INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2024, VOL. 70, NO. 1, PP. 241-246
Manuscript received December 23, 2023; revised March, 2024. doi: 10.24425/ijet.2024.149536

Students' view of Quantum Information Technologies, part 2

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

***Keywords*—ICT; QIT; biomedical engineering; electronics and communications engineering; sensors; quantum Internet; quantum computing; cybersecurity; quantum networks**

I. Introduction

QUANTUM Information Science and technologies [1] 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 [2,3,4,5]. 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 [6], and perhaps even multilateral (multipartite) quantum communications – initial version of the quantum Internet [7]. 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 best relevant source texts.

II. QIT Application Frontiers

Development of QIT applications is associated with the technology readiness level TRL, a system used to estimate technology maturity of critical technology elements CTE. TRL estimation of the QIT depends essentially on the application field and varies considerably. Particular components influencing the TRL dynamics in QIT are sustained funding – public and private, workforce – education to fill the expert gap, hardware – supply chain development for components, performance improvement and cost reduction, software – full quantum software stack development, QEC, and transition processes from NISQ to FTQC.

QIT in HEP experiments and in big, advanced research instrumentation infrastructures [8] is a direct example of joining together two big sciences which may considerably profit from each other. HEP always offered to ICT very challenging computational problems. Two major issues concerned exploration of models which are very hard or impossible to address with classical techniques, and enormous data sets gathered dynamically by new experiments. These issues are

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ideally suiting to be considered for solutions by the advanced QIT systems.

Quantum biology is related with these aspects of biology that cannot be precisely elucidated by classical theories. QIT in biology and biomedical engineering [9] potentially offers methods and tools to help understand these processes. Several research areas are listed in this respect including all biological quantized energy and elementary charge excitation, tunneling, transportation processes by photons, phonons, electrons and protons. Among them there are: vision, respiration, photosynthesis, catalysis etc. Quantum biology discoveries are expected to give practical feedback to health and environment preservation, and generally the QIT development.

QIT in cybersecurity and post-quantum cryptography [10] has recently given a dynamic impulse for the development of new quantum and post-quantum secure algorithms. It is a response not for the threats of today but by the threats included in the serious statement: patiently listen to and gather all the relevant encoded data till they turn transparent. Together with the NISQ epoch we are now using the advancing, yet still relatively simple, bipartite QKD technologies, and are looking for fully multipartite, safe solutions.

QIT in software development [11] is a complex research area embracing all levels of the computational stack related to quantum computing, metrology, timing, communications and networking. In the simplest sense it is a field of software engineering including techniques and tools providing functional efficiency in terms of used resources like time, energy, quality, feasibility, reliability, etc. Quantum software engineering QSE includes: formal methods, modelling languages, physical and logical qubit layers, building QS environments with tools and frameworks, etc.

QIT supremacy [12] has two layers theoretical and practical. In theoretical layer it is related to the demonstration that QIT system can solve a problem insolvable by a classical computer, agnostically to the problem usefulness and applied technologies. In the practical layer it is related to either the advantage or the value the QIT brings to the particular field and the problem to be solved. Advantage is understood as required smaller resources like time and cost. Value is an advantage for a problem that has real commercial relevance.

III. Quantum Cryptography

Field of Quantum cryptography has always been a peculiar one as the theoretical foundation for the most prominent usage was developed over 30 years ago with Shor's algorithm [13] and since then has been thoroughly studied and understood. The problem of applying this domain of research to everyday usage lies in limitations of hardware rather than within quantum cryptography itself. While Shor's algorithm has definitively showcased its potential to efficiently factorize prime numbers in polynomial time, thereby undermining the security of RSA encryptions, the practical realization of such capabilities on quantum processors has been modest. Notably, the most substantial achievement in this regard has been the factorization of the number 21 [14] which, given the industry standard of 256-bit keys used for encrypting traffic, is not yet threatening to security.

