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Influence of IQT on research in ICT part 6

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***Abstract*—The advanced Quantum Information Technologies subject for Ph.D. students in Electronics Engineering and ICT consists of three parts. A few review lectures concentrate on topics which may be of interest for the students due to their fields of research done individually in their theses. The lectures indicate the diversity of the QIT field, resting on physics and applied mathematics, but possessing a wide application range in quantum computing, communications, and metrology. The individual IQT seminars prepared by Ph.D. students are as closely related to their real theses as possible. An important part of the seminar is a discussion among the students. The task was to enrich, possibly with a quantum layer, the current research efforts in ICT. And to imagine what value such a quantum enrichment adds to the research. The result is sometimes astonishing, especially in such cases when the quantum layer may be functionally deeply embedded. The final part was to write a short paragraph for a common paper related to individual quantum layer addition to the own research. The paper presents some results of such an experiment and is a continuation of previous papers of the same style.**

***Keywords*—quantum information technology; quantum nonlocality; quantum metrology; squeezed light; noon states; quantum computing cloud; quantum neural networks; quantum reinforcement learning; quantum agents; quantum-inspired spatio-temporal inference networks; quantum machine learning; quantum technologies**

I. INTRODUCTION

ADVANCED lecture for a group of diverse Ph.D. students is a demanding task. They are strongly concentrated on their individual research efforts. Timing of their Ph.D. study is demanding, and they try to omit things that do not help them to go forward with the research. The subject on Quantum Information Technology is designed in this way as not to slow down their work but to help and perhaps shed a new light on their research from a completely different yet very modern and promising perspective, the quantum one. The quantum perspective, especially when used against your serious personal research effort, is really very useful in most cases. In this article, several distinct quantum topics prepared by individual students are brought together to illustrate the breadth of Quantum Information Technology. These subjects range from quantum-enhanced angular metrology using squeezed light and NOON states, foundational studies of quantum nonlocality, and advances in quantum neural networks to practical developments in quantum computing clouds, quantum agents for reinforcement learning, and quantum-inspired spatio-temporal inference networks applied to earthquake prediction in high-noise environments. Although each topic reflects a different research direction, together they demonstrate how contemporary quantum techniques continue to expand into precision measurement, computation, machine learning, and data analysis. The combined work shows how diverse quantum approaches can support and enrich ongoing scientific research.

II. PROVING QUANTUM NONLOCALITY USING FREE WILL AND VIDEO GAMES

In their article titled "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?", Albert Einstein, Boris Podolsky, and Nathan Rosen presented a famous paradox. Using notions of locality and reality, they argued that quantum theory provides an incomplete description of our world. Aforementioned terms can be explained as follows [1]. Locality (causality) means that no information can travel faster than light and thus no action or observation can have an immediate effect at a foreign location. Realism is the belief that all measurable properties have a definite value even without being measured by an observer. On the other hand, nonlocality means the denial of local realism.

The Local Hidden Variable Model (LHVM) was introduced to serve as an explanation for the phenomenon of "spooky action at a distance" (quantum entanglement). In the model, a property contained within observed particles predetermines the result of observation in given conditions.

John Stewart Bell authored one of the responses to the stated paradox, known as Bell's theorem. He formalized it in the form of an inequality. The goal of the inequality was to become satisfied only if quantum mechanics complied with local realism (i.e., both locality and realism), for example, in accordance with LHVM. However, all quantum experiments conducted to date tend to violate it.

Level 1. CHSH Game. In its original form, Bell's theorem shows LHVM as a probabilistic equation, likewise to (1). Here, x and y are the settings of measurements on two entangled particles. Variables a and b denote the outcomes of the measurements, respectively, for x and y. Then, in a series of formulas, Bell proves that the equation cannot be applied to quantum physics.

$$P(a,b|x,y) = \sum_\lambda P(a|x,\lambda)P(b|y,\lambda)P(\lambda) \quad (1)$$

Even with such a theoretical basis presented, quantum experiments still required a more practical version of the proof. It came in many ways, most notably as the CHSH inequality (2) or test. Here, a_0 and a_1 result from measuring properties A_0 and A_1 for the first particle. Analogously, b_0 and b_1 are the results for the second particle. All the measurements involved are binary, each having the result of ± 1.

