www.czasopisma.pan.pl PAN www.journals.pan.pl

INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2022, VOL. 68, NO. 2, PP. 259–266
Manuscript received May 10, 2022; revised May, 2022. DOI: 10.24425/ijet.2022.139876

Influence of IQT on research in ICT

Bogdan J. Bednarski, Łukasz E. Lepak, Jakub J. Łyskawa, Paweł Pieńczuk, Maciej Rosoł
and Ryszard S. Romaniuk

***Abstract*—This paper is written by a group of Ph.D. students pursuing their work in different areas of ICT, outside the direct area of Information Quantum Technologies IQT. An ambitious task was undertaken to research, by each co-author, a potential practical influence of the current IQT development on their current work. The research of co-authors span the following areas of ICT: CMOS for IQT, QEC, quantum time series forecasting, IQT in biomedicine. The intention of the authors is to show how quickly the quantum techniques can penetrate in the nearest future other, i.e. their own, areas of ICT.**

***Keywords*—ICT; control theory; IQT; Information Quantum Technologies; Quantum 2.0; applications of IQT; quantum systems; qubit neural networks; quantum time series forecasting; Quantum Reinforcement Learning**

I. INTRODUCTION

THE broad area of ICT embraces hardware and software for computer engineering, communications, sensing and measurements, system science and technology, networks, and applications. IQT embraces quantum computing, quantum communications and networks, timing, quantum sensing and measurements. The mutual coverage of research and application areas is surprisingly large.

Artificial Intelligence is an area that has a lot of potential in applying quantum technologies to real-life problems. While normally it would require much larger quantum computers than currently available, a lot of research is done using simulations and small-scale problems. Reinforcement learning, an area of artificial intelligence, is intensively adapted in recent years to be able to utilise quantum technology to its advantage, including integrating non-deterministic aspects of quantum into its design. Control theory is an area of applied mathematics with a broad range of applications in many fields of engineering. Control of qubits and gates in quantum computers reveal many interesting problems both resolved, deeply analyzed ones and those which are in pretty early stage of theoretical development. Owing to specific nature of quantum systems, finding solutions to these problems implies advancement not only to the quantum technology but also to control theory itself.

Classical and quantum technologies in the mentioned areas differ essentially in all aspects. IQT bases on coherence and entanglement as operational resources [1]. Quantum resources are very precious and irreplaceable, thus their usage in single operational steps should be carefully optimized. NISQ processors started to be used as computational coprocessors in classical ICT systems, but so far only for a confined set of problems [2]. Search goes on widening this set.

II. CMOS FOR IQT INTERFACE

Nowadays, the most of the Quantum Devices and Systems work under the cryogenic regime. These devices require special casing and chambers to maintain the extremely low temperatures. It is also needed to interface with existing instruments, like measurement units or control units. The need for miniaturizing and reliability requires integration of parts, working under very hard conditions. Application-specific integrated circuits (ASICs) can address this demand. Although there is a continuing research on semiconductor qubits [3], in this section only the classic electronics interface with is discussed.

CMOS (Complementary Metal-Oxide-Semiconductor) technology is mature yet still developed semiconductor process. Although the standard CMOS target is room temperature, there is much effort put into characterizing and modeling these devices' cryogenic performance. CMOS technology can reduce the number of complex interconnections between the cryogenic chamber and room temperature world. It can result in a more compact and reliable system [4]. To create a chip for these applications, it is needed to develop an EDA platform, known as Process Design Kit (PDK).

Typical PDK consists of valid models, device instances, EDA tools setups (e.g., Design Rule Check), and detailed documentation. Some manufacturers also provide prepared cells (digital gates, memory cells) for automatic digital block generation. Many of them include the I/O blocks with pads and electrostatic discharge (ESD) protection. Availability of generic analog cells (operational amplifiers, references or other) is not obligatory but it speeds up the design process.

A. Models

There are plenty of CMOS PDKs with accurate room temperature models on the market. Standard purpose CMOS processes are characterized within (-40 °C; + 120 °C) range. The Cryo-CMOS should be characterized under shallow temperature, down to a few K. In this region, several effects should be considered.

The broadening of the depletion region under the cryogenic regime is observed [5]. This effect is caused by the incomplete

---

Authors are with Warsaw University of Technology, Warsaw, Poland, (e-mail: {bogdan.bednarski, lukasz.lepak, jakub.lyskawa, pawel.pienczuk, maciej.rosol}.dokt@pw.edu.pl; ryszard.romaniuk@pw.edu.pl).

ionization of dopants in bulk. In effect, the effective dimensions of the transistor are modified, so its performance.

Furthermore, the carrier mobility rises with the lower temperature; however, this rise is strongly correlated with the channel length [5]. It can improve the dynamic performance of the MOS transistors by pushing the cut-off frequency higher. Another result of carrier mobility rise is the higher drain current. Different models can be used for this task. Two most popular are BSIM (industry-standard) and EKV [6]. While BSIM is more accurate (BSIM6.0), especially in the deep submicron nodes [7], EKV requires less parameters to achieve some acceptable fitness level. Even if the computational resources are rather large nowadays, this trade-off is still worth consideration once the complex system simulation is needed.

B. Devices

There are plenty of CMOS PDKs with accurate room temperature models on the market. The Cryo-CMOS should be characterized under shallow temperature, down to a few K. In this region, the operation of MOSFET devices at extremely low temperatures has many advantages. For example, the carrier mobility and speed are enhanced, and the thermal noise is lowered. There are also drawbacks, like hot-carrier effects, which may lead to reduced reliability and device lifetime [8]. Although the physics in the discussed regime is well-known, most of the IC EDA platforms do not allow to perform valid simulations below 230 K because the devices are not characterized in this region [5]. It should be pointed out that both p-channel and n-channel devices (PMOS and NMOS) have the same temperature dependencies.

