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Current Advances in Information Quantum Technologies – Critical Issues

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***Abstract*—This article reviews chosen topics related to the development of Information Quantum Technologies in the major areas of measurements, communications, and computing. These fields start to build their ecosystems which in the future will probably coalesce into a homogeneous quantum information layer consisting of such interconnected components as quantum internet, full size quantum computers with efficient error corrections and ultrasensitive quantum metrology nodes stationary and mobile. Today, however, the skepticism expressing many doubts about the realizability of this optimistic view fights with a cheap optimism pouring out of some popular press releases. Where is the truth? Financing of the IQT by key players in research, development and markets substantially strengthens the optimistic side. Keeping the bright side with some reservations, we concentrate on showing the FAST pace of IQT developments in such areas as biological sciences, quantum evolutionary computations, quantum internet and some of its components.**

***Keywords*—information quantum technologies, quantum sensors and timing, quantum computing applications, quantum genetic algorithms, quantum communications and internet**

I. Introduction

QUANTUM supremacy is one of the most popular metrics of IQT, which shows immediately, sometimes in a very dynamic way, what is expected by the public [1]. The market did not leave this measure as an orphan but generated several analogous ones. Supremacy, showing that a quantum computer solves computational problems unsolvable for classical one, is in between the quantum advantage and value. Advantage concerns the comparison of required resources of time and costs. The Advantage and Supremacy are abstract research metrics not respecting the usefulness of the problem. The value is a real, tough measure of quantum advantage/supremacy for a problem of commercial value.

The metrics were coined not for vein. Just a year after Google published the first-ever landmark supremacy claim using superconducting quantum processor [2], a Chinese team from Hefei beat that record considerably with an all-optical quantum computer [3]. It was shown in the meantime that Google's result was only an advantage, not supremacy. In practice, these achievements cannot be compared. Google used an algorithm checking the outputs from a quantum random number generator while the Chinese team demonstrated boson sampling–the probability of detecting a boson in a particular position [4], [5]. This is further discussed in VIII.

The terms quantum advantage, supremacy, and value are used in reference to all developing applications of information quantum technologies embracing metrology and timing, computing, and telecommunications. Some of them are presented in Table I.

TABLE I
COMPARING QUANTUM VS CLASSICAL

	Metrology	Computing	Network
Advantage	more sensitive	faster, lower computing cost	safer
Supremacy	unreachable sensitivity	classically unsolvable	quantum Internet
Value	competitive, cheaper, ruggedized, integrated	available quantum co-processor	cloud based quantum key distribution

In this paper, we attempt to verify if these terms find justification by providing a survey of emerging fields in quantum technology. Due to the fact that the domain of IQT is exceptionally vast, we will focus only on selected advances that correspond with the authors' research areas. However, we will try to provide a survey comprehensive enough to include recent achievements in fields devoted to either hardware or software applications. Also, we will address issues related to the theoretical background of IQT.

The paper consists of the following sections. In Section II, we highlight concerns about the limitations of IQT and discuss quality indicators like SWAP-C used in the context of quantum technologies by the industry. Section III discusses a notion of nonlocality as a fundamental property of Nature and a key feature of quantum mechanics. Section IV is devoted to atomic clocks and their applications. In Section V, the basic concepts of quantum Internet are introduced, along with highlighting the present limitations of this solution. In Section VI, we summarize recent developments in the field of photonic quantum memory and its prospects for the future. Section VII discusses advances in quantum logic gates research. Section VIII presents the latest achievements in quantum processor technology. Also, this section provides a comparison between the performance of a classical processor and its quantum equivalent. Section IX broaches the transfer of evolutionary

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algorithms into quantum computing. Section X outlines the latest research devoted to quantum neural networks, their relation to classical models, and their application in image recognition tasks. In Section XI, we discuss connections between quantum computing and bioinformatics. The paper is concluded in Section XII.