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$$|S| = a_0b_0 + a_0b_1 + a_1b_0 - a_1b_1 = (a_0 + a_1)b_0 + (a_0 - a_1)b_1 \leq 2 \quad (2)$$

Alternatively, the CHSH test can be depicted as a game (the first layer of gamification of the topic) where there are two players forming a team. They can agree on a strategy beforehand, but after the game starts, they can no longer communicate. Each player receives a random bit from a neutral referee and answers it with a single bit. The goal of the players is to maximize the number of cases when the conjunction of received bits equals the exclusive disjunction of the answers (using previous variables: $x \wedge y = a \oplus b$).
Using the CHSH test, scientists can aggregate data from multiple quantum experiments and show in a simple way that they violate Bell's inequality, thus challenging the existence of local realism.

Unfortunately, the task isn't as easy as just described because there exist many loopholes that may render experiments inapplicable [2]. One of the major problems is the locality loophole. It requires two measurement systems (representing two players from the CHSH game) to be sufficiently far away from each other to exclude the possibility of information being interchanged between them (at the speed of light). The detection loophole is another issue. It points out that with imperfect detectors, we lose a fraction of particles that could otherwise cause aggregated data to satisfy Bell's inequality. Yet another great challenge is posed by the freedom-of-choice loophole. It requires truly random data to be obtained for the results to be free of determinism as well. Before, physicists typically assumed that phenomena such as spontaneous emission, thermal fluctuation, or classical chaos are unpredictable (uninfluenced by prior events). In [1], researchers decided to rely on humans' free will instead.

Interlude. Free Will. Of course, the existence of free will isn't certain. It is more of a philosophical problem that cannot be solved using physics equations. We can only assume that our choices are free and not just the only possible outcomes of chemical processes in our brains. However, a definition of free will ought to be presented in such an article. There exist two kinds of definitions [3]. The "negative" one describes free will as the freedom from complete determination. The "positive" states that it is a freedom of complete self-determination. The "positive" definition is far stronger. It disallows any determination, while the first one allows partial determination. What is even more interesting is that in the context of quantum physics, free will does not only apply to humans, but also to each elementary particle being the subject of research. By showing analogy to results being free of determinism only if the physical random data sources are truly random, Conway and Kochen say that "if indeed there exist any experimenters with a modicum of free will, then elementary particles must have their own share of this valuable commodity." [1]

Level 2. The BIG Bell Quest. On 30 November 2016, a 12-hour-long experiment session ("The BIG Bell Test") was undertaken using human choices as the input random data [1]. Free will of experimenters was "harvested" using an online video game (the second layer of gamification!). About 100'000 volunteers (so-called Bellsters) generated a stream of ones and zeroes at a minimal speed of 1 kbps. The binary data stream was used to conduct 13 experiments for Bell's inequality in 12 laboratories all over the world. Over 97 Mb of random data was generated in total.

Most of the experiments employed the CHSH test. Entangled systems used by laboratories included γ polarization, γ-atom (or γ-atom ensemble), γ time-bin, γ multi-frequency bin, and transmon qubit. Statistical significance of results varied from 3.1 σ to 140 σ.

And how exactly was the data harvested? There were several levels of two types available. The first type, "speed" or "running" levels (see Fig. 1) prompted the player to input ones and zeroes as fast as they can in the most random way possible. The level of randomness was displayed in real time using a machine-learning model, which tried to learn patterns in players' input. The same model was used in "oracle" levels. Here, the goal of the player was to outsmart the oracle, which tried to predict their choice. To pass a level, the player needed to reach a certain score. The two types of levels described above were interwoven, so that the oracle model was getting gradually better (and thus harder to beat). The levels were easily repayable. The appeal of the game was additionally increased by the possibility of sharing one's scores on social media.

Closing word. Using a simple online video game, scientists were able to perform a major step in overcoming the freedom-of-choice loophole of Bell's test. In a non-precedented series of experiments, the participants of "The BIG Bell Test" used free choices of over 100,000 people as truly random input parameters, once more showing the violation of Bell's inequality in quantum physics. The undertaking wasn't fully free of other loopholes [2], with some of the experiments being bothered by the locality loophole or detection loophole. The sole existence of free will cannot be proven too [3]. But assuming that it does exist, "The BIG Bell Test" has been the most meaningful proof of nonlocality to date, exemplifying the worth of the collaboration of thousands of people around the globe as well as the value of using the new media technologies in science.

Fig. 1. A screenshot of a "speed" or "running" level from The BIG Bell Quest.

Fig. 2. A screenshot of an "oracle" level from The BIG Bell Quest.

