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Student review of innovations in quantum biophotonics

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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 r esearch t opics a nd i n s ome c ases t he r ealization stage is advanced. Thus, most of the potential QIT application areas are defined a nd q uite n arrow. I n s uch a c ase, t he i ssue t o 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, nanorobitics, 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 Key distribution

The purpose of cryptography is concealing the contents of a message so that it can be deciphered by a specific group of people and doesn't reveal any information to anybody from outside of that group. Across centuries, people engaged in never-ending race of inventing and breaking them. Secrecy of communication is crucial to war effort, espionage, business

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Authors of chapters, s, ii-WB, iii-KK, iv-AM, v-JK, vi-NC, vii-AK, viii-WS, ix-TZ, x-MCW, xi-BL, xii-JW, xiii-PK.

planning, and preventing cutting edge research results from being stolen, so undoubtedly there are serious funds to be made in both keeping and learning about secrets. Among proposed solutions meant to keep data safe, there is one that is considered provably unbreakable but impossibly hard to implement. However, rapidly developing quantum solutions could make it a reality. The solution mentioned above is a one-time pad. Under very strict conditions it is provably unbreakable [7]. The premise behind it is simple. For each message, one randomly generates a key precisely as long as the message itself. Each message bit is then XORed with the corresponding bit from a key. The message can then be transferred, and the receiver can decrypt it using the same key. After the procedure is done key is discarded and not used again. In that scenario, even if the message is intercepted along the way, the attacker without the key is unable to guess the original message. There is no elaborate mechanism here to analyze and crack, and a brute-force attack won't work because, depending on the used key, any sequence of bits could represent any possible sequence of bits before encryption. However, this solution only works under very specific conditions, which are

- Key length has to match message length.
- Each message has to be encrypted using separate key.
- Key generation process has to be truly random.
- Key must be completely secret.

The last point is the reason why this technique is rarely used. Given that there might be some distance between sender and receiver and the key has to be randomly generated for each message, it has to be somehow transferred to the receiver in order to allow him to decipher it. This created a recurring problem of sending some information in a way that it is concealed. And if the key generation mechanism can be independently replicated by both parties so the key doesn't have to be transferred, then it can also be replicated by an attacker, rendering the entire mechanism useless.

Quantum technologies are emerging as the possible solutions to that problem. For each problem plaguing one-time pads, there are solutions possible by harnessing quantum properties. Random key generation is possible due to true randomness that can be performed by quantum computers [8]. So the last remaining problem is secure transfer of the key used for message encryption. However, that can be achieved by using quantum key distribution. There are multiple protocols for implementation, but the basic idea is as follows: The process begins by storing the key using qubits. This key is then transferred to the sender. Upon receipt, the sender collapses the superposition by measuring the qubits and reads the key. Once the key has been confirmed as successfully received, an encrypted message can be sent securely.

This idea works because qubits used for key transfer are in superposition, and in order to read it, superposition has to be collapsed. Even if qubits were intercepted due to the no-cloning theorem attacker can't have his own copy of the message. Instead, he can either leave superposition intact, and in that case he doesn't know the key, or collapse it, but in that case the sender is going to receive a visibly tampered message. And if the key is visibly compromised, then it will be discarded, rendering the attack ineffective.

One of the most commonly discussed protocols that implements the idea behind quantum key distribution is the BB84 protocol [9]. Here is how communication between two parties traditionally called Alice and Bob would look like if it implemented this protocol. Alice begins by choosing a random bit string along with a random basis for each bit, which can be either rectilinear or diagonal. She then sends this string to Bob. Upon receiving the bits, Bob selects a random basis for measuring each one. If he happens to guess the correct basis, he receives the same bit sent by Alice; otherwise, he obtains a random result. Over a public channel, Bob announces which bases he used. Alice then reveals which of Bob's choices were correct. Both parties discard the bits where Bob's basis choice was incorrect. The remaining bits, for which the basis matched, are the same for both parties and form a shared secret key. To check for eavesdropping, a subset of these key bits is compared over the public channel; if the error rate is too high, the key is declared compromised and discarded. If the check passes, Alice can proceed to send a message that Bob can decode securely using the verified key.

Quantum key development shows promising features. OTP is proven to be safe, and there is concrete proof that it won't be broken. The popularity of this solution is negligible due to the high volatility of qubits, the complexity of the process, and the costs of generating a new key each time there is a need to send a message. There are also cheaper alternatives like RSA that, with quantum hardware still underdeveloped is considered safe, and KYBER, promising to withstand even quantum attack, is achieving the same purpose without the need to build specialized channels for sending qubits.

III. Nanorobots – Tiny Helpers of Future Medicine

Not long ago, nanorobots sounded like science fiction. Today, they are becoming a real tool in the development of modern medical technologies. Sometimes also called nanobots, nanomachines, or nanites, these extremely small devices are being designed to assist with many various, complex medical actions. Their unique advantage lies in their ability to operate on a molecular or even cellular level, achieving unbelievable precision. [10] [11]

Nanobots operate on the nanoscale. Even a billionth of a meter (10^{-9} m). Their size makes them undetectable without dedicated measurement tools like specialized microscopes. Nanobots are built using either advanced synthetic materials like graphene, carbon nanotubes, biodegradable polymers, or biological molecules such as proteins or DNA snippets. [10] [11]

One of the primary challenges facing nanobot engineers is movement inside living organisms. Navigating inside of the human body is not an easy task, so nanorobots have to be equipped with different propulsion systems based on either internal or external effects. Examples of movement types showcased in recent studies [10] are described below:

- Magnetic propulsion - It uses external magnetic fields to steer and move nanobots accurately. For this to work, nanomachines have to be made of ferromagnetic materials like iron, nickel, and cobalt. Thanks to the durability of those materials they have a relatively long lifespan. Figure 1 shows the basic idea standing behind this method.