II. IQT SWaP-C and Quality Factors

The industry sees new technologies, including the IQT components and systems, via value indicators such as SWaP-C and other solution-specific quality factors [6]. These indicators are related primarily to integration but also to technology equalization and system homogenization. Avoiding noncompatible system components is crucial.

Unfortunately quantum systems require cryocooling to fight noise and decoherence. The components for cooling thermal isolation make quantum devices large and heavy. Power consumption is related to powering the quantum circuit and the control-readout system. Cost is lowered by standardization and using off-the-shelf components. Standardization is developing in some areas of the IQT, including software and control systems like Artiq, Sinara, and some quantum qubits solutions like simple ion traps. SWaP-C concerns particular components of the quantum system in a different way. Quality factors are qubits fidelity, length of the coherence time, ruggedness against decoherence, the ability of error suppression and/or correction, effective usage of the Zeno quantum effect to reset accumulating quantum errors, etc. When a possible transition between quantum advantage and value is considered, the following main limitations are of concern. Quantum metrology is limited by the ability to reduce very good laboratory solutions to mobile devices of comparable performance. Quantum computers are limited by imperfections in qubit hardware. Quantum network gathers all these limitations from which metrology and computing suffer plus the necessity to transfer stationary qubits to flying qubits which do not lose the coherence and entanglement during the networking processes along complex multicolor optical paths. The phenomenon of quantum entanglement is discussed in more detail in the next section.

III. Quantum Nonlocality

Nonlocality is a term relating to the fundamental property of Nature ranging from philosophy, biomedicine to physics [7]. Depending on the scale, nonlocality meets the postulates of special and general relativity, quantum mechanics and probably contributes to the BSM [8]. It is related to the concepts of free will and determinism [9], [10]. At the quantum level, the existence of nonlocality has been successfully tested many times experimentally by Bell's inequality [11].

Some discrepancies were found between nonlocality and entanglement, indicating their different origins [12]. This raises several questions that may have an impact on IQT, in particular on information causality [13]. There are some controversies around entanglement and quantum nonlocality related to contextuality [14], [15].

Micius satellite experiment showed the distribution of quantum entanglement over large distances and effective QKD distribution [16]. Ad-hoc network configured on drones and using entangled state photons was used for secure signal transmission [17]. Entanglement was used for quantum data translation between stationary and flying qubits to be transmitted in the long-wavelength window [18]. Free space seawater communication and precision imaging with entangled and nonclassical light is successfully tested for submarines [19].

Quantum imaging with sub-Poissonian light, which omits the quantum resolution limit, opens new application fields in precise functional sub-cellular research [20].

Nonlocality will be subject to further research in philosophy, sociology, psychology and biophysics [21], as well as in fundamental physics [22]. Nonlocality is drastically changing, via the quantum entanglement, the technologies the civilization is using for communications, metrology and computing, even though some of its origins are far from being settled [23].

IV. Atomic clocks exceeding the standard quantum limit

Quantum entanglement is already practically applied to improve sensitivity in quantum metrology, e.g. in atomic clocks. Since the middle of the 20th century, hyperfine transitions between atomic energy states define our measure of time [24]. Atomic clocks enabled experimental proof of fundamental laws such as Einstein's relativity [25] and gravitational waves [26], and have important everyday applications such as the GPS [27] or precise time-keeping in financial markets [28]. The continuous improvement of the accuracy of atomic clocks was so successful that it pushed to the natural limit of the quantum world: Heisenberg's uncertainty relation. But scientists even went beyond this standard quantum limit (SQL) using a specific type of entanglement: squeezed spin states [29], [30].

Electromagnetic (EM) radiation shining on ground-state atoms at the correct frequency will excite them to a higher energy level. When the EM frequency gets slightly off-resonant, we note that less excited atoms are detected and adjust the frequency of the EM radiation accordingly. Via such a feedback loop, an extremely stable frequency reference for a clock is achieved. But for very precise clocks, ultra-low temperatures are needed to have sufficiently long probe times. Furthermore, high frequencies and narrow bandwidths of the atomic transition improve the accuracy of atomic clocks. But compared to microwave frequencies, as used in traditional atomic clocks, optical frequencies are hard to measure [31].