III. QUANTUM-ENHANCED ANGULAR METROLOGY FOR POLYGON CALIBRATION USING SQUEEZED LIGHT AND NOON STATES

Autocollimators serve as primary instruments for high-precision angular metrology and are widely employed in the calibration of polygon prisms, rotary tables, and encoders. In classical operation, a coherent laser beam reflects from a polygon face, and its lateral displacement on the detector provides a direct measurement of the face angle [4]. When technical noise sources are minimized, the ultimate limit is imposed by photon shot noise, which arises from the discrete nature of photons. Figure 3 illustrates the layout of a standard autocollimator interacting with a polygon face of twelve sides configured for calibration.

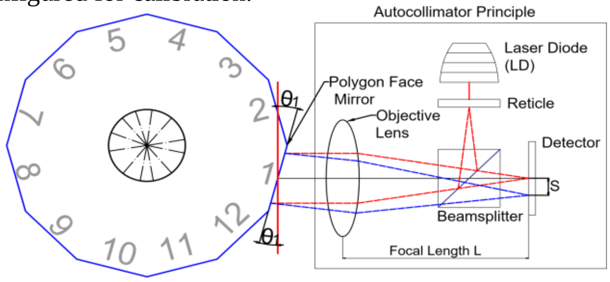

Fig. 3. Laser standard autocollimator with 12 face polygon geometry.

Modern quantum optics provides the means to surpass this classical noise floor. Two approaches are relevant for angular metrology. The first is the use of squeezed light, where quantum fluctuations in one quadrature of the optical field are redistributed such that phase or amplitude noise is reduced below the vacuum limit. The second is the use of NOON states, which consist of maximally entangled photon-number states and achieve phase sensitivity at the Heisenberg limit.

In a typical autocollimator geometry, a polygon face with a tilt θ deflects a reflected beam by approximately 2θ. For a detector positioned at an effective optical distance L, the centroid displacement on the sensor is

$$s = 2L\theta \tag{3}$$

So the recovered angle is

$$\theta = \frac{s}{2L} \tag{4}$$

The uncertainty in θ is determined by the uncertainty in measuring s. For a Gaussian beam of radius $w$and Ndetected photons, the shot-noise-limited centroid uncertainty is approximately

$$\sigma_s \approx \frac{w}{\sqrt{N}} \tag{5}$$

leading to a classical angle uncertainty

$$\sigma_{\theta,SQL} = \frac{w}{2L\sqrt{N}} \tag{6}$$

This expression represents the standard quantum limit for classical coherent illumination and is consistent with the treatment of [5]. For representative laboratory parameters of $w = 0.5$ mm, $L = 0.5$ m, and $N = 10^8$, one obtains

$$\sigma_{\theta,SQL} \approx 5 \times 10^{-8} \text{ rad} \approx 50 \text{ nrad} \tag{7}$$

which defines the typical classical noise floor of a high-quality autocollimator.

A. Quantum Enhancement Using Squeezed Light

Squeezed states reduce quantum noise in a chosen quadrature. The noise variance of the squeezed quadrature is given by

$$V_{sq} = e^{-2r}, \tag{8}$$

where $r$is the squeezing parameter. Noise reduction is commonly expressed in decibels,

$$\text{squeezing (dB)} = -10\log_{10}(V_{sq}) \tag{9}$$

Values of 3 dB, 6 dB, and 10 dB correspond respectively to $V_{sq} = 0.5$, 0.25, and 0.1. Experimental demonstrations exceed 10 dB [6]. In an autocollimator, a squeezed-vacuum field generated by an OPO is injected into the unused port of the system beamsplitter (see Figure 4). This replaces ordinary vacuum fluctuations with reduced-variance fluctuations, lowering the quantum noise on the returning beam without altering the beam's intensity or trajectory.

If the angular information is encoded in the squeezed quadrature, the position noise becomes

$$\sigma_{s,sq} = \sqrt{V_{sq}}\,\frac{w}{\sqrt{N}} \tag{10}$$

and the corresponding angle noise is

$$\sigma_{\theta,sq} = \sqrt{V_{sq}}\,\sigma_{\theta,SQL} \tag{11}$$

For 6 dB squeezing ($V_{sq} = 0.25$), one finds

$$\sigma_{\theta,sq} \approx 0.5 \times 50 \text{ nrad} = 25 \text{ nrad} \tag{12}$$

a factor-of-two improvement consistent with practical squeezed-interferometry results.