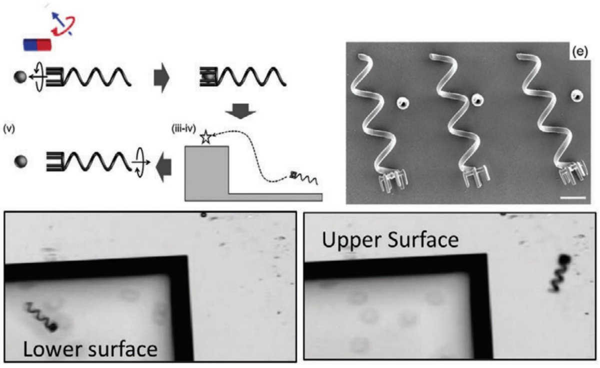

Fig. 1. Magnetically propelled microrobot based on rotating microcoil. [10]

- Ultrasound propulsion - It is based on a similar principle as magnetic propulsion but is based on different external energy sources. Sound waves make nanobots vibrate or rotate toward a certain direction to achieve their target destination.
- Biohybrid propulsion - It combines living microorganisms, like sperm or bacteria, with synthetic materials. The natural ability to move by known bioorganisms is used to achieve particular movement behaviors in specific environments.
- Chemical propulsion - This motion generation solution relies on reactions with surrounding substances, leveraging environmental properties. For example, biodegradable metals like zinc and magnesium can react with stomach acid. Microbubbles created during that reaction generate thrust, which results in desired nanorobot movement. Figure 2 shows the basic idea standing behind this method.

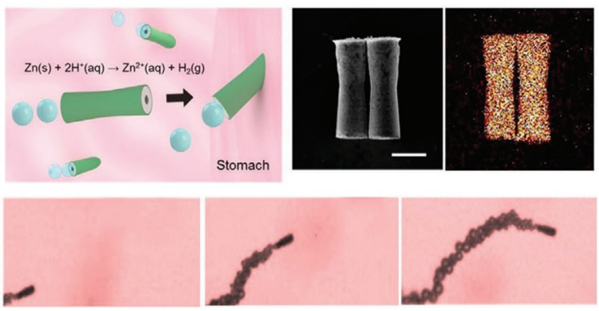

Fig. 2. Chemically propelled motor based on zinc microtube, the microrobot converts gastric fluid into gas bubbles that generate propulsion trust. [10]

Recent studies [10] showcased the huge potential of nanobots to revolutionize medicine. Their capabilities are showcased in the following key areas:

- Targeted Therapy - Nanobots deliver medication selectively to diseased cells, such as cancer, while avoiding damage to healthy areas. This reduces side effects and increases treatment efficiency.
- Minimally Invasive Surgery - Nanorobots with tiny "grippers" are capable of sampling tissue or performing microprocedures deep inside the body without large incisions.
- Diagnostics and Monitoring - Nanorobots detect diseases at very early stages by identifying biomarkers or genetic material. One example is detecting HIV by observing how the nanobots slow down after interacting with amplified genetic fragments.
- Medical Imaging - Nanobots enhance imaging techniques by highlighting specific tissues or even glowing under fluorescence.

As promising as nanorobots are, they still face major challenges like production costs, required precision, and environmental factors. Biocompatibility is essential to avoid harmful effects. Apart from physical difficulties, there are also ethical and legal concerns that include data privacy, responsibility in case of malfunction, and regulatory approval. Risks include potential toxicity, long-term accumulation in organs, and even the threat of external misuse. [10] [11] [12]

IV. Nanotechnologies

Over the years, technology has advanced at an astonishing pace. All of the inventions became smaller, more efficient and extremely compact. After decades of intensive research, humanity reached a new era. Era of nanotechnologies that takes advantage of unique properties of elements at atomic level. When applied to machines or materials, it can dramatically enhance their usage and performance. Implementing them to the daily life can open door to groundbreaking advancements across numerous fields.

Nanotechnology is the use of individual chemical elements or groups of those elements that are embedded within a foreign structure in order to enhance its performance. In some aspects it can be seen as related to thin film deposition such as PVD (Physical Vapor Deposition) or CVD (Chemical Vapor Deposition). However, nanotechnology focuses on properties that were previously unreachable. For example, it enables the creation of self-healing materials at the molecular level or even data storage using individual DNA nucleotides to represent binary information.

One of key domains covered by Nanotechnology are nanorobots. They are revolutionizing water purification. Some of them are designed to capture harmful hormones like α-estradiol using smart surfaces that respond to pH changes, removing up to 80% in two hours. Others remove toxic substances such as arsenic and pesticides at room temperature and can be reused up to 10 times. Semiconductor-based nanorobots can even degrade dyes and drugs using UV light, achieving up to 97% efficiency without harming the environment. [13] Thanks to this humanity could solve problems with polluted seas, oceans and rivers.

Another promising use case of nanotechnologies are nanomaterials. Traditional material engineering often relies on deposing on the base materials specific chemical elements to enhance performance. Nanomaterials go a step further.

Nanoengineered particles or coatings with tailored properties are applied to base structures to enable active responses to damage, much like nanorobots in medicine. [14]
Properties offered by nanomaterials that make them uniquely useful are:

- Enhanced durability and resistance to damage,
- Automatic repair of microscopic cracks,
- Protection against corrosion and wear,
- Reduced maintenance costs over time.

Key material examples include graphene, which strengthens materials and can act as a damage sensor, initiating repair mechanisms. Carbon nanotubes (CNTs) form conductive networks within composites, triggering healing responses and reinforcing structural integrity. Silver nanoparticles provide antimicrobial protection, preventing biological degradation and micro damage. Nanocrystalline titanium dioxide (TiO_2) offers photocatalytic self-cleaning surfaces by breaking down organic pollutants under UV light.
Scientists at Harvard successfully encoded digital data into synthetic DNA, achieving a record-breaking storage density of 700 terabytes per gram. Binary data were converted into nucleotide sequences that are assigning T and G as binary “1” and A and C as binary “0” which can later be read like a genome. This results is extremely high in data density: one bit per DNA base, each consisting of just a few atoms. Each DNA fragment included a 19-bit address, allowing precise data retrieval and organization. Due to DNA’s chemical stability, this method offers exceptional durability and could revolutionize storage of data in long term archiving.