Advancements in hardware are experiencing consistent annual improvements, as evidenced by the substantial investments made by prominent corporations such as IBM, Google, and Microsoft into their respective quantum research initiatives. Industry-wide reports highlight unprecedented levels of financial allocations dedicated to quantum research [16]. The heightened attention and funding have resulted in research proving utility of even currently available solutions. Notably, IBM's implementation using a noisy 127-qubit processor “Eagle” demonstrated computing expectation values of circuit volumes, specifically applied to Trotterized time evolution in the context of a 2D transverse-field Ising model with precision that is not achievable through classical methodologies [16]. It is noteworthy that the processor utilized for this demonstration has already been superseded by an enhanced “Ospray” model boasting 433 qubits, showcasing IBM's commitment to advancing quantum computational capabilities, as outlined in their roadmap [17].

As computing power continues to increase, attacks from quantum technology today can be withstood by our current encryption methods. However, there exists a genuine concern that these safeguards might be at risk in the future. This raises the possibility to retain confidential data and wait for the eventual breakthrough that will allow for its decryption. To address this potential issue, a proactive stance needs to be adopted. Rather than waiting for quantum computers to become sufficiently powerful to compromise any encryption, the implementation of post-quantum cryptography should be initiated well before that point. The task of determining the approach that will be adopted as the industry-wide standard for securing future communication has been addressed by the National Institute of Standards and Technology (NIST). This initiative involves NIST announcing a contest for the identification and selection of suitable cryptographic algorithms. After almost 6 years and 3 rounds of submissions they selected winners and based off them, they proposed first drafts of standards FIPS-203 [18] FIPS-204 [19] and FIPS-205 [20] that moving forward should guarantee security of data.

As a public key encryption and key establishing algorithm a lattice encryption based algorithm KYBER [22] was selected as the only suitable option. The fundamental principle underlying this cryptographic scheme involves the representation of messages as polynomials characterized by large coefficients. The subsequent step involves the generation of ciphertext in the form of a matrix-vector pair. The public key is concomitantly presented as a vector-matrix pair, denoted as (A, t). In parallel, the private key manifests as a vector comprising polynomials with diminutive coefficients, denoted as s. A fundamental relationship is established between these components, articulated as $As + e = t$, where 'e' represents an arbitrary small error introduced deliberately. The deliberate introduction of this error serves to thwart the deduction of 's' from 'A' and 't', as varying values of 'e' yield disparate outcomes. The encryption methodology pivots on the application of module learning with errors, ensuring that the decryption process utilizing the private key does not yield the original message but rather a polynomial inclusive of the it, albeit accompanied by errors. The removal of these errors is facilitated through rounding processes, thereby enabling the recovery of the intended message from the decrypted polynomial.

More variety can be observed in the digital signature algorithm, with 3 different approaches accepted as safe. It is worth noting that even though first standards are drafted the competition is still open to new submissions, and currently round 4 is being hosted with new proposals and improved versions of previous candidates. This contest does not have a singular winner but rather it determines usability of a submission.

The limitation on the number of available qubits represents just one facet constraining the practical applications of quantum cryptography. In the prevailing era of NIST processors, a substantial portion of processing power is underutilized owing to the imperative of error correction. A multitude of approaches has been explored over the years to address this issue, spanning from the refinement of error correction methods [23] to the exploration of alternative architectures, including a transition from qubit-based designs to those leveraging qdits for the storage and processing of information [24].

However new research published [25] in August 2023 considers yet another approach. The study delves into the efficacy of a solution centered around "cat qubits," a specialized type of qubit encoding information in superpositions of coherent states with opposing phases. They proposed an analysis of the performance of quantum computing architectures using Shor's algorithm, which is designed to solve discrete logarithm problems on elliptic curves. The published paper elucidates various versions of Clifford gates employed within Shor's algorithm, specifically tailored to leverage cat qubits instead of conventional ones. The study concludes by asserting that, based on their calculations, the construction of a processing unit capable of operating on 126,133 cat qubits could potentially break encryption in under 9 hours.