In IQT, photodetectors can be used for the detection of low power optical signal from photon-based qubit systems. It can be used for interfacing data transmitting optical fibers as well. CMOS processing allows embedding the photodiode to the semiconductor structure, as in popular CMOS cameras. Integration of the detector with a readout circuit can improve signal to noise ratio (SNR) and minimize the size of the entire system. In low temperatures, CMOS Avalanche Photodiodes (APD) have generally lower quantum efficiency but non-monotonic relative quantum efficiency. APDs have higher forward burn-on voltage, higher drop voltage, and lower reverse breakdown voltage [9]. Although the parameters are different, it is reasonable to characterize and model these devices to push the development of IQT further.

Passive devices, like resistors, capacitors, and inductors, have different characteristics while cooled down. All types of resistors (metalized, diffusion, and poly) have much lower resistance in low temperatures [5]. The benefit is that the interconnects are less resistive in low-temperature. On the contrary, it is harder to achieve high-value resistors, often required by the designers. Salicide block (SAB) resistors have almost constant R-T dependency in low temperatures, which can be useful in temperature-independent reference generators.

C. Circuits and Systems

Fig. 1 represents the potential scheme of the system. Once there are available models of devices operating at discussed conditions, correlated to the physical layout of the device, the designer is capable of creating whole blocks. They can be used for interfacing low temperature region with room temperature world. From the system point of view, it could be profitable to move some of the operation to this regime, once the specific circuits would be designed and properly characterized. It may reduce the complexity of interconnections, reduce overall size of the system and improve the reliability.

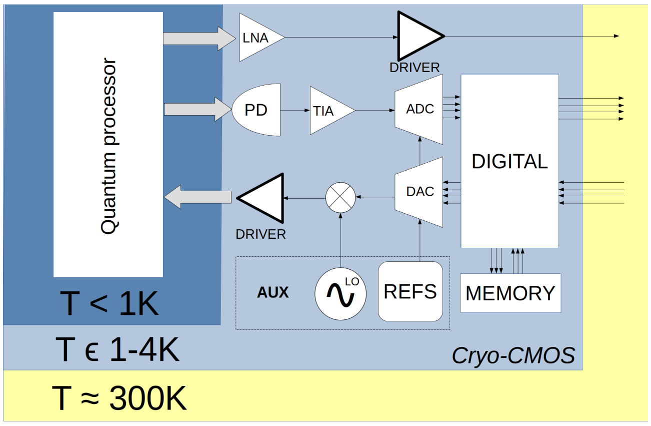

Fig. 1. Cryo-CMOS system applied in IQT - an idea

The low-noise amplifiers (LNAs) are used to amplify the weak signal with lowest noise and distortion possible. The line drivers are required to connect to room temperature devices (like measurement devices with 50Ω inputs). A lot of electronic circuits also need stable, process, voltage and temperature (PVT) independent references, both voltages and currents. Transimpedance amplifiers (TIAs) are used for high-speed current to voltage signal conversion from the photodiodes. Such systems may work in radio frequencies (RF), so typical blocks of RF signal chain can be required (like mixers or local oscillators, LO).

Designing the analog-to-digital converters (ADCs) in the cryogenics region can help capture the signal with lowest distortion possible. The counterpart, digital-to-analog converter (DAC) can be used for control both the quantum electronics as well as classical electronics. DACs are also the part of successive-approximation (SAR) ADCs, which are golden mean in terms of ADC parameters.

Since the amount of the data transmitted via Quantum Devices is expected to be huge, it seems that some digital domain operations should be performed in the low temperature region, e.g. error-checking interfacing with room temperature parts of the system. It may be beneficial to perform some digital signal processing (DSP) on the signals. That fast data stream may require some caching within on-chip memory.

III. ERROR-CORRECTED, FAULT-TOLERANT QUANTUM SYSTEMS AND THE UNDERLYING CONTROL THEORY

There was a short way from the formalization of control techniques, which had given rise to a control theory as a field of applied mathematics, to the emergence of optimal control as the key concept of this discipline. The strong interest in this topic initiated by Pontryagin [10] proved to be a milestone in technological and scientific research in general.

In quantum computing the optimal control is widely explored w.r.t. two concepts: correction of qubit errors and fault tolerance of quantum operations. These control objectives belong to different sections of a cascaded control system, with sections respecting quantum computer layers as proposed by N. C. Jones [11]. In this section another, rather heuristic perspective is chosen where control of logical qubit is considered with tighter relation with control of physical qubit.

A. *Single qubit and quantum gates control aspects*

Error correction is term related to both physical and logical qubits. As a design principle it is realized via encoding of single quantum state into a whole system of physical qubits which yields additional degrees of freedom. Additional degrees of freedom present in such system can be used to accomplish detection and correction of errors. Those in turn arise due to partial decoherence of a system of physical qubits [12] and represent as a whole an instance of logical qubit [13]. The problem of qubit control is therefore considered on two levels: control of the whole quantum system defining the logical qubit and direct control of individual physical qubits. The additional layer of abstraction associated with the former allows for introduction of more advanced control methods [14]. On the other hand the implementation-specific nature of the latter currently tends to better exploit the characteristics of an underlying physical quantum system [15].

The control theory behind quantum gates has been pushed towards more advanced methods by Eastin-Knill theorem [16] which effectively rules out the existence of a universal quantum computer composed solely of transversally implemented logical unitary operations [17]. Ever ince then, there is a constantly growing interest not only in circumventing the use of non-Clfford gates via magic states but also in more advanced methods of error correction and fault tolerance implementation [17].