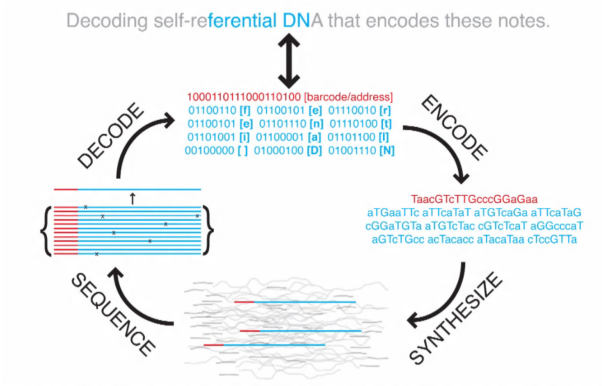

Fig. 3. Converting DNA sequence to high density binary data [15]

Nanotechnologies have great potential to revolutionize many industries and aspects of everyday life. Creating materials with tailored properties such as self-healing or self-cleaning materials could cut maintenance costs. Nanotechnology has the potential to found use cases in various industries by enabling the creation of materials with exceptional properties. Self-healing materials, such as graphene and carbon nanotubes, can enhance durability and reduce the need for repairs, cleaning, and maintenance. These advancements could significantly improve efficiency and sustainability in construction and manufacturing. The list of benefits from this technology grows every day from long term natural data storage to environmental benefits. In summary, nanotechnology promises to improve material performance, reduce costs, and drive innovation in data storage, making it a critical area for future development.

V. Quantum techniques of solving differential equations in Biomedical Modeling and Biophotonics

Many important and pressing challenges in biology, medicine, and photonics depend on solving complex systems of differential equations. These range from modeling tumor development and drug transport in tissues to simulating the behavior of light in biological media for cutting-edge imaging techniques. Classical numerical methods, while powerful, often struggle with the scale, precision, or computational cost required by these models–particularly when they exhibit nonlinearities, spatial heterogeneity, or random behavior. Quantum computing, by exploiting principles such as superposition and entanglement, presents an alternative route to solving such equations more efficiently under specific conditions.

In cancer research, reaction-diffusion equations are used to model tumor growth, the formation of new blood vessels (angiogenesis), and the delivery of chemotherapeutic drugs [16]. These models often involve multiple interacting elements, such as various cell types, signaling molecules, and spatial domains. Quantum algorithms that solve partial differential equations (PDEs) [17], [18] could greatly speed up these simulations, enabling more practical in silico testing of personalized therapies and the optimization of drug delivery methods.

Similarly, neuroscience relies heavily on differential equations to describe the electrical activity of neural circuits, synaptic plasticity, and the transmission of action potentials [18]. Simulating these processes at the scale of brain regions or entire neural networks is very computationally demanding. Quantum-enhanced solvers and Hamiltonian simulation techniques [19] could make it possible to study emergent phenomena in neural dynamics, such as seizure propagation or learning mechanisms, with greater detail and speed than classical methods allow.

In biophotonics, quantum computing shows the potential to significantly enhance optical imaging and diagnostic methods. Techniques such as diffuse optical tomography and photoacoustic imaging rely on models of photon transport in tissue, typically described by the radiative transport equation or its approximations [20]. Solving both the forward and inverse problems in these methods usually requires iterative solutions of PDEs across 3D domains, a task well-suited for quantum linear system solvers and hybrid quantum-classical approaches [21]. This could enable faster and more accurate image reconstruction, especially in deep-tissue imaging where classical methods are often slow or badly conditioned.

Beyond solving PDEs directly, researchers are also investigating quantum machine learning as a way to develop surrogate models that approximate solutions to complex differential equations using limited experimental or patient-specific data [22]. For example, quantum neural networks could be trained to estimate physiological parameters in personalized simulations or forecast disease progression by learning from longitudinal imaging and biomarker data.

Although these applications are mostly theoretical at this stage, the direction is promising. As quantum hardware scales and algorithms improve, quantum computing may become an excellent tool in biomedical modeling and biophotonics, opening new pathways for diagnostics, therapy planning, and understanding of biological systems.

VI. Quantum Signal Processing in Biophotonics and Radar Applications

The ability to extract meaningful information from weak or noisy signals is fundamental in both modern biomedicine and advanced sensing systems. Although biophotonics and radar operate in different domains — one within the human body, the other in open space — they share common technical challenges: achieving high resolution, sensitivity, and robustness in noisy environments. Quantum signal processing (QSP) addresses these needs by using the unique properties of quantum systems to unlock capabilities beyond the limits of classical detection.

Classical signal processing relies on measurable properties such as intensity, frequency, and time delay. While effective, it is constrained by the standard quantum limit, a boundary dictated by quantum uncertainty. QSP overcomes this limit by leveraging superposition, entanglement, and interference, enabling the detection of signals previously considered inaccessible [23]. These phenomena open the door to entirely new imaging and sensing techniques, often at much lower power and signal levels.

In biophotonics, QSP has found early success in methods like ghost imaging, which creates images through the correlation of paired photons — one that interacts with the object and another that does not. Surprisingly, the image can be reconstructed using only the correlation data between these spatially separated detection events [24]. This method is especially valuable in biological applications where exposure to strong light must be minimized, or where scattering environments make traditional imaging ineffective.

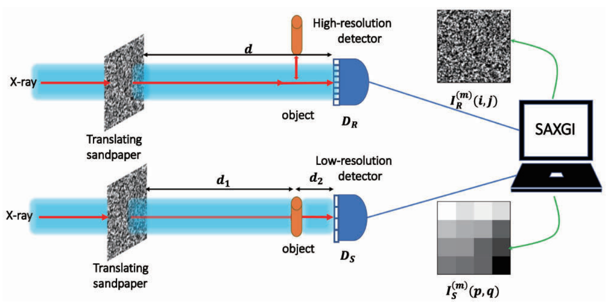

Fig. 4. Illustration of a ghost imaging setup using speckle patterns and two detectors. The image is reconstructed from correlations between intensity maps [25].