Today, atomic clocks operating in the optical regime are realized due to technological advances in laser cooling and trapping of atoms, high-finesse Fabry-Pérot cavities, laser spectroscopy, and femtosecond-laser frequency combs [31]. Spin squeezing techniques already enabled microwave clocks to operate beyond the SQL [29]. In 2020 for the first time spin squeezing of many atoms (350±40 171Yb atoms) was achieved on an optical atomic transition, where phase coherence is harder to maintain [30]. Therefore, at first, a radio frequency transition of the hyperfine structure of 171Yb was squeezed, and then the spin squeezing was mapped onto an optical transition via a π laser pulse without significant losses. A cavity with a finesse of $F = 12,000$ was used, and the atoms were cooled down to 1.8μK. a clock operating $4.4(+0.6, -0.4)$dB above the SQL is the result.

In the future, the high accuracy of modern atomic clocks will find practical applications, e.g., in geodesy [32] and in tests of general relativity [33]. Spin squeezing on optical transitions of many atoms will also be used for other optical quantum sensors to perform precise measurements beyond the SQL. Furthermore, the many years of atomic clock experience in manipulating ensembles of atomic qubits with unprecedented accuracy and reliability form a basis for the development of quantum computing.

V. Quantum internet

Quantum technologies that rely on operations with entangled qubits play a crucial role in the development of the quantum internet. The accomplishment of the quantum internet would be an answer to limitations that bother classical communication that are mainly related to the level of security, privacy and computational clout. It would also be an excellent tool for some other promising tasks such as distributed quantum computing [34] or precise clock synchronization [35]. However, despite the considerable recent interest in quantum technologies, the quantum internet is still at its first stages of implementation [36], and many of its fundamental elements are still under development.

The concept of the quantum internet is based on entangled qubits that remain connected even if they are far away. Distanced qubits are linked by using a pair of photons that are produced in an entangled state. Such photons are sent to qubits over communication channels, which could be optical fibres as already used for classical communication. The main disadvantage of this solution is the fact that photos after traveling around 100 km tend to interact with the cable, which affects their state. This problem, due to the no-cloning principle, cannot be solved by amplifiers as it is done with classical signals. To address this issue, quantum repeaters are introduced between the end nodes of the network. The repeater catches and stores the photon from a sender and re-emit the new one to the next node. As soon as the entanglement is heralded, the Bell-state measurement in the repeater is performed. This allows entangling, one after another, adjacent quantum memories and therefore sharing the information between distanced nodes of such a communication chain.

A very important issue of the quantum internet is the realization of quantum memory in end nodes and repeaters that is needed for storing the state until the entanglement is created. The current realization of the quantum memory (usually performed by atomic ensembles and ions in traps) need further investigation and development to increase the efficiency of saving and receiving back photons (the recent record [37]). However, there are already some ideas that can overcome the quantum memory issue in repeaters, e.g., by applying so-called all-photonic repeaters based on only optical devices and flying qubits [38].

The alternative solution to communication through optical fibres is using a free space e.g., between ground and satellites. Free space communication allows for faster transmission and reduction of the number of devices between the communicating points. Here, the quantum repeaters set for several dozen kilometres are not needed to create the entanglement on even 1120 km (reported in 2017 [39]). Nevertheless, this solution also has its disadvantages, like dependence on weather conditions or satellite resources.

After dealing with obstacles related to the basics of communication and storing devices, the scientists would focus on new, more advanced challenges and improvement of the quantum internet. Many projects already work on some of them, e.g., on new materials that would decrease the probability of possible errors [40], connecting quantum devices [41], flexibility and easy extension on new users [42], or connecting quantum memories [43]. However, even if teleportation is possible through thousands of kilometres and the first quantum network already exists [44], it is still a long way to the full-blown quantum internet.