B. *Error correction and fault tolerance in terms of the optimal control*

The main body of novel work done on the topic of error correction retains strong ties with optimal control. In 2007 Brańczyk et al. [18] presented optimal solution for denoising of two-level quantum system based on optimization of convex, fidelity-based objective function. In the same paper a family of classical control methods - namely ”discriminate and reprapare” and ”do nothing” strategies - are also analyzed in terms of optimal control. A recent study of T. Shibata et al. [19] exemplifies an interesting shift in the system optimization techniques, where an optimal control is applied to quantum gates on the basis of realistic models of molecular spin qubits.

Geometric Quantum Computation is a recent example of the same trend for quantum gates [20] [21] and is posing an interesting technoscientific challenge due to the discrepancy between its theoretical robustness w.r.t. control errors and current problems with environmentally induced decoherence [14]. The importance of physical level events for the logical level systems is clearly visible in this topic.

C. *From local to global optimization*

While distinguishing between concepts of physical and logical layers seems very natural and desirable in quantum computer, it is worth noting that their existence is not so obvious from the control system’s perspective. In more recent publications one can observe emergence of more detailed physical descriptions of qubits inside models of whole logical gates [20]. This suggests that construction of a universal quantum computer calls for a shift in perspective – possibly the needed level of precision together with overall sensitivity of quantum systems is enough to force the use of control methods based on global optimization.

Subsystem-oriented approach which results in decoupled and/or cascaded control schemes may in the long run hinder the possibility of achieving high qubit fidelity with the error in range of 10^{-4} [22] and below as well as further advancing decoherence time. Alternatively, such approach can provide valid solution at the possibly unacceptable expense of low logical system dynamics as even interference from control electronics itself can become problematic in quantum systems [23]. Thus global, possibly even multi-objective optimization may become crucial aspect of control system design for logical qubits and quantum gates, being the strongest solution able to satisfy broad spectrum of requirements set on quantum processors. If this should be the case, an interesting problem then emerges whether classical electronics will be able to accomplish control schemes for such distributed problems in real time. Negative answer to this question can be a spur to use high speed quantum systems – initially NISQs – as a control platform for a larger and/or more precise quantum systems. Possibly in the future besides ancilla there will be also a place for control qubits in a partially self-regulating, error-correcting and fault-tolerant system. This would allow quantum computers to retain some elegant analogy to the history of classical computer evolution with analog circuitry retaining the supportive and control role in larger digital systems. In the meantime, regardless of a specific nature of their future implementations, quantum computers can become a strong incentive for popularization of advanced state-space optimal control methods in other areas of technoscience.

IV. QUANTUM TIME SERIES FORECASTING

Time series are a popular kind of datasets, in which every sample contains information about time it was measured or created. In most cases, these samples come from sequential measures or observations. Example time series datasets may include:

- weather data - i.e. wind and temperature changes
- financial data - i.e. stock and asset prices
- credit card transactions of a given user
- voltage and current measurements in an electrical circuits

Essentially, any dataset with sequential timestamps may be considered a time series.

In this section, we will focus mainly on **time series forecasting**, as it is the application to which quantum computing techniques are applied with success.

A. *Time series forecasting task*

Formally, a time series dataset may be defined as a sequence:

$$(x_t), x_t \in \mathbb{R}^m, t = 1, ..., n \tag{1}$$

where x_t is a sample containing m real values, called features, for time t, and n is the number of samples in time series [24]. A value of the given feature at the given time is x_t^i.

Time series forecasting uses historical time series data to predict future values in the series. This may be defined as follows:

$$\hat{y}_{(t+i,...,t+j)} = \hat{f}(x_{(t-l,...,t-k)}, \theta) \tag{2}$$

where:

- $j - i + 1 \in \mathbb{N}$ define *output window* width - number of time steps being predicted.
- $l - k + 1 \in \mathbb{N}$ define *input window* width - number of time steps being used to make predictions.
- θ represent parameters of the approximator used to make predictions, i.e. weights in neural network model.
- $\hat{f}$ is an approximation function represented by the model, used to make predictions based on time series samples.
- $\hat{y}$ is a prediction returned from the model.

For example, if we would like to forecast the weather for the next 6 hours from now using data from the previous 12 hours, we would have $i = 0, j = 5, m = 1, n = 12$.

B. *Classical forecasting methods*

Many classical forecasting methods utilize statistics to make predictions. In the case of financial series, technical and fundamental analysis techniques are also used. Examples of such methods include exponential smoothing, moving average, autoregression, and their combinations, such as Autoregressive [Integrated] Moving Average (AR[I]MA) and [Generalized] Auto-Regressive Conditional Heteroskedasticity model ([G]ARCH) [25].

Recently, machine learning models, such as random forests, are used in time series forecasting, achieving good results [26]. Also, deep neural networks, especially recurrent and attention-based, gain more popularity, due to their generalization abilities and increased computing capabilities [27]. In some applications, hybrid models using both statistical and machine learning methods achieve the best results [28].

Looking at the progress of classical time series forecasting methods, it is clear that the next step in evolution of these methods is quantum computation.

C. *Time series forecasting - quantum computing applications*

Time series forecasting may be realized using qubit neural networks (QNNs). First QNN models were modelled as complex neural networks, working similarly to artificial neural networks, but with complex numbers. They were able to match performance of simple artificial neural networks and ARIMA models [29]. Now, qubit neural networks are based on parametrized quantum circuits (PQCs) [30]. Forward propagation in such QNNs is fully quantum and PQCs gate parameters are learned with classical back propagation algorithms. QNNs built on top of parametrized quantum circuits are able to achieve equal or even better results than state-of-the-art recurrent neural networks. These QNNs also have significantly less learned parameters than their artificial neural network counterparts, making them less susceptible to overfitting [31].