Although ghost imaging originated in optical laboratories, its principles are now influencing radar systems — especially in the form of quantum illumination. In this approach, one microwave signal from an entangled pair is sent toward a target, while the other is stored as a reference. After reflection and decoherence, the noisy return is compared with the reference, exploiting residual quantum correlations to enhance detection probability, even in hostile or jammed environments [26].

What makes quantum illumination particularly practical is that it does not require entanglement to survive the journey. The system gains its advantage from statistical comparison at the detection stage. Notably, Barzanjeh et al. demonstrated a microwave quantum illumination setup using a digital receiver with significantly improved detection capability compared to classical radar [27]. Because of its low emission power and improved stealth capabilities, quantum radar is attracting growing attention from defense initiatives and research laboratories worldwide [28].

However, developing functional quantum radar systems is still a major engineering challenge. Entangled microwave sources typically require cryogenic temperatures and complex superconducting circuits. Integrating quantum elements with conventional radar hardware — optimized for classical signal paths — poses additional difficulties. Moreover, the lack of technical standards for quantum sensing platforms slows down industrial scaling [29].

On the other hand, recent advances in photonic integrated circuits (PICs) — compact chips that manipulate light at the nanoscale — may accelerate the adoption of quantum technologies in real-world systems. Biophotonics again serves as inspiration: methods such as optical coherence tomography (OCT) and its quantum-enhanced version Q-OCT [30] are now being adapted for radar tomography. These adaptations could enable detection of internal structures under surfaces — from hidden defects in materials to layers beneath armor.

Another exciting direction is the use of quantum-enhanced signal processing in security and communication systems. Quantum radar could serve as an effective tool in identifying low-signature aerial threats such as drones, which are becoming increasingly difficult to detect using conventional technologies. Ghost imaging in the microwave domain has also shown potential for surveillance in visually obstructed environments — such as through fog, smoke, or thin walls — where traditional optics and radar fail. Additionally, hybrid systems that combine classical and quantum techniques are being tested for use in autonomous platforms, enabling real-time adaptation to changing environments. These innovations suggest that QSP may soon become essential in a wide spectrum of applications, from urban security and border control to autonomous robotics and disaster response.

The growing impact of QSP is not limited to imaging. Emerging concepts like quantum-enhanced lidar for autonomous vehicles, or underground sensors for geophysical monitoring, point to a much broader role for quantum sensing in future infrastructure. Researchers are even exploring space-based quantum sensors to improve Earth observation or deep-space communication.

As quantum signal processing continues to evolve, it may become a key technology for systems that must perceive, adapt, and react to complex environments — whether inside a human body or across a battlefield.

VII. QUANTUM COMPUTING FOR FINANCIAL RISK

Financial sector faces some of the computationally largest and most complex problems, which come with high-stakes decision-making. However, growing potential of quantum computing technologies has potential to become the future framework in this area.

Quantum computing offers a promising approach to strengthen fraud detection systems by boosting the efficiency of calculations done on high-dimensional datasets. Quantum machine learning algorithms, such as quantum support vector machines (QSVM), can identify subtle patterns in transaction data that can be often missed by classical methods. By combining classical and quantum methods together fraud detection accuracy can be improved, while at the same time, reducing false positives, which are critical for minimizing financial losses, as demonstrated in studies like ”Mixed Quantum–Classical Method for Fraud Detection With Quantum Feature Selection” [31].

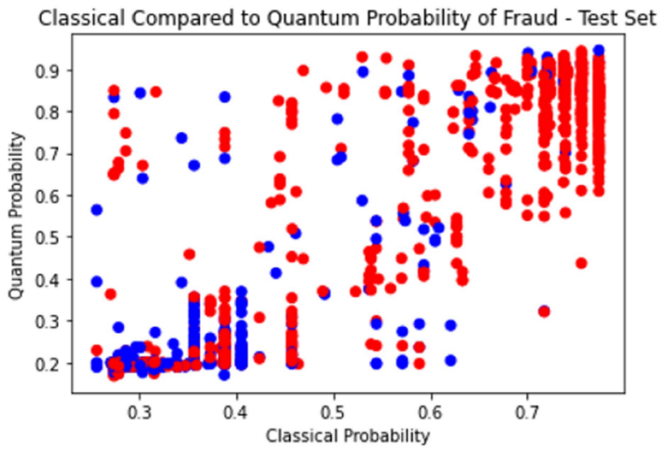

Fig. 5. Scatter plot showing agreement (diagonal) and disagreement (off-diagonal) between classical and quantum fraud probability predictions

Financial risk assessment evaluates and manages risks, such as market, credit and operational risks, using correlation analysis, loss prediction and many other techniques, such as Value at Risk (VaR) and Conditional Value at Risk (CVaR). Quantum computing offers significant advantages in this area by enabling more efficient analysis of complex financial systems. For example, quantum algorithms like the Quantum Approximate Optimization Algorithm (QAOA) can optimize portfolio allocation by balancing risk and return more effectively. Studies [32] demonstrate that integrating CVaR as an aggregation function in quantum optimization boosts algorithmic efficiency, yielding accelerated convergence and superior solutions for combinatorial challenges. These advancements strengthen portfolio diversification and comprehensive risk mitigation strategies.
Another area where quantum computers can be advantageous is modeling and modeling and analyzing the stock market. Stock prices can be represented in quantum world using wave functions and operators, which in turn allows for usage of models such as the Schrödinger equation for prediction of stock prices. Reaserchers [33] have demonstrated, that well established physics models, such as infinite quantum well can simulate stock price equilibrium states and calculate important metrics such as return on investment rates.
Moreover, quantum computing has the potential to revolutionize credit score calculations by innovating a hybrid quantum-classical machine learning models to improve prediction accuracy. Recent research [34] demonstrates, that this novel fusion of classical neural networks and quantum circuits improves credit scoring for small and medium-sized enterprises (SMEs). Introduction of a quantum layer into traditional neural networks can reduce training time by a factor of 10, which is main pain point of classical approach. This improvement allows for development of even more complex models, further boosting their accuracy. However, there are many practical deployment issues, particularly scalability beyond 12 qubits or addition of multiple quantum classifier layers. Despite this challenges, hybrid quantum-classical machine learning models seem to be promising step in the evolution of credit score calculation.
In conclusion, quantum computing holds immense potential to address some of the most challenging problems in the financial sector. From enhancing fraud detection and risk assessment to improving stock market modeling and credit scoring, quantum algorithms and hybrid quantum–classical approaches offer unprecedented efficiency and accuracy. While practical challenges such as scalability and hardware limitations remain, ongoing advancements in quantum technologies continue to pave the way for transformative applications in finance, promising a future of more robust and efficient financial systems.