VI. Photonic quantum memory

The development of quantum memories is essential for applications in quantum computers, quantum networks, or communication. It is driven by a constant strive for improving the storage efficiency and fidelity, as well as for obtaining longer memory times. Memory efficiency may be defined as the probability of storing and retrieving a single photon, whereas fidelity is a measure of similarity between stored and retrieved quantum states. A number of different methods for storing and recovering single photons utilizing different physical phenomena have been proposed [45], [46].

Quantum memories for polarization qubits based on electromagnetically induced transparency (EIT) in cold cesium [47] and rubidium [48] atom ensembles with high efficiency and fidelity exceeding 99% have been reported. In [47], efficiencies at the level of 68% for arbitrary polarization states were obtained for storage times of $1.2\mu s$ and weak coherent pulses with a mean number of photons per pulse $\bar{n} = 0.5$. In [48], a quantum memory with efficiency above 85% for $1\mu s$ storage time for pure single-photon states is presented. In the system, spontaneous four-wave mixing (SFWM) within a magneto-optical trap was used for the generation of single photons with a well-defined Gaussian temporal waveform. Based on the experiments, two thresholds for the useful storage time were defined. Firstly, based on the measurement of the conditional second-order autocorrelation function, the faithful storage time was taken as $3\mu s$, since up to this time, values below 0.5 were obtained, indicating the retrieval of a single-photon state. Another definition of storage time was based on the time for which the efficiency drops to 50%. It is equal to $15\mu s$. Achieving an efficiency above 50% is crucial for practical applications since it enables beating the no-cloning limit without post-selection. Obtaining such high efficiencies was possible due to the use of cold atoms with high optical density above 250, suppressed noise, and single photons with controllable temporal waveforms. The obtained values significantly surpass the previously reported efficiencies for single-photon polarization qubits.

In [49], quantum memory based on a magneto-optical trap of cesium atoms used for storage of single photons generated in a cavity-enhanced spontaneous parametric down-conversion (SPDC) is described. An efficiency of 36% was obtained. It is lower compared to the system described in [48]. However, it exceeds previously reported results for photons generated in SPDC process. The bandwidth of such photons is the limiting factor for efficiency. On the other hand, it has the advantage of decreased experimental complexity and increased photon generation rate, making it easily scalable and potentially very useful for future large-scale applications.

Atomic Frequency Comb (AFC) is another commonly used quantum memory protocol [45], [46]. Its retrieval efficiency can theoretically reach 54% in forward and 100% in backward direction [46]. Rare-earth ion-doped solids, such as $Nd^{3+}{:}YVO_4$ have been commonly utilized as the storage material [45]. Because of the requirement for high stability of the frequencies of different atoms with respect to each other, this method has been limited to solids at low temperatures. Recent research [50] suggests that it is possible to build a quantum memory for pulsed light based on the AFC protocol using room temperature cesium vapor. In that solution, velocity-selective optical pumping is used to prepare the frequency comb from the inhomogeneously broadened line. This solution is an important step towards realizing a quantum memory with multimode capacity at room temperatures. It was also proposed to build the frequency comb based on multiple transitions between the hyperfine levels of single atoms in the cesium vapor cloud [51]. The authors show a numerical model of cesium-based quantum memory for polarization qubits with calculated maximal efficiency of 48% for forward and 90% for backward propagation. Initially, it was claimed that the system could be operated as high-temperature quantum memory. However, further investigations [52] limited the maximal useful operating temperature to 10 K.

Another development of the AFC protocol is presented in [53]. The authors report having built an on-chip waveguide memory for time-bin qubits with a fidelity exceeding 99%. It enables on-demand retrieval of photonic qubits with storage times above $2\mu s$. The memory was fabricated using femtosecond-laser machining on the surface of $^{151}Eu^{3+}{:}Y_2SiO_5$ crystal.