IV. Quantum Radiolocation

Advancements in Quantum Information Technology (QIT) have garnered significant interest from the military, particularly in the development of quantum compasses as a replacement for traditional Inertial Navigation Systems (INS). This innovation holds the potential to revolutionize nautical navigation, initially enabling submarines to navigate with precision down to one meter, a vast improvement over the INS precision of 1 km, especially in areas where GPS signals are unreliable [26].

Within the realm of military applications, radar surveillance stands out as a crucial area. Traditional radars, relying on radio waves, often face challenges such as signal loss in noise. The emergence of QIT has paved the way for the exploration of quantum radars, which operate on the principle of quantum entanglement. Quantum radar, utilizing the entanglement of at least two particles, elevates target detection capabilities. Upon dispatching a single entangled particle that interacts with the target, its state undergoes a transformation. Upon the photon's return to the radar, a comparison of the states of the entangled protons occurs. This enhanced clarity not only improves radar visibility, diminishing the impact of noise, but also facilitates more accurate recognition of target types. Additionally, its reduced susceptibility to enemy interference further solidifies its effectiveness [27]. In military operations, the ability to accurately detect and track targets is of paramount importance, and quantum radar's capabilities offer a strategic advantage in overcoming the limitations posed by conventional radar systems. The potential to operate in contested and electronically noisy environments makes quantum radar a critical asset for national defense, contributing to a more robust and secure defense infrastructure. Nevertheless, the expense associated with quantum radars remains notably high, hovering around a minimum of 1 billion dollars for a radar with a range of 10 kilometers. This stands in stark contrast to the significantly lower costs of classical radars, which are often thousands of times less expensive [28].

In addition to hardware advancements, there is a noteworthy impact on the software side of radar surveillance. Existing tracking algorithms predominantly rely on a one-measurement-to-one-track association model due to the complexities of multi-target approaches. Algorithm, leveraging qubits, facilitate efficient multi-target tracking by holding multiple track states simultaneously. This capability is especially advantageous for predicting and updating tracks of airborne targets, offering a significant enhancement over current tracking methods [29]. The topic of multi-target/multi-hypothesis quantum algorithms is still in its early stages. However, it appears that these algorithms have the potential to significantly enhance current tracking methods. Quantum algorithms introduce a level of computational prowess that extends beyond the capabilities of classical counterparts. This is particularly evident in scenarios where real-time tracking of fast-moving targets demands rapid and intricate computations, a feat for which quantum algorithms are uniquely equipped.

In envisioning the future trajectory of QIT its transformative potential extends beyond the confines of military applications, reaching into various facets of civilian life. The development of QIT not only promises advancements in precision navigation and radar surveillance but also holds the key to addressing computational challenges that conventional technologies grapple with today. The multifaceted impact of QIT on both military and civilian spheres suggests a paradigm shift in how we approach and harness information technology.

While the accessibility and affordability of QIT may currently pose challenges, the ongoing rapid pace of its development paints a promising picture. As research and innovation propel the field forward, the prospect of QIT becoming more widespread and cost-effective appears increasingly likely. The years or decades, along with substantial investments, for QIT to reach broader availability may witness breakthroughs and optimizations that accelerate its integration into various applications, further solidifying its status as a transformative force [30].

In summary, QIT is poised to shape the future, providing solutions to problems that current computing technologies struggle with and accelerating the advancement of existing algorithms. The rapid pace of QIT development underscores its potential to usher in a new era of technological capabilities.

V. Ghost Imaging

Quantum technologies find their application in imaging. One such technique is ghost imaging, which has its main versions: classical and quantum[31]. The following chapter will focus on presenting the possibilities and operation of the quantum variety, but the issue will be presented in a broader way.