VIII. QUANTUM CONCEPT OF BIRDS’ GEOGRAPHIC NAVIGATION

The extraordinary ability of birds to precisely return to their breeding or wintering grounds, even from distant and unknown locations, has fascinated scientists for years. One of the most intriguing mechanisms used in this ”true navigation” is magnetoreception - the ability to detect the Earth’s magnetic field. Contemporary research suggests that birds not only feel the magnetic field, but can even ”see” it. [35]

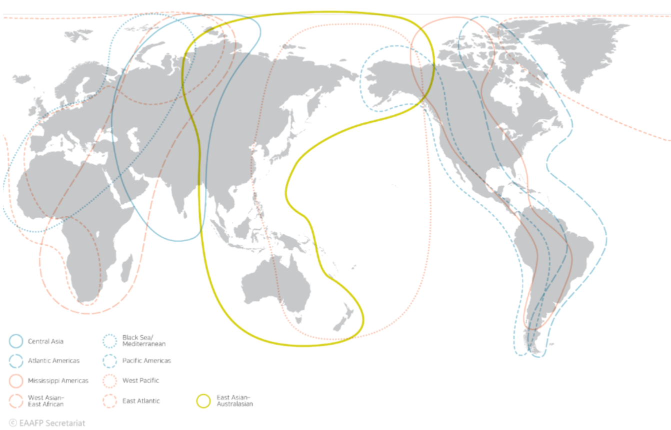

Fig. 6. Flyway Site Network [36]

There are many hypotheses about how birds navigate. There are also studies [37] confirming that birds are guided by the arrangement of stars or their movement in the sky.

The two main mechanisms of magnetoreception are the cryptochrome model and the ferromagnetic model. The first assumes that quantum radical reactions occur in the eyes of birds, or more precisely in proteins called cryptochromes. Light activates pairs of electrons, which - although separated - remain quantum entangled. The magnetic field can affect their spins, changing the chemical properties of molecules and allowing birds to read spatial orientation as light patterns.

The second mechanism suggests the presence of magnetite particles in the birds' beaks, acting like microcompasses, connected to the trigeminal nerve. Although studies [38] have shown the effect of beak anesthesia on orientation, recent discoveries question this model - cells with magnetite turned out to be macrophages, not neurons.

Many studies are carried out on birds Erithacus rubecula, they travel at night and thanks to them we learned, for example, that in the cryptochrome model most of the functionality is performed by the right eye of the bird. [39]

The use of quantum mechanisms can also act as one of the elements supporting navigation, just as humans use a map and compass, birds can use observations of the sky and stars (studies on robins) and support themselves in determining direction using quantum mechanisms.

Studies [40] confirm that magnetic field disruptions already at the level of 15 nanoTesla microTesla affect the loss of navigation ability in birds, which confirms that the earth's magnetic field is in some way information necessary for navigation for birds.

The importance of quantum geonavigation goes beyond biology - it inspires the development of new navigation technologies and deepens the understanding of the impact of artificial electromagnetic fields on living organisms. Although many questions and controversies remain, the cryptochrome model is gaining the most recognition as the key to understanding the biological compass of birds.

IX. Quantum sensors

Modern physics increasingly draws on quantum phenomena not only as a subject of study but also as a means of gaining knowledge. Phenomena such as superposition, coherence, or quantum entanglement — for decades confined to the domain of theory — are now becoming the basis for real-world measurement technologies. Quantum sensors — devices that take advantage of the sensitivity of quantum systems to interactions with their surroundings — are opening a new chapter in the detection of ionizing radiation. Among the most promising solutions are superconducting transmon qubits, cryogenic TES detectors, and diamonds with nitrogen-vacancy centers. Although they originate from different research traditions, they share a common feature: the use of fundamental properties of matter to register the most subtle forms of energy, such as single photons or radiation particles. This approach does not only increase the sensitivity of measurement but also reshapes our understanding of the limits of detection and the interaction between observer and system.