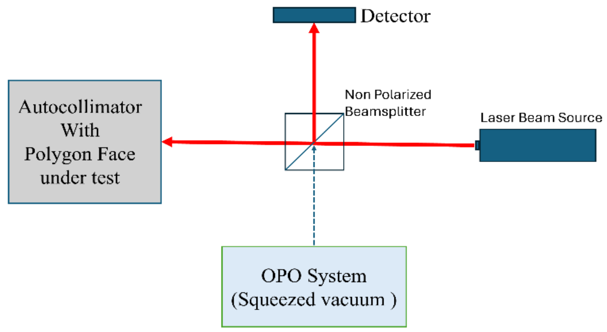

Fig. 4. shows the squeezed-light injection layout.

B. Heisenberg-Limited Calibration Using NOON States

A k-photon NOON state is defined as

$$|\,\text{NOON}\rangle = \frac{1}{\sqrt{2}}(|\,k,0\rangle + |\,0,k\rangle), \tag{13}$$

and exhibits phase sensitivity

$$\Delta\phi_{NOON} = \frac{1}{k}, \tag{14}$$

in contrast to the classical scaling [7]. In the autocollimator analogue, a NOON state is split into two paths, one reflecting from a reference mirror and the other from the polygon face under test. After recombination at a second beamsplitter, an N-photon detector recovers the phase shift amplified by the factor k (Figure 5). This enables angle estimation with enhanced sensitivity,

$$\sigma_{\theta,NOON} = \frac{\sigma_{\theta,SQL}}{\sqrt{k}} \tag{15}$$

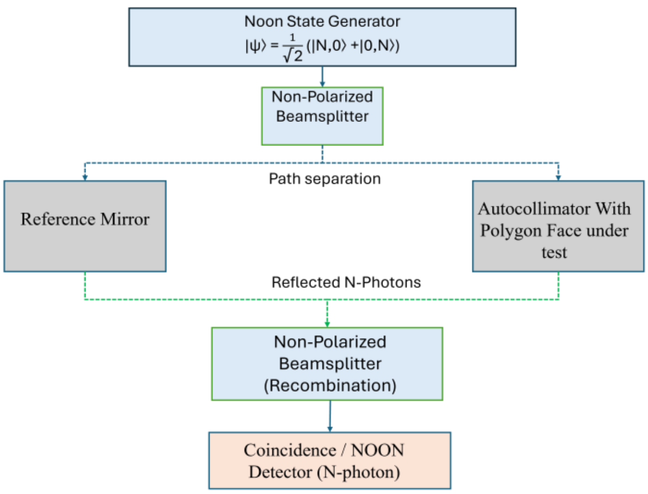

Fig. 5. NOON state split, reflected, and recombined to enhance phase sensitivity for polygon angle measurement.

Using the classical limit of 50 nrad, a progression of improvements is obtained: k = 2 yields ~35 nrad, k = 4 yields 25 nrad (equivalent to 6 dB squeezing), k = 10 yields ~16 nrad, and k = 100 yields ~5 nrad. (See Figure 6).

While theoretically powerful, NOON states degrade rapidly under optical loss. Loss of even a single photon collapses the entangled superposition into a mixed state, eliminating the Heisenberg advantage. Experiments above k = 5 exhibit severe fidelity reduction [8], rendering NOON-based metrology impractical for real calibration systems.

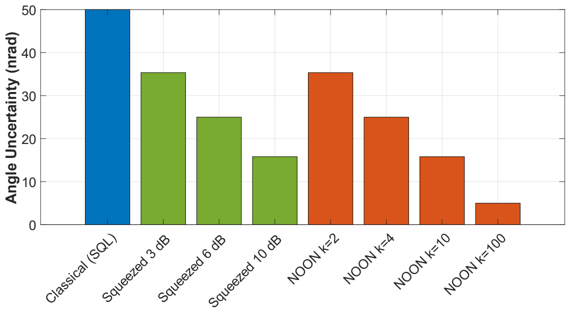

Fig. 6. Comparison of angle uncertainties for classical, squeezed-light, and NOON-state illumination.

C. Discussion and Practical Implications

Squeezed-light enhancement is feasible with existing optical parametric oscillators and is compatible with classical autocollimator systems. It tolerates moderate optical loss and has demonstrated stability in long-baseline interferometers. Implemented in a polygon calibration context, squeezed light can reduce the classical quantum-noise floor of ~50 nrad to ~25 nrad in conditions dominated by shot noise.

NOON states, by contrast, provide a theoretical ideal through Heisenberg scaling but are extremely fragile, rapidly destroyed by loss, and difficult to generate with high photon numbers. Their use in practical metrology remains unlikely in the near term, and they presently serve as a theoretical benchmark rather than a deployable technology.