Quantum methods are also utilized in fuzzy time series forecasting. In fuzzy datasets, values are split into some sets, for which intervals are not known. In [32], the authors presented a hybrid method connecting quantum computations and linear programming for fuzzy time series datasets. [33] introduced a quantum method that achieves better results on fuzzy datasets than state-of-the-art fuzzy forecasting methods. Another use of quantum computing is for parameter optimization for classical time series forecasting methods [34].

V. QUANTUM REINFORCEMENT LEARNING

Reinforcement learning is an area of artificial intelligence. It focuses on creating agents that make decisions based on the current state of the environment to perform specific tasks in a way that maximizes both short- and long-term rewards. Current and potential applications include notably robot control [35], bots for video games [36], and natural language processing [37].

Reinforcement learning methods meet a number of challenges that prevent or make it difficult to apply them for real-world problems. However, some of these problems, such as the exploration-exploitation balance [38] may be mitigated by the use of Quantum Information Processing (QIP) systems via the use of Quantum Reinforcement Learning (QRL) methods [39]. Furthermore, [39] shows that QRL can offer quadratic increase in learning speed as compared to classical reinforcement learning, and the speedup of some methods can be even exponential for some settings [40].

An important feature of current quantum computers is the probability of the occurrence of errors during computations [41], which is a serious obstacle to fully employing quantum computers [42]. This phenomenon however can be beneficial and enhance the learning process when using QRL methods [43].

A. *Classical Reinforcement Learning framework*

The framework for reinforcement learning is that of the Markov Decision Process. It is defined by a set of states S, a set of actions A, initial state probability $P_0(s)$, state transition probabilities conditional on actions $P(s_{t+1}|s_t, a_t)$, and a reward function $R(a_t, s_t)$. The agent is defined by a decision policy $\pi(a|s)$ that for each state defines probabilities of each action. The goal of the reinforcement learning process is to find a decision policy that maximizes the expected rewards [44].

B. *Quantum Reinforcement Learning framework*

The framework for quantum reinforcement learning methods reflects that of the framework for classical RL methods, but with either policy and/or the decision process realized using quantum circuits.

A quantum environment may be organized as follows. An observable of a quantum system is selected. The eigenvectors of this observable form a set of complete orthogonal bases. The eigenvectors are called eigen states and correspond to the states of a classical reinforcement learning environments. A quantum state $|S\rangle$ is defined as a superposition of eigen states $|s_n\rangle$

$$|S\rangle = \sum_n \alpha_n |s_n\rangle \tag{3}$$

where α_n are the probability amplitudes of the corresponding eigen states, constrained by

$$\sum_n |\alpha_n|^2 = 1 \tag{4}$$

Analogously, eigen actions of an observable correspond to the classical reinforcement learning actions. A quantum action $|A\rangle$ is defined as a superposition of eigen actions $|a_m\rangle$

$$|A\rangle = \sum_m \beta_m |a_m\rangle \tag{5}$$

with probability amplitudes β_m being constrained by

$$\sum_m |\beta_m|^2 = 1 \tag{6}$$

[39].

The action can also be represented by a parameterized unitary $U(\theta)$ on state $|s\rangle$, where θ is a parameter, thus allowing a quantum environment realization to have continuous action space [45].

One approach to storing a reward is to use classical register [39]. Another approach replaces classical reward registers with quantum register $|r_t\rangle$ for calculating the quantum reward function. It is updated using a functional f, a unitary U_r, and measurement observable M with a reward for the time step $t+1$ being calculated as follows

$$r_{t+1} \equiv f(\langle s_t| \langle 0| U^\dagger(\theta_t) U_r^\dagger M U_r U(\theta_T) |0\rangle |s_t\rangle) \tag{7}$$

where f, U_r and M are selected for the specific problem [45].

C. QRL algorithms

- An approach introduced in [39] implements the policy for a quantum environment by storing quantum actions in a single quantum register for each eigen state of the environment. Whenever the action $|A\rangle$ is measured, it randomly collapses into an eigen action $|a_m\rangle$ with the probability $|\beta_m|^2$. Furthermore, the efficiency of exploration is increased by the state and action being in a superposition state. This way, the algorithm provides good balance between exploration and exploitation based on the physical properties of the underlying quantum system. An additional quantum register is used to save $|A\rangle$ to prevent the memory loss associated with the collapse.

  The initial probability amplitudes are equal. The proposed QRL algorithm works by amplifying the probabilities of the actions that provide better rewards using the Grover algorithm.
- A similar approach was used to improve the classical RL methods. A fair quantum model of an environment was used as an oracle. This algorithm was able to outperform classical algorithms on tested benchmark problems by utilizing the quantum parallelism. It was able to search faster for rewarding action sequences using the Grover algorithm. [40].
- Introduction of the Variational Quantum Circuits [46] allowed another approach to quantum reinforcement learning. A number of classical reinforcement learning algorithms were adapted to utilize Variational Quantum Circuits as Quantum Neural Networks, including Deep Q-Learning [47], Deep Deterministic Policy Gradient [45] and Proximal Policy Optimization [48]. Such approach allows to use inherent uncertainty of NISQ circuits for exploration.

D. QRL applications

Quantum reinforcement learning, similarly to reinforcement learning, can be used as a model for analyzing learning process and decision making of humans and animals, with quantum approach giving promising results for explaining human decision making [49].

A dedicated quantum reinforcement algorithm was also applied to a task of cloning an unknown state, a critical task required for many applications of quantum computing. This approach allowed to obtain high fidelity copies with relatively low cost when compared to the usual method used for this task i.e., tomography [50].