The first distinguishable type is transmon qubit is operating at extremely low temperatures — on the order of a few millikelvin [41]. Although originally designed as a building block for quantum processors, its high sensitivity to environmental disturbances also makes it a promising tool for the detection of ionizing radiation. When a particle of radiation interacts with the material surrounding the qubit, it deposits energy that generates phonons — vibrations of the crystal lattice. These, in turn, disrupt the fragile quantum state of the qubit, leading to decoherence. Measuring the reduction in coherence, such as a shortening of the relaxation time (T_1) or dephasing time (T_2), can be used as a detection signal. A distinctive feature of this technology is its range of response. Unlike conventional detectors, which require direct interaction with the active sensing element, a qubit can respond even to energy deposited in its immediate surroundings, without the need for a direct hit. Additionally, its low operating temperature makes the system relatively immune to classical sources of noise, such as thermal vibrations or electromagnetic interference. However, this temperature requirement also represents the main limitation of the technology: operation at ultralow temperatures is achievable only with advanced cryogenic refrigeration systems. Such equipment is expensive, requires continuous maintenance, and is difficult to implement outside of laboratory conditions. At present, it is these engineering and operational constraints — rather than the physical limitations of the qubit itself — that pose the greatest obstacle to practical deployment. Another barrier is the limited scale of existing research, as most efforts to date have focused on applications in quantum computing rather than radiation detection.
Another promising technology for the detection of ionizing radiation is the Transition Edge Sensor (TES) — an exceptionally sensitive radiation detector that operates at cryogenic temperatures, typically below 100 millikelvin [42]. Its operating principle is based on superconductivity: the TES material functions at the boundary between the superconducting and normal conducting states, known as the "transition edge." At this point, even a slight temperature increase caused by the absorption of radiation results in a sharp change in electrical resistance. Detection is carried out by precisely measuring this change, which is proportional to the amount of energy deposited in the sensor. TES devices are capable of registering single photons or extremely weak energy pulses with remarkable accuracy — their energy resolution can reach tens of electronvolts, even in the hundreds of keV range. One of the greatest advantages of TES detectors is their precision. Owing to their sharp superconducting phase transition, they enable measurements with extremely high energy resolution, making them well suited for applications in particle physics, X-ray astronomy, and dark matter experiments. On the other hand, much like transmon qubits, TES technology remains highly demanding — it can only function under extreme thermal conditions, near absolute zero. In a sense, TES devices embody a certain paradox: in order to detect the subtlest manifestations of energy, we must first create an artificially "perfect"

environment that does not exist in nature. Thus, although the technology is well developed in scientific research settings, it still requires significant expertise in design and operation — a factor that continues to limit its broader adoption in fields such as medicine or industry.

Another example is diamonds with nitrogen-vacancy (NV) centers [43]. These are unique materials in which the removal of a carbon atom from the crystal lattice (a vacancy) and its replacement with a nitrogen atom creates a quantum defect. The NV center has a spin quantum state that can be optically initialized and read out — green light excites the system, while red fluorescence reveals its current state. This property makes NV diamonds one of the most intriguing materials for detecting subtle changes in magnetic fields, temperature, and pressure, as well as — as recent studies have shown — for registering ionizing radiation. In experiments involving radiation in the 80–1200 eV range, it has been demonstrated that NV centers can be excited without the need for a green laser — the energy of the incident photon alone is sufficient. This interaction produces electron–hole pairs, which in turn excite fluorescence, the intensity of which depends on the energy of the incoming radiation. The diamond thus functions as a quantum scintillator — emitting light in response to radiation. However, this system has a fundamental limitation. Radiation with excessively high energy can not only excite the NV center but also damage the diamond's crystal structure itself. Paradoxically, the very process of removing carbon atoms from the lattice using high-energy ions is the method by which NV centers are created in the first place. For this reason, the energy range in which NV centers can function as detectors is inherently limited.

X. Encephalography

Encephalography is a collective term for non-invasive techniques that record and analyze brain activity by placing appropriate sensors on the patient's skull. The most commonly used technique for encephalography is electroencephalography (EEG) that provides relevant information by measuring changes in electrical potential. There exists also alternative quantum techniques which are magnetoencephalography (MEG) and magnetoencephalography based on optically pumped magnetometers (OPM-MEG) that rely on measuring magnetic activity of a brain. Thanks to harnessing of quantum properties they are capable of measurements with greater resolutions and therefore more accurate diagnosis. [44]

The first measurement of bioelectricity was made by Richard Caton in 1875 on animal brains. And Hans Berger conducted the first EEG recordings on the human brain in 1929. Electroencephalography involves placing electrodes on the scalp according to the 10-20 system. The electrodes measure changes in electrical potential on the scalp surface, reflecting neuronal electrical activity. One advantage of EEG is that it is non-invasive and safe method, and it has high temporal resolution. However, it has low spatial resolution and it is sensitive to artifacts.

Another measurement type is Magnetoencephalography. It measures magnetic fields generated by ionic currents in neurons. It uses SQUID sensors, allowing the detection of magnetic fields as low as a few femtoteslas. This method requires cooling with liquid helium. In MEG measurements, 200 sensors are distributed in a dome around the head. The system has to be in a magnetically shielded room to reduce external noises, and patients must remain still during the examination. The MEG has high temporal and spatial resolution and allows precise mapping of neuronal sources. The main limitations of the MEG are high costs of equipment, its maintenance and restrictions due to patients' immobility. [45]

Lastly, OPM stands for Optically Pumped Magnetometers, and it uses optical sensors based on alkali gases (rubidium) optically pumped with laser light. Changes in atomic spin orientation in the magnetic field translate into signal modulation. OPM sensors are small, which enables a conformal arrangement around the head. It does not need cryogenic cooling, and the OPM-MEG helmet can be adapted to head shape so the patient can move during the measurement. OPM-MEG has high spatial resolution because sensors are close to the scalp. However, the costs of helmets and sensors are high, and the technology is still in development. [46]

The impact of aformentioned techniques is best shown where applied to real world data. In 2021, over 3 billion people worldwide suffered from various neurological disorders. [47] Thanks to descriptions of brain activity provided by encephalography techniques process of diagnosis of neurological diseases has become more accurate. Patients can undergo an assessment that will result in earlier treatment and allow usage of preventive measures. The most commonly diagnosed diseases diagnosed this way are

- Alzheimer's Disease,
- Parkinson's Disease,
- Epilepsy,
- Migraine,
- Neurodegenerative disease.

Moreover, encephalography is used in all stages of the treatment of neurological problems. It allows monitoring coma patients, assessing how effective given therapy is, and determining if the illness is progressing. It is also an invaluable source of research material needed to progress medical knowledge in the domain of brain surgery.

EEG, MEG, and OPM-MEG are complementary diagnostic and research tools in neurophysiology. Electroencephalography offers accessibility and good temporal resolution, but it is spatially limited. Magnetoencephalography with SQUID provides precise localization of neuronal sources, but costs and cryogenic requirements are significant. Optically pumped magnetometers are a promising future, offering mobility, high spatial resolution, and the ability to study movement, though availability and costs remain challenges.