IV. AGNOSTIC IMPERATIVE: THE ROLE OF ABSTRACTION AND STANDARDIZATION IN QUANTUM CLOUD EVOLUTION

Modern computer science stands at the threshold of a quantum revolution, yet the physical and economic barrier to entry for owning one's own quantum infrastructure remains insurmountable for most organizations. In response to these constraints, the model of Quantum Computing as a Service (QCaaS) has emerged, which is not just a logistical convenience but rather a technological necessity in the era of Noisy Intermediate-Scale Quantum (NISQ). [9]

The complexity of maintaining quantum processors (QPU), which require extreme environmental conditions such as cryogenic cooling and electromagnetic isolation, necessitates the centralization of resources in specialized data centers. Nguyen et al. (2024) argue that a cloud-based model is crucial for democratizing access to this technology, allowing researchers and businesses to experiment with algorithms without investing in hardware [9].

As Döbler and Jattana (2025) observe, the future of high-performance computing (HPC) lies in the tight integration of classical and quantum resources. In this paradigm, QPU does not replace the classical processor (CPU), but rather acts as a specialized accelerator, similar to GPU architectures in machine learning [10]. This hybrid architecture defines new requirements for the software stack, where orchestrating tasks between diverse computational components becomes a key challenge.

To understand the direction of quantum ecosystem development, it is worth referring to the history of classical IT. The first decade of cloud computing's evolution was characterized by the phenomenon of "vendor lock-in." Applications built on specific, proprietary solutions from a single vendor (e.g., AWS or Azure) became extremely difficult to migrate, which limited business and technological flexibility for enterprises.

The solution to this problem came in the form of introducing abstraction layers such as containerization (e.g., Docker) and orchestration systems (e.g., Kubernetes). These technologies have enabled the separation of application logic from the infrastructure on which it runs. This has resulted in a significant degree of infrastructural agnosticism - code became more portable, and cloud provider choice evolved towards an economic decision. However, it should be noted that while this model effectively reduced hardware dependence, it did not completely eliminate the problem of API fragmentation at higher service levels, which is an important lesson for the emerging quantum ecosystem. Ahmad et al. (2025) suggest that quantum software engineering (QSE) should draw from these patterns by adapting proven practices such as microservices and service-oriented architecture (SOA) to the specifics of the quantum world [11].

In the quantum world, the "vendor lock-in" problem resurfaces in a much deeper and riskier form. While in classical cloud it concerns differences in provider APIs, in the quantum cloud it involves fundamental differences in hardware technology.

The current landscape of quantum hardware is highly heterogeneous. Different approaches to building qubits - from superconductors, trapped ions, to neutral atoms - exhibit distinct physics, connection topologies, coherence times, and sets of logical gates [9]. Unlike classic x86 processors, which are largely interchangeable, an algorithm optimized for one quantum architecture may be completely useless on another.
Faced with uncertainty about which quantum technology will ultimately dominate the market, an agnostic strategy becomes a form of risk management. Investing in software tightly coupled to one type of hardware carries the risk of technological dead ends. The agnostic imperative in QSE aims to create an abstraction layer that allows developers to focus on algorithms rather than the physics of a specific machine [11].

Implementing full agnosticism in the current NISQ era faces a barrier of so-called "leaky abstractions." In an ideal model, the software layer should completely hide hardware complexity. However, due to high noise levels and errors in present devices, physical hardware properties "leak" into the application layer, affecting result correctness.

Nguyen et al. (2024) emphasize that resource management in a quantum cloud is much more complex than in a classical one due to the need to consider parameters such as gate fidelity or coherence time [9]. The programmer often needs to be aware of processor topology to minimize the number of SWAP operations, which introduce additional errors.

Despite this, the industry strives to develop tools that bridge these gaps. Key players in this endeavor are:

1. Aggregating Platforms: Solutions such as Amazon Braket or Azure Quantum act like brokers, providing a unified interface for accessing machines from different vendors (e.g., IonQ, Rigetti). This allows testing the same code on various backends. [9]

2. Transpilers and Middleware: This is a critical layer of software that translates abstract code (written in, for example, Qiskit or Cirq) into instructions understandable by a specific machine, optimizing it based on its specifics. Döbler and Jattana (2025) point to the growing role of middleware in managing hybrid workflows [10].

3. Design Patterns: Ahmad et al. (2025) propose the use of patterns such as "Quantum API Gateway" and "Quantum-Classic Split," which help structure the application architecture in a modular and hardware-independent manner [11].