Quantum memories were improved significantly in recent years. The research focused on two main areas. Firstly, the performance of the memories has been improved by building systems with higher efficiency, fidelity, or duty cycle. Secondly, there is a constant effort to decrease the complexity of the memory itself and photon sources. While there is still a long road before creating the first quantum memory that can be integrated into personal consumer devices, recent developments bring quantum memories closer to large-scale applications in quantum communication or information processing.

VII. Fast Quantum Logic Gates with Trapped-Ion Qubits

Two-qubit logic gates are essential to creating a quantum processor. Taking into account current parameters of other techniques used for building trapped-ion quantum processor, such as qubit readout [54], laser cooling [55], or ion-shuttling [56], [57], two-qubit gates limits could negatively impact the clock speed of such quantum processors based on CCD architecture [58]. Such CCD architecture enables the implementation of error-correction codes [59] for logic gates.

For conventional quantum logic gates, the gate time is controlled in an adiabatic regime with single, rectangular laser pulses. The disadvantage of this method is the achieved gate duration limit of approximately $30\mu s$ to $100\mu s$ (with the lowest reported error rates) [60], [61]. This limit is not caused by physical constraints. However, simply reducing the gate time (consequently controlling the gate in a non-adiabatic regime) leads to several major complications, which are discussed in [62]. The final result is a complicated gate error rate dependency on gate time. The achieved reported results of a single rectangular pulse in a non-adiabatic regime are $2.13\mu s$ gate time with gate error of 2.0(5)%.

[62] also propose a different solution, which uses fast laser pulses with shaped amplitude. A characteristic feature of this method is a greater number of controllable parameters. By discovering a proper combination of the aforementioned parameters, satisfying results can be achieved. With this method, two-qubit gates with up to an order of magnitude lower gate time were achieved. Additionally, the development of numerical modeling, including effects beyond the Lam-Dicke regime, made it possible to achieve particularly good results. The consequence of this approach is the lowest achieved gate time of $480ns$. However, the gate error rate observed with such gate speed is 40%, which is too big for practical use in a quantum processor but might find uses in other areas. A significantly more useful result obtained is $1.6s$ gate time with a 0.22% gate error rate. This is an order of magnitude below the required threshold. Theoretically, the total gate error rate with such gate time can be as low as approximately 0.18%.

The achieved two-qubit gate speed with trapped-ion qubits is significantly faster than in previous works. However, they are still one or two orders of magnitude greater than typical gate times of superconducting ($50ns$ [63]) or silicon-based ($480ns$ [64]) qubits. Quantum logic gates' speed will be subject to further research, as the requirements for quantum processors as well as the speed of other parts of such processors will develop. The need for faster circuits will grow in time and will need to be satisfied in the future.

VIII. Quantum Supremacy in Quantum Computing

Quantum computing using quantum processors promises significant change in different scientific fields [65], such as biology [66], chemistry [67], and physics simulation [68]. However, despite the recent advances in the field, commodity quantum processors are still not available. Many researchers worldwide progress step by step towards the achievement of quantum supremacy. However, it is still impeded by the nature of the quantum physics itself - naturally occurring noise at the quantum level that limits the reliability of readouts of quantum computation results.

As mentioned in the introduction, one of the most remarkable steps in attaining quantum supremacy was announced by Google by Arute et al. [2] in 2019. The authors introduced the Sycamore processor - a programmable device consisting of 53 superconducting qubits corresponding to a computation Hilbert space of 2^{53} states. The authors summarize the following two main contributions. One of them was connecting qubits with programmable couplers that can be switched on and off on-demand. These couplers allowed the authors to achieve high fidelity results in the quantum circuit sampling experiment. Moreover, sampling a single 53 qubit device million times takes about 200 seconds, while a classical theoretical computer needs 10,000 years to perform the exact computation, thus achieving the first quantum supremacy. However, the calculation time for the classical computer is still disputed [69].