One of the first mentions of this technique was in 1995, an article was published about the experiment made by T.B. Pittman, Y.H. Shih, D.V. Strekalova and A.V. Sergienko, who described use of quantum connections between entangled pairs of photons[32]. Over time, as the new technique began to be explored more deeply, divisions began to be created between illumination classes used for ghost-imaging: thermal-state (classical), biphoton-state (quantum), and classical-state phase-sensitive light[33]. In the quantum version, i.e. the experiment conducted by Pittman et al., the creation of an image based on correlation measurements was presented[34]. One photon traversed an object meant for transmission and proceeded to a photon counter lacking spatial resolution. Simultaneously, the other photon was directed to a photon counter specifically designed for spatial resolution. In other words: one of the photons interacts with the object and the detector, while the other takes a distinct route to the camera. The camera is designed to record pixels from entangled photon pairs that engage with both the bucket (single-pixel) detector and the camera's image plane. This process enables the gradual accumulation of numerous registered entangled pairs, culminating in the creation of a general image[35]. Ghost imaging has introduced fresh possibilities for acquiring finely detailed images, even in cases where they might be distorted by interference or turbulent conditions. Even though this method originated from quantum physics, it was later proven that it is possible to use it using classical physics, specifically "classical incoherent light, as the radiation produced by a thermal (or quasithermal) source[36]." At the beginning, it was assumed that the classical approach could not provide all the possibilities offered by quantum physics for GI, but over time, scientists managed to obtain them.

One application of GI is medicine, and more specifically, medical imaging. When looking for irregularities, we start with an interview and taking images, but they are often associated with certain risks: even a slight movement of the patient may disturb the result, and irregularities in equipment and radiation (in the case of e.g. X-ray) are often very harmful to the patient. By using GI and restoring certain image elements, we can firstly reduce the radiation dose, which will be healthier for the patient, and secondly, obtain a better quality image[37]. Another place where this technology is used is the military (satellites, radars, etc.). It is intended to detect objects in conditions where conventional imaging techniques are limited or insufficient [38][39].

VI. Quantum Software Development Kits

As quantum programming can be said to currently be in its infancy, there are many existing Software Development Kits (SDK) that are somewhat overlapping each other. This chapter aims to create a list of those.

First on the list is Qiskit, a Software Development Kit created by IBM. It was chosen as the first on the list due to IBM's policy to allow limited free access to their quantum computers. This allows everyone to make their first steps in Quantum programming and may probably lead to Qiskit's strong position in the future. The compatibility list has considerable size and includes IBM, IonQ, AQT and Rigetti companies[40]. Like most SDKs on this list, Qiskit is open-source and uses Python as its base language, further reducing the entry barrier. Qiskit operates on a low level of abstraction which may pose a challenge for beginners.

Although most SDKs utilize Python as their basis, there are some that do not. One of those is Quantum Development Kit, a Microsoft's SDK which use their programming language, Q#. It is paired with Azure Quantum cloud services which allows a time-limited free trial. In comparison to Qiskit, Q# has more abstract syntax which may make it easier to start with. The compatibility list consists of IonQ, Azure Quantum, Pasqal, Quantinuum and Rigetti[41].

Another SDK with a big name in front is Cirq, created by Google. It shares similarities with Qiskit being based on Python. Hardware compatibility list includes Alpine Quantum Technologies, Azure Quantum, IonQ, Pasqual and Rigetti[42].

Many SDKs are created for specific hardware in mind by a company producing said hardware. In this category belong, among others, Forest[43], Strawberry Fields[44] and Ocean[45]. All of those cater to specific types and manufacturers of hardware. Ocean is used for formulating optimization problems to solve them on D-Wave's quantum annealers, Strawberry Fields is compatible with Xanadu Quantum Technologies' quantum photonic hardware and Forest was developed by Rigetti for use on their machines. All are based on Python.

There are also SDKs made by market leaders in classical computing. Cuquantum by Nvidia is intended for simulating quantum circuits utilizing Tensor cores available on Nvidia's GPUs [46]. Intel is currently taking first steps with their quantum cpus but also has created an SDK for quantum programming[47].