VI. INFLUENCE OF IQT ON BIOMEDICINE

Quantum technologies are a very promising field of research in terms of biomedical applications. The main hopes for quantum technologies relate to the sequencing of the human genome, aid in the diagnosis, personalization of treatment using artificial intelligence and drugs discovery [51].

A. Molecular biology

Better understanding the human genome is a challenge scientists take to understand the causes of cancer, diseases risk factors, or to personalize medical treatment. Currently computing the DNA-profile of an individual person takes about one week with big computational power in use. With quantum computing, this process could be significantly accelerated as input data would be analyzed in parallel as a superposition of wave function [52]. In genomics, it is popular to use hidden Markov models (HMM) for the structural annotation of genes. The quantum version of this algorithm, hidden quantum Markov models (HQMM) has already been proposed. The usage of quantum properties allows for modeling the data with fewer hidden states than classical HMM [53]. Different quantum algorithms might be applied in many branches of molecular biology. In tasks of gene sequencing besides HQMM also Grover's algorithm and quantum least-squares algorithms are also very promising techniques, which may lead to development in the field and in the long term perspective of personalized medicine based on individuals' DNA [54].

B. Drug discovery

The process of drug discovery is not only very expensive but also time-consuming. Currently, the process of computer-aided drug design begins with modeling interactions between the drug candidates and biological target and estimating the parameters of molecules such as absorption, distribution, metabolism, extraction and toxicity. Those calculations demand very high computational power and are time-consuming. The usage of quantum computers could not only accelerate computations but also create opportunities for modeling which is impossible using classical computers [55]. An example of the algorithm which can help in modeling molecules structure and chemical reactions is variational quantum eigensolver (VQE) [56]. It is a hybrid quantum-classical algorithm that minimizes the energy of the Hamiltonian, which was proposed to omit the limitation of the quantum phase estimation algorithm, which demands hardware much more advanced than present quantum computers. This algorithm is based on the following steps [57]:

1) Construction of fermionic Hamiltonian
2) Representation of fermionic Hamiltonian as a sum of Paulis strings (mapping into qubit Hamiltonian)
3) Generation of ansatz with initial parameters ϑ
4) Computation of the energy of Hamiltonian on a quantum computer
5) Summation of calculated energies on a classical computer and update of the parameters ϑ based on a chosen optimization algorithm.
6) Steps 4 and 5 are repeated until the convergence criterion is met.

C. Diagnostics

Quantum computing might also be a breakthrough in computer-aided diagnostics (CAD) as it allows for a speedup of calculations of many conventional machine learning algorithms, which are broadly used in CAD systems. In the imaging diagnostics techniques like MRI or CT CAD systems often use convolution neural networks (CNN) for images analysis [58]. Thanks to the usage of quantum computing the time complexity of CNN could be reduced from O(N) (using classical computers) to O(logN) [59]. Another algorithm that finds application in medicine is Bayesian deep learning, which is used for image classification, segmentation and reconstruction, analysis of electronic health records and classification tasks in different diseases [60]. Its computational complexity on a classic computer is equal to O(N), while with a quantum computer it can be reduced to O($\sqrt{N}$) [59]. Quantum computing could be also beneficial for genetic data analysis as it allows for the reduction of time complexity to O(log(N)) in the case of algorithms such as PCA and SVM which are commonly used for this type of data and their time complexity for the classical computer is equal to O(N) and O(N^2) or O(N^3) respectively [59].

VII. CONCLUSIONS

From the above collection of analyzes of relations between specific branches of ICT and IQT one can draw a conclusion that quantum computing is far from reaching the state of maturity. This is especially obvious when considering the proliferation of articles related to this topic published in a broad range of journals. What possibly makes IQT such an scientifically attractive topic is its ability to not only raise new knowledge in its own merit, but also induce advancements in the related fields when they are mutually applied to one another.

Quantum computing benefits both from new and well-established technologies stemming from other fields of techno-science. This blend of state-of-the-art and new methods may strengthen further the scientific strive for quantization.

The ongoing improvement of both quantum hardware and algorithms allow new practical applications of IQT to emerge. The analyzes presented in this paper suggest that this development is gaining momentum at an unprecedented scale. On the other hand those advancements' undeniably limited visibility outside of a pretty confined scientific group can possibly provide a clue to the contemporary direction of IQT's development as specialized tool for scientific and military purposes, outside of reach of consumer electronics in general.

REFERENCES

[1] E. Chitambar and G. Gour, "Quantum resource theories," *Reviews of modern physics*, vol. 91, no. 2, 2019. [Online]. Available: https://doi.org/10.48550/arXiv.1806.06107

[2] J. Preskill, "Quantum computing in the nisq era and beyond," *Quantum*, vol. 2, p. 79, 2018. [Online]. Available: https://doi.org/10.48550/arXiv.1801.00862

[3] Blokhina, Elena and et al., "CMOS Position-Based Charge Qubits: Theoretical Analysis of Control and Entanglement," *IEEE Access*, vol. 8, pp. 4182–4197, 2020. [Online]. Available: https://doi.org/10.1109/ACCESS.2019.2960684

[4] Sebastiano, Fabio et al., "Cryogenic CMOS interfaces for quantum devices," in *2017 7th IEEE International Workshop on Advances in Sensors and Interfaces (IWASI)*, 2017, pp. 59–62. [Online]. Available: https://doi.org/10.1109/IWASI.2017.7974215

[5] Wang, Zewei et al., "Designing EDA-Compatible Cryogenic CMOS Platform for Quantum Computing Applications," in *2021 5th IEEE Electron Devices Technology Manufacturing Conference (EDTM)*, 2021, pp. 1–3. [Online]. Available: https://doi.org/10.1109/EDTM50988.2021.9420957

[6] Stefanovic, Danica and Kayal, Maher, *Structured Analog Design*. Springer Netherlands, 2008.