XI. Quantum Aspects of Photosynthesis

Photosynthetic organisms achieve remarkably high efficiencies—often exceeding 95%—in harvesting sunlight and funneling excitation energy to reaction centers. Classical "hopping" models cannot fully account for such performance, especially given the complex network of pigment–protein complexes and the thermal disorder present in biological systems. Recent research suggests [48]–[50] that the phenomena *quantum coherence* and *superposition* allow excitons to exploit multiple pathways simultaneously, effectively performing a natural optimization that minimizes energy loss.
Upon absorbing a photon, a pigment molecule (e.g. chlorophyll or bacteriochlorophyll) is promoted to an excited electronic state, creating an *exciton* (a pair of correlated electrons - holes). In a quantum framework, the exciton is not localized on a single pigment but exists as a coherent superposition across several sites. This delocalization permits *wave–like* propagation: the exciton explores alternative routes in parallel, and constructive interference enhances the most efficient trajectories to the reaction center, while destructive interference suppresses inefficient ones. The result is an ultrafast, low–loss energy funneling mechanism that is robust against static disorder and thermal fluctuations.
The experimental evidences for this phenomena was documented in following studies

- Engel *et al.* (2007) [48] pioneered two-dimensional photon-echo spectroscopy in the Fenna-Matthews-Olson (FMO) complex of green sulfur bacteria at 77 K. They observed oscillatory 'quantum beats' in cross-peak amplitudes, lasting several hundred femtoseconds, which unambiguously demonstrate electronic coherence between pigment sites.
- Collini *et al.* (2010) [49] extended these measurements to physiological temperatures. By applying similar 2D spectroscopic methods to FMO and to antenna complexes of marine cryptophyte algae at 300 K, they recorded coherence lifetimes on the order of 200–400 fs under ambient conditions.
- Zhang *et al.* (2023) [51] introduced the 'city under glass' experiment on the LH2 complex of purple bacteria. Using entangled photon pairs produced via spontaneous parametric down–conversion, they heralded single–photon absorption events in LH2. Subsequent detection of 850 nm fluorescence confirmed that individual photons could reliably initiate the complete excitation transfer cascade.

Although the presence of quantum coherence is well established, its functional advantage remains debated. Some authors [50], [52] propose that coherence accelerates transfer beyond classical limits, similar to quantum search algorithms, whereas others argue that the observed oscillations may arise from *vibronic coupling* - mixed electronic-vibrational states - without significantly altering the net transfer yield [53], [54]. The true impact of coherence under *incoherent* sunlight, which has a coherence time orders of magnitude shorter than laser pulses, is still under active investigation [55], [56].
However, Theoretical models [57], [58] now emphasize the role of vibronic coupling: vibrational modes of pigment scaffolds can resonate with electronic energy gaps, creating hybrid states that prolong coherence and facilitate energy hopping. This interplay can soften the energetic barriers between sites and provide a dynamic 'bridge' for excitons to tunnel efficiently across the pigment network.
Most experiments employ highly coherent laser pulses; however, natural sunlight is temporally incoherent. Recent simulation studies [59], [60] and emerging single–molecule measurements [61], [62] aim to determine whether transient quantum effects survive under solar flux. Early results suggest that even brief femtosecond coherences can bias energy flow before dephasing, hinting that quantum mechanisms may contribute, although subtly, under real-world conditions.

Integrating quantum principles into artificial light harvesting architectures presents a promising path toward next-generation renewable energy devices. Engineered pigment arrays, semiconductor nanostructures, or hybrid bio–inorganic materials designed to support controlled superpositions could achieve ultrafast, low–loss energy routing. In addition, advances in ultrafast spectroscopy, entangled–photon techniques, and quantum sensors will deepen our understanding of coherence–assisted processes in biology and beyond.

XII. Brain Imaging Using Quantum Biophotonics in Neurological Theranostics

Modern neuroimaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI) and positron emission tomography (PET) provide rich structural and functional insights but remain constrained by limited spatial resolution, insufficient molecular specificity, and the inability to couple localized therapy with diagnosis across the blood–brain barrier [63]. Semiconductor quantum dots (QDs), with core diameters typically in the 2–9.5 nm range, exhibit size-dependent emission wavelengths, high resistance to photobleaching, and broad absorption spectra, making them attractive candidates for both deep-tissue imaging and theranostic applications [64].

In order to understand the advantages of quantum dots (QDs), one must take a closer look at their optical and surface properties. Compared to conventional organic fluorophores, QDs exhibit absorption cross-sections up to an order of magnitude larger and can achieve quantum yields of 60–90

In addition to their brightness, QDs offer remarkable photostability due to their inorganic core–shell architecture, typically comprising a CdSe core encapsulated in a ZnS shell. This structure provides protection against photobleaching and yields fluorescence lifetimes that often exceed 10 nanoseconds. The extended lifetime enables the use of time-gated detection techniques, which can effectively suppress tissue autofluorescence in long-term in vivo experiments [64]. Moreover, the surface chemistry of QDs allows for versatile bioconjugation. Functionalization strategies employ thiol ligands, amphiphilic polymers, or peptides to render QDs hydrophilic and introduce reactive groups for conjugation with biomolecules such as antibodies, peptides, or oligonucleotides. Polymeric coatings and the protective ZnS shell further enhance oxidation resistance while maintaining high quantum efficiency [64], [65].

Quantum Dots have their applications in Deep Brain Multiphoton Microscopy. Multiphoton microscopy (MPM) utilizes nonlinear absorption of infrared photons, allowing optical scanning of deep tissue layers. Due to large two- and three-photon absorption cross-sections, QDs have enabled imaging up to 2100 µm depth in the mouse hippocampus at 1700 nm, outperforming traditional dyes by over 50% (e.g., 1340 µm for Texas Red dextran) [63]. Furthermore, QDs allow functional measurements such as blood flow velocities of 0.96 mm/s at 200 µm depth and 0.75 mm/s at 600 µm and open the way to detect single action potentials with sampling rates ≤ 2 kHz [63].