A very interesting trend is the prevalent use of Python programming language as base for which libraries enabling quantum computing are created. Most SDKs tend to utilize Python as their base, at least from the perspective of users.

The presented list is by no means a complete one. Due to early stages of development there are many platforms created, most of them will probably be extinct in near future. A very interesting analogy can be made with Qiskit and allowing access to quantum computers for free to when IBM chose open architecture for their PCs which allowed them to become a de-facto standard. Time will show if this strategy will allow them to repeat that success

VII. Quantum Techniques in Medical Imaging

Multiple attempts have been made to provide further improvement in medical imaging using different approaches. Medical images are one of those of specific origin and purpose and being widely used for high-responsibility diagnostics it is crucial to provide best, available processing techniques. Medical image sources can be divided into two major groups: anatomic (such as RTG, CT, MRI) and physiological (scintigraphy for instance). Most often an anatomical display is necessary to diagnose a patients' condition, thus most scientific efforts have been focused on them. As the so-called "quantum techniques" (although some of them might be disputed whether they are quantum or not) became widely recognised around the world, some innovations have been made to medical imaging. Most data considering the topic is no older than ten years and therefore most of them are either theoretically described or still on trial. Many papers also cite well-known paper "Quantum imaging with undetected photons" by G. Lemos, V. Borish, G. Cole, S. Ramelow, R. Lapkiewicz and Nobel prize laureate A. Zeilinger[48], which provides the basis of quantum imaging. The paper explores a quantum imaging technique using entangled photons, where one photon remains undetected but influences the measurement outcomes of its entangled partner. This concept allows for the creation of images with enhanced resolution compared to classical imaging methods, demonstrating the unique capabilities offered by quantum entanglement in the field of imaging.

There are multiple papers describing quantum image processing emerging to this day. Even though most publications do not provide technical development per se, yet there seem to be ones worth reading. First of all, an Indonesian paper titled "Identification of Image Edge Using Quantum Canny Edge Detection Algorithm" by D. Sundani et al.[49] introduces a new approach to a well-known edge detection Canny algorithm. The algorithm itself is a mathematical tool switching from classical bit probability to a quantum qubit probability. Quantum Canny replaces the classical bit with a qubit in a mathematical sense. As the classical algorithm efficiently detects weak edges by connecting pixels with low contrast to those with high contrast, the probability that a given low-contrast pixel is an edge is stored in a qubit. To uniquely assign each pixel, a sequence of random numbers is generated within the range of [0-1], and a quantum equation is solved. The algorithm is outlined as follows: ● Apply a Gaussian filter to the image with specified parameters. ● Determine the gradient matrix enhancement vertically and horizontally. ● For uncertain pixels, replace classical probability with quantum probability (p1). ● Generate a sequence of as-random-as-possible numbers and check the condition [0, p1] by solving quantum equations.

Comparing the results to classical algorithms (classical Canny) the edge-detected images are outstanding. Several butterfly images who served as input images turned out to be very promising in terms of further development. Unfortunately the lack of vital information such as how the random numbers were generated or thorough algorithm implementation remained unclear. The Quantum Canny was further developed in publication "Edge Detection Based on Quantum Canny Enhancement for Medical Imaging" by S. Widiyanto et al.[50] First tests using database CT, X-Ray and Mammography images have been introduced, as well as comparison to various classical algorithms using either Sobel, Roberts or Prewitt parameters image results. Each image has been documented with proper PSNR and MSE value, so their performance seems to be clearer. Especially the Mean Square Error calculated for the Quantum Canny is everytime lower than the other ones. Having considered this strong optimistic indicator, further development in the medical field should be considered.