[7] Singh, Kirmender and Jain, Piyush, "BSIM3v3 to EKV2.6 Model Parameter Extraction and Optimisation using LM Algorithm on 0.18µ Technology node," *International Journal of Electronics and Telecommunications*, vol. 64, pp. 5–11, 01 2018. [Online]. Available: https://doi.org/10.24425/118139

[8] Simoen, Eddy and Claeys, Cor, "Impact of CMOS processing steps on the drain current kink of NMOSFETs at liquid helium temperature," *IEEE Transactions on Electron Devices*, vol. 48, no. 6, pp. 1207–1215, 2001. [Online]. Available: https://doi.org/10.1109/16.925249

[9] Johnson, Erik B. et al., "Characteristics of CMOS avalanche photodiodes at cryogenic temperatures," in *2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC)*, 2009, pp. 2108–2114. [Online]. Available: https://doi.org/10.1109/NSSMIC.2009.5402104

[10] L. S. Pontryagin, *The Mathematical Theory of Optimal Processes*. New York: Interscience, 1962.

[11] N. C. Jones, R. Van Meter, A. G. Fowler, P. L. McMahon, J. Kim, T. D. Ladd, and Y. Yamamoto, "Layered architecture for quantum computing," *Physical review. X*, vol. 2, no. 3, p. 031007, 2012. [Online]. Available: https://doi.org/10.1103/PhysRevX.2.031007

[12] P. Faist, S. Nezami, V. V. Albert, G. Salton, F. Pastawski, P. Hayden, and J. Preskill, "Continuous symmetries and approximate quantum error correction," *Physical Review X*, vol. 10, no. 4, oct 2020. [Online]. Available: https://doi.org/10.1103%2Fphysrevx.10.041018

[13] L. Egan, D. M. Debroy, C. Noel, A. Risinger, D. Zhu, D. Biswas, M. Newman, M. Li, K. R. Brown, M. Cetina, and C. Monroe, "Fault-tolerant control of an error-corrected qubit," *Nature (London)*, vol. 598, no. 7880, pp. 281–286, 2021. [Online]. Available: https://doi.org/10.1038/s41586-021-03928-y

[14] T. Chen, Z.-Y. Xue, and Z. D. Wang, "Error-tolerant geometric quantum control for logical qubits with minimal resource," 2021. [Online]. Available: https://doi.org/10.48550/arXiv.2112.08823

[15] H. Levine, A. Keesling, A. Omran, H. Bernien, S. Schwartz, A. S. Zibrov, M. Endres, M. Greiner, V. Vuletić, and M. D. Lukin, "High-fidelity control and entanglement of rydberg-atom qubits," *Physical review letters*, vol. 121, no. 12, pp. 123 603–123 603, 2018. [Online]. Available: https://doi.org/10.1103/PhysRevLett.121.123603

[16] B. Eastin and E. Knill, "Restrictions on transversal encoded quantum gate sets," *Physical review letters*, vol. 102, no. 11, pp. 110 502–110 502, 2009. [Online]. Available: https://doi.org/10.1103/PhysRevLett.102.110502

[17] Y. Yang, Y. Mo, J. M. Renes, G. Chiribella, and M. P. Woods, "Optimal universal quantum error correction via bounded reference frames," 2020. [Online]. Available: https://doi.org/10.48550/arXiv.2007.09154

[18] A. M. Brańczyk, P. E. M. F. Mendonça, A. Gilchrist, A. C. Doherty, and S. D. Bartlett, "Quantum control of a single qubit," *Physical review. A, Atomic, molecular, and optical physics*, vol. 75, no. 1, 2007. [Online]. Available: https://doi.org/10.48550/arXiv.quant-ph/0608037

[19] T. Shibata, S. Yamamoto, S. Nakazawa, E. H. Lapasar, K. Sugisaki, K. Maruyama, K. Toyota, D. Shiomi, K. Sato, and T. Takui, "Molecular optimization for nuclear spin state control via a single electron spin qubit by optimal microwave pulses: Quantum control of molecular spin qubits," *Applied magnetic resonance*, 2021. [Online]. Available: https://doi.org/10.1007/s00723-021-01392-5

[20] T. Chen and Z.-Y. Xue, "High-fidelity and robust geometric quantum gates that outperform dynamical ones," *Physical review applied*, vol. 14, no. 6, 2020. [Online]. Available: https://doi.org/10.48550/arXiv.2001.05789

[21] C.-Y. Ding, L.-N. Ji, T. Chen, and Z.-Y. Xue, "Path-optimized nonadiabatic geometric quantum computation on superconducting qubits," 2021. [Online]. Available: https://doi.org/10.1088/2058-9565/ac3621

[22] J. M. Gambetta, J. M. Chow, and M. Steffen, "Building logical qubits in a superconducting quantum computing system," *npj quantum information*, vol. 3, no. 1, pp. 1–7, 2017. [Online]. Available: https://doi.org/10.48550/arXiv.1510.04375

[23] J. van Dijk, E. Kawakami, R. Schouten, M. Veldhorst, L. Vandersypen, M. Babaie, E. Charbon, and F. Sebastiano, "Impact of classical control electronics on qubit fidelity," *Phys. Rev. Applied*, vol. 12, p. 044054, Oct 2019. [Online]. Available: https://doi.org/10.1103/PhysRevApplied.12.044054

[24] P. Esling and C. Agon, "Time-series data mining," *ACM Computing Surveys (CSUR)*, vol. 45, no. 1, pp. 1–34, 2012. [Online]. Available: https://doi.org/10.1145/2379776.2379788