In addition, quantum dots can serve as multifunctional nanocarriers combining imaging and therapy:

- Targeted drug delivery: Conjugation of QDs with cytostatic agents or photosensitizers and blood–brain barrier–penetrating ligands allows precise, localized drug release [63].
- Real-time monitoring: Simultaneous multicolor emission enables tracking of drug distribution, cellular uptake, and therapeutic effect [64].
- Photodynamic therapy (PDT): QD–photosensitizer complexes generate reactive oxygen species upon light activation, enabling destruction of tumor cells or pathological tissues [63].

From studies mentioned above several clear advantages of quantum dots can be distinguished

- Exceptional sensitivity: Detection of single particles even in complex neuronal environments [64].
- High spatial resolution: Micrometer-level imaging of synapses and microangiography.
- Multiplexing capability: Simultaneous labeling of multiple biomarkers via emission wavelength control.
- Minimal invasiveness: Near-infrared excitation reduces photodamage and enables transcranial imaging.
- Integration of diagnostics and therapy: A single platform for imaging and treating tumors or pathological tissues.

However, apart from positives there are also limitations and safety considerations to that approach. Cationic Cd^{2+} ions released upon degradation of the CdSe core exhibit hepatotoxicity at concentrations of 100–400 µM and although surface shells reduce ion leakage, they do not eliminate this risk [65]. Additionally, rapid clearance of QDs by the reticuloendothelial system and potential immunogenicity hinder in vivo applications. Comprehensive studies on long-term biodistribution and clearance of QDs from the nervous system are also lacking [65].

All in all, quantum dots combine unique optical properties with the ability for deep tissue imaging and precise therapy. Key directions for future research include:

- Development of durable, biocompatible shells resistant to oxidation.
- Design of QDs capable of efficient transport across the blood–brain barrier.
- Creation of multifunctional nanocrystals combining imaging, catalysis, and controlled drug release.
- Conducting long-term in vivo studies to determine biodistribution, toxicity, and clearance pathways of QDs in the nervous system.

Realization of these goals could revolutionize brain theranostics, offering deep imaging, targeted intervention, and sustained functionality simultaneously.

XIII. Quantum Biomedical Sensors

Quantum biomedical sensors are revolutionizing medical diagnostics and research by leveraging quantum phenomena to achieve unprecedented sensitivity and spatial resolution. These sensors, particularly optically pumped magnetometers (OPMs) and nitrogen-vacancy (NV) centers in diamond, are transitioning from laboratory prototypes to clinical tools, offering transformative applications in neurology, oncology, and personalized medicine. [66] [67] [68]

OPMs excel in detecting weak biomagnetic fields, such as those generated by neural activity. Recent advancements enable wearable OPM-based magnetoencephalography (MEG) systems, allowing patients to move freely during brain recordings-a significant improvement over bulky superconducting quantum interference device (SQUID) setups. [66] This mobility facilitates functional brain imaging in naturalistic settings, aiding the study of neurological disorders like Alzheimer's and Parkinson's. Clinical trials demonstrate OPMs' potential for early diagnosis of traumatic brain injuries and fetal heart abnormalities, with sensitivity down to femtotesla levels.

NV centers in diamond provide subcellular-resolution magnetic imaging, enabling single-neuron activity mapping and detection of magnetic biomarkers at nanoscale precision. [66] [67] Their quantum coherence properties allow nuclear magnetic resonance (NMR) spectroscopy of single proteins and metabolites, critical for studying transmembrane protein structures or cancer cell metabolism. [67] [68] Nanodiamonds functionalized with NV centers can also probe intracellular temperature gradients, revealing heat generation patterns during cell division or drug responses. [66] [67]

In oncology, quantum sensors address key challenges in tumor detection and treatment monitoring. NV-center magnetometry identifies circulating tumor cells via their unique magnetic signatures, while OPMs track iron-oxide nanoparticle labels in targeted drug delivery systems. [68] Correlation spectroscopy with multiqubit sensors enhances signal-to-noise ratios in deep-tissue imaging, enabling early detection of microcalcifications in breast cancer. [68]

Diagnostic applications extend to infectious diseases and systemic conditions. Quantum-enhanced NMR detects pathogen-specific biomarkers at low concentrations, potentially replacing polymerase chain reaction (PCR) methods for rapid sepsis diagnosis. [68] Portable OPM devices are being tested for point-of-care monitoring of heart arrhythmias and muscle disorders, leveraging their miniaturized form factor and operation at ambient temperatures.

Despite these advances, clinical adoption faces barriers. Quantum sensors require validation against gold-standard techniques, with regulatory hurdles complicating approvals for novel diagnostic modalities. Cost remains prohibitive for NV-center systems, though economies of scale in diamond synthesis are reducing prices. [66] [68] Cross-disciplinary collaboration is critical-developers must align sensor designs with clinical needs, such as optimizing NV-center protocols for biocompatibility or refining OPM arrays for pediatric applications. [68]

The Quantum Economic Development Consortium (QED-C) outlines three priorities to accelerate translation: establishing testbed facilities at national labs, increasing venture capital for high-impact projects, and creating standardized benchmarking frameworks for quantum sensor performance. [68] Parallel efforts in quantum algorithm development aim to mitigate decoherence in biological environments, enhancing in vivo measurement reliability.

XIV. Conclusions

Presented research showcases that Quantum technologies are finding applications in various domains. As research progresses is becomes clear that quantum properties are crucial in many natural phenomena such as photosynthesis and sense of navigation observed in birds. There are multiple methods when applying quantum methods allows for measuring and observing certain things with much greater precision that currently used classical methods. Common concerns shared between previously discussed technologies are costs of equipment, volatility of measurements and hardware limitations. Many of those techniques are also still in research phase and although some of it presents promising results society is far from considering quantum solutions as mainstream for quite some time.

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