Another interesting paperwork describes experimental validation of quantum-enhanced detection within the realm of X-ray wavelengths. „Quantum Enhanced X-ray detection" by S. Sofer et al[51] introduces experimental ways to enhance X-ray images by considering X-ray photons entanglement. The authors are focused on utilizing X-ray radiation, studying time-energy correlation to eliminate noise, and observing sub-Poissonian statistics. To achieve this goal, an experiment has been conducted: ● SPDC1 pump pumps photons to a diamond which divides them into two beams in accordance with the law of conservation of energy and law of conservation of momentum. ● The idler beam comes through its detector while the signal beam comes through the object and then through its detector. ● The detectors are plugged into coincidence circuit. ● The generated photons' entanglement allows better distinction between the image and noise

This approach combines the generation of photon pairs through SPDC, advanced detection capabilities, and the exploration of correlations in time and energy to not only enhance imaging in noisy environments but also set the stage for the future development of quantum imaging technologies, specifically in the realm of X-ray photon entanglement. The authors claim that such measured SNR of the image has been significantly improved to a classical X-ray image and moreover the lower photons energy the better the improvement is. The experiment itself also has a long-term aim to prove X-ray photons entanglement and therefore would introduce a brand new era of quantum-calculated X-ray medical images.

This short overview of quantum medical imaging workpapers allow the world of science to truly consider quantum computing as the next step into medical imaging. Provided publications are but a mere introduction to the possibilities of quantum computing and although they describe promising results, cannot be considered as sole ready-to-use tools, without further work and comparison to classical in-use methods. Nonetheless, the basic concept mentioned in "Quantum imaging with undetected photons" has proven its significance, thus we should expect much more different, improved medical image processing tools in the near future

VIII. Discussion, Conclusions

The convergence of Quantum Information Science and Technologies (QIT) with established disciplines in Information and Communication Technology (ICT) presents both formidable challenges and unprecedented opportunities. Our exploration, guided by the perspectives of diverse engineering students engaged in specialized research areas, has unveiled the intricate interplay between QIT and domains like biomedical engineering, electronics, software, communications, and cybersecurity.

Medical quantum imaging points towards a potential revolution in the field. The experimental validation of quantum-enhanced X-ray detection introduces an intriguing dimension to the discussion, highlighting the prospect of not only improving signal-to-noise ratios, but also paving the way for a paradigm shift in X-ray medical imaging. The emphasis on entanglement and the correlation of time and energy in this context represents a pioneering effort that could redefine how we capture and interpret medical images, especially in noisy environments.

Current quantum Software Development Kits are in multitudes and appear to have overtaken hardware in advancement, probably due to being able to run on simulators and generally being mainly run as Python libraries on classical computers. This fact, paired with availability of some quantum computers for the wider public, should allow for a bigger pool of potential developers when the need arises.

REFERENCES

[1] R.Manetti, M.Motta, edit., 2023, Quantum Information Science, Oxford University Press, ISBN: 9780198787488

[2] K.Nałęcz-Charkiewicz et al., 2021, Current advances in Information Quantum Technologies – critical issues, IJET 67(03) 497-505, doi:10.24425/ijet.2021.137839

[3] B.Bednarski et al., 2022, Influence of IQT on research in ICT, IJET 68(02) 259-266, doi: 10.24425/ijet.2022.139876

[4] M.Lelit, et al., 2023, Selected advances of quantum biophotonics – a short review, IJET 69(02) 399-405, doi:10.24425/ijet.2023.144376

[5] D.A.Drecka et al., 2023, Students' view of Quantum Information Technologies, IJET 69(03) 627-633, doi:10.24425/ijet.2023.146503

[6] A.Paler, S.J.Devitt, 2015, An introduction to fault-tolerant quantum computing, arXiv:1508.03695

[7] Quantum Internet Alliance, 2023, [quantuminternetalliance.org]

[8] A.DiMeglio et al, 2023, Quantum computing for High-Energy Physics, State of the art and challenges, Summary of the QC4HEP Working Group, arXiv:2307.03236

[9] C. van der Kerk, et al., 2019, Quantum computing in the biomedical sciences: a brief introduction into concepts and applications, Computer and Information Science 12(3) 104-116, doi:10.5539/cis.v12n3p104