[25] J. G. De Gooijer and R. J. Hyndman, "25 years of time series forecasting," *International journal of forecasting*, vol. 22, no. 3, pp. 443–473, 2006. [Online]. Available: https://doi.org/10.1016/j.ijforecast.2006.01.001

[26] V. Cerqueira, L. Torgo, and C. Soares, "Machine learning vs statistical methods for time series forecasting: Size matters," *arXiv preprint arXiv:1909.13316*, 2019. [Online]. Available: https://doi.org/10.48550/arXiv.1909.13316

[27] B. Lim and S. Zohren, "Time-series forecasting with deep learning: a survey," *Philosophical Transactions of the Royal Society A*, vol. 379, no. 2194, p. 20200209, 2021. [Online]. Available: https://doi.org/10.1098/rsta.2020.0209

[28] Z. Hajirahimi and M. Khashei, "Hybrid structures in time series modeling and forecasting: A review," *Engineering Applications of Artificial Intelligence*, vol. 86, pp. 83–106, 2019. [Online]. Available: https://doi.org/10.1016/j.engappai.2019.08.018

[29] C. R. Azevedo and T. A. Ferreira, "The application of qubit neural networks for time series forecasting with automatic phase adjustment mechanism," in *Proc. XXVII Congr. Brazilian Comput. Sci. Soc.(VI Nat. Meeting Artif. Intell.)*, vol. 2007, 2007, pp. 1112–1121.

[30] M. Benedetti, E. Lloyd, S. Sack, and M. Fiorentini, "Parameterized quantum circuits as machine learning models," *Quantum Science and Technology*, vol. 4, no. 4, p. 043001, 2019. [Online]. Available: https://doi.org/10.1088/2058-9565/ab4eb5

[31] D. Emmanoulopoulos and S. Dimoska, "Quantum machine learning in finance: Time series forecasting," *arXiv preprint arXiv:2202.00599*, 2022. [Online]. Available: https://doi.org/10.48550/arXiv.2202.00599

[32] P. Singh, G. Dhiman, S. Guo, R. Maini, H. Kaur, A. Kaur, H. Kaur, J. Singh, and N. Singh, "A hybrid fuzzy quantum time series and linear programming model: Special application on taiex index dataset," *Modern Physics Letters A*, vol. 34, no. 25, p. 1950201, 2019. [Online]. Available: https://doi.org/10.1142/S0217732319502018

[33] P. Singh, "Fqtsfm: A fuzzy-quantum time series forecasting model," *Information Sciences*, vol. 566, pp. 57–79, 2021. [Online]. Available: https://doi.org/10.1016/j.ins.2021.02.024

[34] Z.-k. Feng, W.-j. Niu, Z.-y. Tang, Z.-q. Jiang, Y. Xu, Y. Liu, and H.-r. Zhang, "Monthly runoff time series prediction by variational mode decomposition and support vector machine based on quantum-behaved particle swarm optimization," *Journal of Hydrology*, vol. 583, p. 124627, 2020. [Online]. Available: https://doi.org/10.1016/j.jhydrol.2020.124627

[35] J. Kober, J. A. Bagnell, and J. Peters, "Reinforcement learning in robotics: A survey," *The International Journal of Robotics Research*, vol. 32, no. 11, pp. 1238–1274, 2013. [Online]. Available: https://doi.org/10.1177/0278364913495721

[36] K. Shao, Z. Tang, Y. Zhu, N. Li, and D. Zhao, "A survey of deep reinforcement learning in video games," *CoRR*, vol. abs/1912.10944, 2019. [Online]. Available: https://doi.org/10.48550/arXiv.1912.10944

[37] V. Uc-Cetina, N. Navarro-Guerrero, A. Martín-González, C. Weber, and S. Wermter, "Survey on reinforcement learning for language processing," *CoRR*, vol. abs/2104.05565, 2021. [Online]. Available: https://doi.org/10.48550/arXiv.2104.05565

[38] G. Dulac-Arnold, N. Levine, D. J. Mankowitz, J. Li, C. Paduraru, S. Gowal, and T. Hester, "Challenges of real-world reinforcement learning: definitions, benchmarks and analysis," *Machine Learning*, vol. 110, no. 9, pp. 2419–2468, Sep 2021. [Online]. Available: https://doi.org/10.1007/s10994-021-05961-4

[39] D. Dong, C. Chen, H. Li, and T.-J. Tarn, "Quantum reinforcement learning," *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, vol. 38, no. 5, pp. 1207–1220, oct 2008. [Online]. Available: https://doi.org/10.1109/tsmcb.2008.925743

[40] V. Dunjko, J. M. Taylor, and H. J. Briegel, "Quantum-enhanced machine learning," *Phys. Rev. Lett.*, vol. 117, p. 130501, Sep 2016. [Online]. Available: https://doi.org/10.1103/PhysRevLett.117.130501

[41] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information: 10th Anniversary Edition*, 10th ed. USA: Cambridge University Press, 2011.