The other contribution involved the way to calculate the fidelity of the quantum processor. The computation requires a classical computer to obtain ground truth values of the circuit's distribution. Therefore, the authors proposed three simplified scenarios that enabled calculating the fidelity with an ordinary machine while still retaining the architecture of 2^{53} qubits. These two contributions provide a feasible quantum processor and an experimentation protocol that can be followed up in future research. While Sycamore was not designed for general computation, it is considered a milestone in quantum computing.

In 2020, Zhong et al. [3] claimed to push quantum supremacy even further by providing 10^{14} speed-up over state-of-the-art Sycamore. They proposed an interferometer-based quantum computer, Jiuzhang, that performs boson sampling instead of the circuit sampling experiment. To that date, the main limiting factor to use interferometer-based quantum computers was its difficulty to scale to more qubits. Similar to Arute et al., the authors made the following contributions to achieve a new state of the art. Firstly, they developed an active phase-locking system covering the optical path of photons. The system allowed them to limit the influence of external perturbations, thus scaling Jiuzhang to 76 qubits. Secondly, the experimentation protocol was split into two scenarios - feasible and infeasible regimes. In the feasible regime, the authors used the ground truth probability distributions of photon clicks obtained with a classical computer. That showed that Jiuzhang achieves nearly perfect fidelity for 23 qubits. For the infeasible regime, the authors devised a theoretical tool for computing the expected output distributions. With that tool, they showed the agreement between the frequency of photon coincidences and the derived distribution. Finally, the authors presented that it would take 2.5 billion years to perform the exact computation Jiuzhang did in 200 seconds.

The progress in quantum computing does not stop here. However, these two remarkable achievements are considered milestones that can get us closer to commonly available quantum computers for other fields of science.

IX. QUANTUM EVOLUTIONARY ALGORITHMS

Evolutionary algorithms (EA) are a rich family of heuristic search algorithms. Based on the metaphor of Darwinian evolution, each variant of EA relies almost on the same sequence of operations, which consists of selection, replication, and succession iteratively applied to a population $P = \{x_1, \ldots, x_n\}$ of $n \geq 1$ individuals. A critical difference between variants that determines the shape of mentioned operations is a representation of population members. The most popular types of EA are genetic algorithms ($x \in \{0, 1\}^d$) [70], genetic programming (x are represented as a abstract syntax trees) [71], and evolution strategies ($x \in R^d$) [72].

Quantum computing offers the tempting possibility of highly parallel processing due to the superposition property, which evolutionary algorithms may employ and therefore tremendously increase their performance of exploring a search space. This potential has made quantum evolutionary computing a vibrant topic in the community devoted to EA. Nonetheless, it is crucial to mention that "quantum EA" may refer to the two essentially different approaches. One of them focuses on algorithms solely inspired by quantum mechanics and fits into metaheuristic research more than quantum computing (e.g. [73]). Thus, these algorithms are dedicated to classical computers, and their connection with IQT is purely nominal.

The rest of this section is devoted to the actual quantum evolutionary algorithms, i.e., algorithms designed to be executed on quantum computers.

Udrescu et al. attempted to design feasible quantum EA at the beginning of 2000 [74], and one may find a brief summary of their work in an overview paper written by Sofge [75]. They noticed that it is hard to qualify Udrescu's algorithm (Reduced Quantum Genetic Algorithm, RQGA) as a genetic algorithm because of a lack of genetic operators, i.e., mutation and crossover, which are an essential feature of each EA. Also, he concluded that so far (2008), quantum versions of genetic operators had not been developed. Nevertheless, Uderscu's paper pointed out that quantum EA should be built upon routines specific to quantum computing like Grover search algorithm [76] and its variants. In 2008 Malossini et al. proposed their quantum genetic algorithm (Quantum Genetic Optimization Algorithm, QGOA) [77], but like its predecessor, it did not utilize quantum genetic operators and instead relied on classical variants. In 2010, Johannsen et al. introduced (1 + 1) QEA [78], which utilized an actual quantum mutation operator. However, the first instance of quantum genetic algorithm that employed both genetic operators, i.e., mutation and crossover, in a quantum manner was proposed in [79]. The authors designed a 1-point crossover procedure based on the labeling of qubits in a quantum register. To our best knowledge, their work is the last advance in the research of quantum evolutionary algorithms.

