, while quantum dots and tailored nanostructures are driving significant gains in lithium-ion and lithium-sulfur battery energy density and cycle life. On the computational front, Shor's and Grover's algorithms underscore both the transformative potential of quantum speedups and the pressing need for post-quantum cryptographic standards, even as hybrid quantum-classical frameworks and quantum-inspired solvers are already tackling real-world optimization, simulation, and machine learning tasks on noisy intermediate-scale devices.

Taken together, these advances chart a pragmatic roadmap: in the near term, hybrid and quantum-inspired approaches will bridge theory and application, while long-term progress in error correction, materials engineering, and system integration will unlock fully scalable quantum advantages. Realizing this vision will demand sustained interdisciplinary collaboration—uniting physicists, engineers, computer scientists, and industry partners—to translate quantum breakthroughs into robust, scalable technologies that will reshape sensing, computation, communication, and beyond.

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