[42] C. Ryan-Anderson, J. G. Bohnet, K. Lee, D. Gresh, A. Hankin, J. P. Gaebler, D. Francois, A. Chernoguzov, D. Lucchetti, N. C. Brown, T. M. Gatterman, S. K. Halit, K. Gilmore, J. A. Gerber, B. Neyenhuis, D. Hayes, and R. P. Stutz, "Realization of real-time fault-tolerant quantum error correction," *Phys. Rev. X*, vol. 11, p. 041058, Dec 2021. [Online]. Available: https://doi.org/10.1103/PhysRevX.11.041058

[43] F. Flamini, A. Hamann, S. Jerbi, L. M. Trenkwalder, H. P. Nautrup, and H. J. Briegel, "Photonic architecture for reinforcement learning," *New Journal of Physics*, vol. 22, no. 4, p. 045002, apr 2020. [Online]. Available: https://doi.org/10.1088/1367-2630/ab783c

[44] L. P. Kaelbling, M. L. Littman, and A. W. Moore, "Reinforcement learning: A survey," *CoRR*, vol. cs.AI/9605103, 1996. [Online]. Available: https://doi.org/10.48550/arXiv.cs/9605103

[45] S. Wu, S. Jin, D. Wen, and X. Wang, "Quantum reinforcement learning in continuous action space," 2020. [Online]. Available: https://doi.org/10.48550/ARXIV.2012.10711

[46] Y. Du, M.-H. Hsieh, T. Liu, and D. Tao, "Expressive power of parametrized quantum circuits," *Physical Review Research*, vol. 2, no. 3, jul 2020. [Online]. Available: https://doi.org/10.1103/physrevresearch.2.033125

[47] S. Y.-C. Chen, C.-H. H. Yang, J. Qi, P.-Y. Chen, X. Ma, and H.-S. Goan, "Variational quantum circuits for deep reinforcement learning," 2019. [Online]. Available: https://doi.org/10.48550/ARXIV.1907.00397

[48] Y. Kwak, W. J. Yun, S. Jung, J.-K. Kim, and J. Kim, "Introduction to quantum reinforcement learning: Theory and pennylane-based implementation," 2021. [Online]. Available: https://doi.org/10.48550/ARXIV.2108.06849

[49] J.-A. Li, D. Dong, Z. Wei, Y. Liu, Y. Pan, F. Nori, and X. Zhang, "Quantum reinforcement learning during human decision-making," *Nature Human Behaviour*, vol. 4, no. 3, pp. 294–307, Mar 2020. [Online]. Available: https://doi.org/10.1038/s41562-019-0804-2

[50] K. S. Shenoy, D. Y. Sheth, B. K. Behera, and P. K. Panigrahi, "Demonstration of a measurement-based adaptation protocol with quantum reinforcement learning on the ibm q experience platform," *Quantum Information Processing*, vol. 19, no. 5, p. 161, Apr 2020. [Online]. Available: https://doi.org/10.1007/s11128-020-02657-x

[51] N. Bruining, R. Barendse, and P. Cummins, "The future of computers in cardiology: 'the connected patient'?" *European Heart Journal*,

vol. 38, no. 23, pp. 1781–1794, 06 2017. [Online]. Available: https://doi.org/10.1093/eurheartj/ehx264

[52] K. Bertels, A. Sarkar, T. Hubregtsen., M. Serrao, A. A. Mouedenne, A. Yadav, A. Krol, and I. Ashraf, "Quantum computer architecture: Towards full-stack quantum accelerators," in *2020 Design, Automation Test in Europe Conference Exhibition (DATE)*, 2020, pp. 1–6. [Online]. Available: https://doi.org/10.23919/DATE48585.2020.9116502

[53] S. Srinivasan, G. Gordon, and B. Boots, "Learning hidden quantum markov models," in *Proceedings of the Twenty-First International Conference on Artificial Intelligence and Statistics*, ser. Proceedings of Machine Learning Research, A. Storkey and F. Perez-Cruz, Eds., vol. 84. PMLR, 4 2018, pp. 1979–1987. [Online]. Available: https://doi.org/10.48550/arXiv.1710.09016

[54] E. Prashant S., W. Jonathan, A. Alan, B. Stefan, G. Michael, M. Michael J., S. Guillermo, A.-G. Alán, B. Justin T., B. Matteo, M. John D., S. Stamatios N., T. Jacob, S. Geetha, L. Thomas, G. Mark B., and H. Aram W., "Quantum computing at the frontiers of biological sciences," *Nature Methods*, vol. 18, pp. 701–709, 01 2021. [Online]. Available: https://doi.org/10.1038/s41592-020-01004-3

[55] Y. Cao, J. Romero, and A. Aspuru-Guzik, "Potential of quantum computing for drug discovery," *IBM Journal of Research and Development*, vol. 62, no. 6, pp. 6:1–6:20, 2018. [Online]. Available: https://doi.org/10.1147/JRD.2018.2888987

[56] P. Alberto, M. Jarrod, S. Peter, Y. Man-Hong, Z. Xiao-Qi, L. Peter J., A.-G. Alán, and O. Jeremy L., "A variational eigenvalue solver on a photonic quantum processor," *Nature Communications*, vol. 5, no. 4213, 07 2014. [Online]. Available: https://doi.org/10.1038/ncomms5213

[57] F. Dmitry A., P. Bo, G. Niranjan, and A. Yuri, "VQE method: a short survey and recent developments," *Matherials Theory*, vol. 6, no. 2, 01 2022. [Online]. Available: https://doi.org/10.1186/s41313-021-00032-6

[58] Y. Song, Y.-D. Zhang, X. Yan, H. Liu, M. Zhou, B. Hu, and G. Yang, "Computer-aided diagnosis of prostate cancer using a deep convolutional neural network from multiparametric MRI," *J. Magn. Reson. Imaging*, vol. 48, no. 6, 12 2018. [Online]. Available: https://doi.org/10.1002/jmri.26047

[59] C. Outeiral, M. Strahm, J. Shi, G. Morris, S. Benjamin, and C. Deane, "The prospects of quantum computing in computational molecular biology," *Wiley Interdisciplinary Reviews: Computational Molecular Science*, vol. 11, 05 2020. [Online]. Available: https://doi.org/10.1002/wcms.1481

[60] A. A. Abdullah, M. M. Hassan, and Y. T. Mustafa, "A review on bayesian deep learning in healthcare: Applications and challenges," *IEEE Access*, vol. 10, pp. 36 538–36 562, 2022.