One may observe that the community devoted to EA has not paid much attention to developing true quantum evolutionary algorithms. The causes of such a condition may be various, but a lack of easily accessible quantum computers or a weak notion of quantum search routines may be decisive in this matter.

X. A QUANTUM DEEP CONVOLUTIONAL NEURAL NETWORK FOR IMAGE RECOGNITION

Deep learning is successful in many areas (e.g. image recognition, translations, speech recognition, image generation) [80], but demands on memory and time performance have long been challenges. Quantum computing, on the other hand, is superior to certain computational problems, and could provide a new path to solving these problems. One of the challenges that arouse curiosity is inventing the QDCNN quantum deep convolutional neural network model based on a parameterized quantum image recognition circuit [81].

Quantum computing uses qubit features like superposition and entanglement to perform calculations, and their parallelism accelerates to the classical computational paradigm [82]. In recent decades, many quantum algorithms have been proposed [81]. In turn, as a result of hardware development and the increase in the amount of data, machine learning (ML) caught great interest among scientists and the industry. Scientists decided to check how quantum computing can support ML algorithms [83].

One of the best-known ML models is the deep convolutional neural network (DCNN) [84]. It is widely used, e.g. in image recognition. However, a major challenge is the increase in computational cost due to the increase in the width and depth of the layers.

New advances in the development of a quantum information processor [85] prove that a quantum computer can be used to discover the combination of quantum computing and deep learning. A quantum deep learning platform should integrate non-linear dynamics in calculations related to neural networks and linear dynamics related to quantum computing [86], follow the laws of quantum mechanics, and create an efficient quantum transformation to obtain deep semantic features [81].

In QDCNN image recognition, the input image is first represented as a quantum state with base encoding. In the next step, a parameter-dependent unit transformation sequence is used to perform quantum evolution. Quantum evolution consists of a convolution quantum layer and a quantum-classified layer. The pool layer is skipped, and sub-sampling is performed by increasing the convolution step. Then the quantum measurement is performed on specific quantum bits to obtain the category labels. A hybrid quantum-classical learning algorithm is used to optimize parameters in a quantum circuit. Conducting experiments on the widely known MNIST and GTSRB datasets has shown that QDCNN neural networks provide satisfactory accuracy [81].

In the quantum convolution layer, the QRAM algorithm from quantum random access memory is used for the quantum preparation of the input image [87]. In the next step, a quantum multiline system and Hadamard controlled rotation operation are used to perform the internal quantum product calculations in parallel in the workspace of the nucleus. The conversion between amplitude encoding and base encoding is performed by quantum phase estimation (QPE), and non-linear mapping is performed on a computational basis. Then, a non-computing operation is used to obtain an input state in the next layer by separating the desired state and an intermediate state. An additional bit resource is needed when mapping multiple features. In the quantum-classified layer, the feature representations are generated from the quantum convolution layer and are further changed. The main feature revealing the superiority of the QDCNN model over the classic DCNN is the quantum parallelism that allows simultaneous work with all the permissible states in which there is an exponential acceleration [81].

The QDCNN model can be used to recreate the classic DCNN efficiently. It takes full advantage of the quantum paradigm during storage and computation, resulting in exponential acceleration compared to DCNN. The result of the numerical experiment indicated the rightness to use the QDCNN model in image recognition [81]. It is needed to address several limitations in future work, such as increasing the size of the input image and the need for additional study of the arbitrary step and kernel [81].