Modern literature validates concerns regarding the fragmentation of the QCaaS ecosystem, indicating that despite available infrastructure, interface diversity remains a critical barrier. As Nguyen et al. (2024) observe, the lack of a standardized quantum programming model is currently one of the main software engineering challenges in this domain. Each cloud service provider operates on distinct platforms and toolkits (SDKs), complicating the development of applications that run across multi-cloud environments [9].

Ahmad at al. (2025) add that this heterogeneity forces developers to recompile and adapt the application code for each backend individually. As a result, despite physical access to multiple machines, users are technologically "locked in" to one provider's ecosystem, replicating problems known from the early stages of classical cloud development [11]

The answer to the fragmentation risk identified in recent research is the development of an intermediary layer (middleware) and adaptation of architectural patterns known from SOA (Service-Oriented Architecture). Ahmad et al. (2025) propose a wide application of the "Quantum API Gateway" pattern. This mechanism acts as an intermediary that centralizes request handling and abstracts the complexity of individual backends, enabling dynamic hardware selection without requiring client code modifications [11].

Döbler and Jattana (2025) emphasize that urgent standardization of interfaces and integration methods for HPC systems with quantum units is necessary to avoid permanent divisions in the ecosystem. The authors point out the promising development of frameworks such as XACC, which aim for hardware agnosticism by enabling single-source compilation to various target architectures, representing a step towards unifying industry standards [10].

V. QUANTUM NEURAL NETWORKS

The machine learning (ML) sector is growing rapidly. The significant advancements in the Natural Language Processing (NLP) and Computer Vision (CV) sectors have led to the wide adoption of machine learning algorithms in the industry, such as artificial neural networks (ANNs), currently seen as a state-of-the-art solution for many ML problems. However, the increasing computational power required by the latest approaches may challenge that growth. Quantum Neural Networks (QNN) are algorithms that leverage Quantum Computing (QC) in order to tackle that problem.

A. Quantum Perceptron

The most basic type of ANN is the Multilayer Perceptron (MLP). This network consists of a few layers, given by Equation (16).

$$y = f(\langle x, 1 \mid w \rangle) \tag{16}$$

Each layer uses an inner product between the input feature vector $|x\rangle$ and weights vector $|w\rangle$ in order to find a new feature associated with a given neuron. This feature is then projected by some nonlinear activation function f. That allows the model to learn more efficiently by pruning values that are not interesting for the next layer. Their presence is not necessary; however, in many cases, it will decrease overall model performance, thus requiring more layers to compensate.

Quantum Perceptron, described in [12], removes activation functions from the MLP, which leads to some advantages. Each parameter tensor $|w\rangle_1$can be efficiently applied to the input vector $|x\rangle$as a matrix U_1^1. That means that the entire layer can be expressed as a singular matrix,

$$U^1 = \prod_{j=0} U_j^1 \tag{17}$$

That leads to the n-th model layer being described as Equation (18).

$$\rho_n = U^n (\rho_{n-1} \otimes |0\ldots0\rangle\langle0\ldots0|) (U^n) \dagger \tag{18}$$

By pruning activation functions, the Quantum Perceptron can stack all of the layers' parameters into one parameter matrix,

$$U = \prod_{j=0} U^j \qquad 19)$$

Then the entire network can be described by Equation (20), which can be implemented by a single quantum gate.

$$\rho\_out = U (\rho\_in \otimes |0\ldots0\rangle\langle0\ldots0|) U \dagger \tag{20}$$

B. Quantum Transformer

A transformer is an ANN architecture that is considered state-of-the-art in many applications. Transformer relies on the operation of attention, described by Equation (21).

$$A = softmax\left(\frac{QK^T}{\sqrt{d_k}}\right) \tag{21}$$

Tensors Q-Query, K-Key, and V-Value are dynamically calculated by the minor layers called mapping. Attention allows the model to find correlations in spatial data regardless of the input data points' position in the input vector. That makes it very useful, for example, for NLP tasks, where the major part of the information is held by verbs and nouns, whose position may change. In the transformer, the attention layer is followed by the MLP in the feature dimension, which estimates a non-linear activation function. Both MLP and attention are preceded by normalization and residual layers.

In terms of Quantum Transformers, described in [13], the current implementation approaches are split into hybrid and fully-quantum. Hybrid approaches utilize quantum circuits to speed up parts of attention calculations (for example, QKV mapping). Those approaches allow for more error, and so they can utilize early NISQ devices. The more advanced purely quantum solutions are currently only theoretical ones since they require much more stable circuits.