[10] R.Badhwar, 2021, The CISCOs next frontier: AI, Post-quantum cryptography and advanced security paradigms, Springer, ISBN:3030753530

[11] M.A.Serrano, et al. edit., 2022, Quantum software engineering, Springer, ISBN:978-3-031-05323-8

[12] M.Kaku, 2023, Quantum supremacy, AllenLane Publ., ISBN: 1409286929

[13] Shor, P.W. (1994). "Algorithms for quantum computation: Discrete logarithms and factoring," Proceedings 35th Ann.Symp. on Foundations of Computer Science. IEEE Comput. Soc. Press. pp. 124–134.

[14] Skosana, U., Tame, M. Demonstration of Shor's factoring algorithm for N =21 on IBM quantum processors. Sci Rep 11, 16599 (2021).

[15] https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-technology-sees-record-investments-progress-on-talent-gap#/

[16] Kim, Y., Eddins, A., Anand, S. et al. Evidence for the utility of quantum computing before fault tolerance. Nature 618, 500–505 (2023). doi:10.1038/s41586-023-06096-3

[17] "Technology for the Quantum Future." IBM Quantum Computing | Technology. Accessed December 23, 2023. https://www.ibm.com/quantum/roadmap

[18] National Institute of Standards and Technology. "Module-Lattice-Based Key-Encapsulation Mechanism Standard." CSRC, August 24, 2023. https://csrc.nist.gov/pubs/fips/203/ipd

[19] National Institute of Standards and Technology. "Module-Lattice-Based Digital Signature Standard." CSRC, August 24, 2023. https://csrc.nist.gov/pubs/fips/204/ipd

[20] National Institute of Standards and Technology. "Stateless Hash-Based Digital Signature Standard." CSRC, August 24, 2023. https://csrc.nist.gov/pubs/fips/205/ipd

[21] CRYSTALS-Kyber – Submission to the NIST post-quantum project.

[22] Roberto Avanzi, Joppe Bos, Léo Ducas, Eike Kiltz, Tancrède Lepoint, Vadim Lyubashevsky, John M. Schanck, Peter Schwabe, Gregor Seiler, and Damien Stehlé.2017-11-30

[23] Kandala, A., Temme, K., Córcoles, A.D. et al. Error mitigation extends the computational reach of a noisy quantum processor. Nature 567, 491–495 (2019).

[24] Majumdar, R., Saha, A., Chakrabarti, A., & Sur-Kolay, S. (2022). On Fault Tolerance of Circuits with Intermediate Qutrit-assisted Gate Decomposition.

[25] Gouzien, É., Ruiz, D., Le Régent, F.-M., Guillaud, J., and Sangouard, N., "Performance Analysis of a Repetition Cat Code Architecture: Computing 256-bit Elliptic Curve Logarithm in 9 Hours with 126 133 Cat Qubits", *Physical Review Letters*, vol. 131, no. 4, 2023. doi:10.1103/PhysRevLett.131.040602

[26] Guy, Dennis C.; Gravely Naval Research Group, Naval War College. The Weaponization of Quantum Physics: How Technology is Transforming Warfare. Gravely Naval Research Group, Naval War College, 2018.

[27] Torromé, Ricardo Gallego; BekhtI-Winkel, Nadya Ben; KNOTT, Peter. Introduction to quantum radar.

[28] F. Daum, "Quantum Radar Cost and Practical Issues," in IEEE Aerospace and Electronic Systems Magazine, vol. 35, no. 11, pp. 8-20, 1 Nov. 2020.

[29] T. M. McCormick et al., "Multiple Target Tracking and Filtering Using Bayesian Diabatic Quantum Annealing," 2022 Sensor Data Fusion: Trends, Solutions, Applications (SDF), Bonn, Germany, 2022, pp. 1-9,

[30] Ezratty, Olivier. "Mitigating the Quantum Hype", 2022

[31] Moreau P-A, Toninelli E, Gregory T, et al. Ghost imaging using optical correlations. Laser Photonics Reviews. 2018;12:1700143

[32] Pittman TB, Shih YH, Strekalov D v, et al. Optical imaging by means of two-photon quantum entanglement. Physical Review A 1995; 52: R3429-R3432.