XI. QUANTUM COMPUTING IN THE SERVICE OF BIOINFORMATICS

The dawn of the quantum age – this phrase can be found more and more often in scientific and popular science articles. In this chapter, we will try to look at how much quantum computing has already entered the world of bioinformatics [88], [89] and what are the current possibilities and prospects for the development of the quantum computing paradigm in this area.

In recent decades, bioinformatics has seen a tremendous increase in the amount of data to be processed. A good example is genomics and the dynamic development of next-generation sequencing methods [90]. On the other hand, there are unprecedented opportunities for acquiring knowledge from them – without looking far, let us take ML and, more broadly, various AI algorithms. The challenges generated by the Big Data era make it necessary to look for new computing possibilities, also in the area of biological sciences. One of the possible answers – apart from the use of classical supercomputers or parallelization of computations with the graphics processing unit (GPU) – might be quantum computers.

Currently, scientists exploring the potential of quantum computing in bioinformatics are focusing on the following areas [89]:

- Quantum Machine Learning (QML) – is used in structural biology, including, e.g., the prediction of secondary- and three-dimensional protein structure. An example of an application where quantum computing offers real acceleration is the inversion of covariance matrices. In the classic version, this operation has a complexity of $\mathcal{O}(N^3)$. The Harrow–Hassidim–Lloyd (HHL) quantum algorithm, proposed by [91] has, under certain conditions, the complexity of just $\mathcal{O}(\log N)$.
- Statistical methods – an example is a use of Hidden Markov Models in gene annotation [92].
- Quantum simulation – a big advantage of this group of algorithms is the ability to run them on a noisy device (unlike, for example, QML algorithms). An exemplary application is a work on drug discovery [93], [94].

- Quantum Image Processing – the computing power of quantum computing can be used to increase the precision of medical imaging (which will allow, for example, to detect cancer at an early stage of its development) and to support real-time diagnosis [95].

The combination of the potential of quantum computing and AI algorithms can supporting the interpretation of medical images can also, for example, support the analysis of large-scale data to predict directions of disease development or create epidemic models.

Bioinformatics quantum computing researchers face many challenges. As mentioned before, existing devices for quantum computing still have a low number of qubits and are highly error-prone. Input/output operations are also a problem. For example, the abovementioned HHL algorithm, although it significantly reduces the computational complexity of the processing itself, requires $\mathcal{O}(2^N)$ measurements of the state of the qubits register to read the result, which negates any benefit derived from its use. In turn, for example, many QML algorithms (and more) require access to qRAM [96], which has not been implemented in practice yet.

It appears that the direction of development of specialized algorithms, dedicated to specific bioinformatics problems and taking into account the properties of biological data, will allow the most effective use of the capabilities of quantum computers (both general-purpose ones and quantum annealers). In addition, hybrid computational models that combine the acceleration resulting from the use of quantum algorithms with the potential of classic supercomputers are gaining more and more importance.

Currently, when it comes to QC in bioinformatics, we are still at the stage of searching for areas where this computational model can bring measurable benefits. It will be a long time before quantum computers are included in the actual pipelines of biological data analysis or, for example, in tools used in medical diagnostics. There is no doubt, however, that the question we are asking ourselves is not "If?" but "When?".

XII. Conclusion

Information Quantum Technology is a rapidly developing field in natural sciences that promises a significant improvement in the accuracy and speed in simulating real-world phenomena. We found a gap in existing surveys in quantum physics and identified the need to create a review devoted to advances and milestones devoted to information quantum technology. We started with bringing the first inception of the quantum computation idea. Then in each section, we highlighted advantages as well as limitations of respective technologies. We concluded these sections and indicated possible future research directions. We believe that this survey will help understanding the diversity of the IQT field and how it progresses.

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