C. Training of Quantum Neural Network

As shown in previous subchapters, the parameters of the models are embedded into the parametrized quantum gates. That means they are not quantum and are trained using classical optimization techniques. Before model usage, the data has to be encoded. It can be done using rotation gates as described in [14]. Then the training data are propagated through the network. Then the result has to be measured, and the loss function calculates the error. This error is then propagated backwards by a classical computer, which updates weights in the quantum gates (and also classical layers if the approach is hybrid). Research in [12] describes such a process for the Quantum Perceptron.

VI. QUANTUM AGENTS AND REINFORCEMENT LEARNING IN AGILE CONTEXTS

The software development life cycle in Agile methodologies often involves processing various correlated tasks, changing and evolving requirements, technical debt, and limited capacity. The typical Scrum Planning methods even when enhanced by using modern techniques may struggle to appropriately consider the dimensions like code quality, risk, and unbalanced team workload. Many team members may have limited knowledge about a good Sprint Backlog composition, that is even more relevant in large, modular codebases. The number of possible Sprint Backlogs is huge, even with a Product Backlog containing only fifty user stories. This work describes a multi-agentic system working in a Scrum framework combined with a quantum-enhanced optimization algorithm, which can support the teams by effectively transforming project data (user stories, commits, issues/defects, test metrics, dependencies, team history) into structured state representations and then exploring optimal task assignments and sprint configurations under complex constraints [15], [16]. At this stage, the objective is not to replace human decisions but to provide decision support proposals that balance competing objectives and reveal nontrivial tradeoffs.

A. Theoretical & Methodological Foundations

1. Reinforcement Learning

Reinforcement Learning (RL) is a learning method in which agents learn optimal behavior through interaction with an environment and feedback in the form of rewards. The solution can be extended by adding a critic to evaluate the final reward for an agent. Over time the agent learns which actions lead to better results. If we use multiple agents (Multi-Agent RL, MARL), we can treat them like a software-team: each agent is a developer or potentially sub-team. Agents share limited resources, like time, skills, attention, and they work together on a shared task or objective [16]. In a software project setting, an agent's action can mean assigning a task or allocating resources. The reward can combine various things, including how many features were delivered, how much technical debt was reduced, how balanced the team workload is, or how much risk was avoided. MARL is used in problems like resource scheduling, load balancing or coordination under uncertain conditions. These are the problems very similar to those faced in real large software projects.

2. Quantum Reinforcement Learning and Quantum Multi-Agent Systems

Given current limitations of quantum hardware such as noise, limited qubit number, and short time to decoherence the proposed system is only theoretical. It uses a hybrid architecture combining a classical semantic reasoning layer with well-known quantum inspired optimization. The semantic layer handles inputs such as code, metadata of issues, test metrics, historical performance producing structured state encodings: dependency graphs, technical debt metrics, backlog items, risk estimates, team capacity vectors and backlog priorities defined by Product Owner. The optimization layer (QMARL) operates on the given structure. It searches many possible ways to assign tasks and provide the configurations of potential sprint backlogs.

3. Quantum Methodology

Given current limitations of quantum hardware such as noise, limited qubit number, and short time to decoherence the proposed system is only theoretical. It uses a hybrid architecture combining a classical semantic reasoning layer with well-known quantum inspired optimization. The semantic layer handles inputs such as code, metadata of issues, test metrics, historical performance producing structured state encodings: dependency graphs, technical debt metrics, backlog items, risk estimates, team capacity vectors and backlog priorities defined by Product Owner. The optimization layer (QMARL) operates on the given structure. It searches many possible ways to assign tasks and provide the configurations of potential sprint backlogs.

B. Proposed Algorithm

The proposed system uses Quantum Multi-Agent Reinforcement Learning (QMARL) to support dynamic sprint planning in Agile projects. Starting from the product backlog which contains user stories with attributes such as business value, effort, risk, and dependencies. The backlog serves as the initial state of the environment. A team of agents modelled by LLMs, each corresponding to typical Agile roles (Product Owner, Developer, QA, Architect, DevOps), iteratively propose modifications, like adding, removing, or swapping user stories to form multiple candidate sprint configurations.

The core optimization is made by a quantum-enhanced policy exploration module. Sprint-planning decisions, like including or excluding user story, are encoded as a QUBO or Hamiltonian problem and solved via a variational quantum algorithm (e.g. Quantum Approximate Optimization Algorithm, QAOA) or quantum-inspired optimization [17], [18]. The quantum circuit generates a superposition of many candidate plans, explores them in parallel, and samples promising candidates. As a result, it is effectively acting as a global search engine over a combinatorial space of possible sprint plans, while respecting constraints such as capacity, dependencies, and risk.