[33] Erkmen, Baris I. and Shapiro, Jeffrey H., "Ghost imaging: from quantum to classical to computational," Adv. Opt. Photon. **2**, 405-450 (2010) doi:10.1364/AOP.2.000405

[34] Dixon, P. Ben, et al., "Quantum ghost imaging through turbulence"

[35] B.J. Hoenders, „Chapter One - Review of a Bewildering Classical–Quantum Phenomenon: Ghost Imaging" doi:10.1016/bs.aiep.2018.08.001

[36] Gatti A, Brambilla E, Bache M, Lugiato LA. Ghost imaging with thermal light: comparing entanglement and classical correlation. Phys Rev Lett. 2004 Aug 27;93(9):093602. doi: 10.1103/PhysRevLett.93.093602. Epub 2004 Aug 26. PMID: 15447100

[37] Pelliccia, Daniele and Rack, Alexander and Scheel, Mario and Cantelli, Valentina and Paganin, David M., "Experimental X-Ray Ghost Imaging"

[38] Zizhao Xie & Jingru Sun & Yiping Tang & Xin Tang & Oluyomi Simpson & Yichuang Sun, 2023. "A K-SVD Based Compressive Sensing Method for Visual Chaotic Image Encryption," Mathematics, MDPI, vol. 11(7), pages 1-20, March.

[39] "The Army's Secret Weapon Is This Quantum Physicist, Pioneer Of "Ghost Imaging", https://www.fastcompany.com/3009438/the-armys-secret-weapon-is-this-quantum-physicist-pioneer-of-ghost-imaging

[40] "Qiskit Is the Open-Sourcetoolkit for Useful Quantum." IBM Quantum. Accessed December 6, 2023. https://www.ibm.com/quantum/qiskit

[41] Bradben. "Azure Quantum Documentation, Qdk & Q# API Reference - Azure Quantum." Azure Quantum documentation, QDK & Q# API reference - Azure Quantum | Microsoft Learn. Accessed December 6, 2023. https://learn.microsoft.com/en-us/azure/quantum/

[42] "Google Quantum Ai." Google Quantum AI. Accessed December 6, 2023. https://quantumai.google/

[43] Welcome to the Docs for the Forest SDK! - pyQuil 2.7.2 documentation. Accessed December 6, 2023. https://pyquil-docs.rigetti.com/en/v2.7.2/

[44] Strawberry Fields. 6.12. 2023. https://strawberryfields.ai/

[45] "OceanTM Developer Tools: D-Wave." D. Accessed December 6, 2023. https://www.dwavesys.com/solutions-and-products/ocean/.

[46] "Cuquantum SDK." NVIDIA Developer. Accessed December 6, 2023. https://developer.nvidia.com/cuquantum-sdk

[47] "Quantum Computing and Systems with Intel Labs: Intel®." Intel. 6.12.2023. https://www.intel.com/content/www/us/en/research/quantum-computing.html

[48] Lemos, G., Borish, V., Cole, G. et al. Quantum imaging with undetected photons. Nature 512, 409–412 (2014)

[49] Sundani, D., Widiyanto, S., Karyanti, Y., & Wardani, D. T. (2019). Identification of Image Edge Using Quantum Canny Edge Detection Algorithm. Journal of ICT Research and Applications, 13(2), 133-144.

[50] S. Widiyanto et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 536 012118 „Edge Detection Based on Quantum Canny Enhancement for Medical Imaging" doi:10.1088/1757-899X/536/1/012118s

[51] S. Sofer, E. Strizhevsky, A. Schori, K. Tamasaku, and S. Shwartz Phys. Rev. X 9, "Quantum Enhanced X-ray Detection", 031033 – 23.08.2019