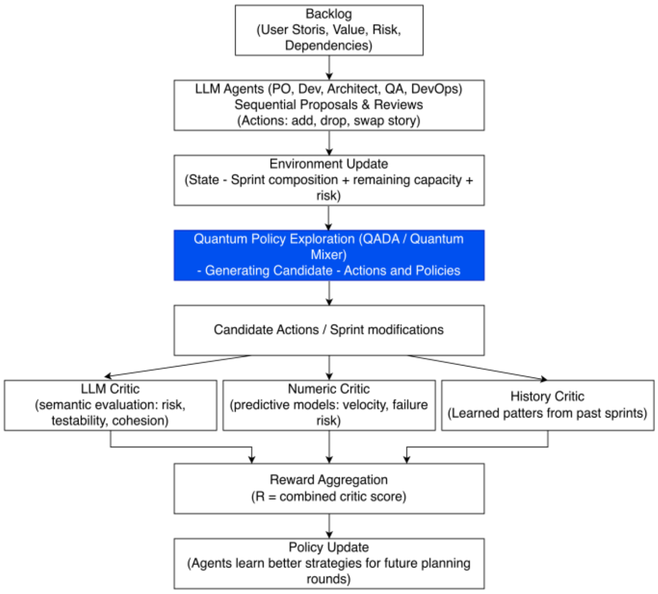

Fig. 7. The proposed Sprint Planning algorithm

Every candidate plan generated through quantum exploration is assessed by a critic (LLM-based) that verifies coherence, risk and feasibility. Moreover, a numeric critic predicts speed, while a historical critic reviews sprint outcomes to identify trends of delays or buildup of technical debt. These critics generate a combined reward signal that directs agent learning. Through repeated planning cycles, agents modify their policies to suggest balanced and stable sprint arrangements. The result is not a single "optimal" sprint plan, but a set of proposals, accompanied by quality estimates and explanations. This will give human teams options and will retain human oversight.

VII. REVIEWING QUANTUM-INSPIRED SPATIO-TEMPORAL INFERENCE NETWORKS (QSTIN) FOR EARTHQUAKE PREDICTION IN HIGH-NOISE INDONESIAN ENVIRONMENTS

Earthquakes are one of the disasters that cause significant material losses. The Flores, Indonesia, earthquake of December 12, 1992, with a magnitude of 7.8, demonstrated that this threat resulted in deaths, injuries, and damage to buildings and infrastructure. In the Flores Sea, the monitoring of three stations shows that the region has high-noise levels from ocean microseismic noise and cultural noises, such as human activities and industrial operations [19]. These noise sources hide earthquake-related signals, making it difficult to determine real seismic activity from background noise. Therefore, forecasting seismic activity, such as assessing occurrence probability, magnitude range, and spatial distribution, is essential for improving preparedness.

To address seismic activity forecasting under high-noise conditions, deep learning approaches have shown superiority to conventional statistical methods. For instance, Convolutional Long Short-Term Memory (ConvLSTM) achieved good results, enhancing precision by 14.7% over the existing model in predicting the spatiotemporal distribution of short-term seismic risk [20]. However, ConvLSTM struggles to model long-range spatial dependencies. In contrast, it is highly efficacious at capturing local dependencies by extracting spatial features via convolution but remains sensitive to high levels of noise.

Traditional deep learning architectures may fail to model the nonlinear, high-dimensional, and nonstationary complexity of the real world. Hence, it affects the accuracy and the adaptability. Additionally, these models rely on heuristic optimization, have limited applicability, and frequently fail to comprehend intricate temporal, spatial, and spatiotemporal connections [21]. These motivate the exploration of other frameworks, such as the Quantum-Inspired Spatio-Temporal Inference Network (QSTIN) [21]. Additionally, the QSTIN framework combines the Quantum-Inspired Neural Network (QINN) model and Quantum Particle Swarm Optimisation (QPSO). In this extended framework, QINN is used to incorporate complex-valued representations, and QPSO for efficient global optimisation.

This article will review the possibility of applying the QSTIN framework from car-sharing to seismic forecasting. Although the literature on QINNs for direct application to seismology remains scarce, both domains share key characteristics such as sudden spikes, long-term hidden dependencies, and non-linear relationships.

The proposed QSTIN for car-sharing prediction [21] uses rental patterns (temporal), Point of Interest (POI) distribution (spatial), and weather conditions (spatio-temporal). For seismic, the temporal inputs are past earthquake magnitudes (at daily, weekly, and monthly intervals) and event frequency. The spatial inputs are station locations, Network geometry, fault line locations, and historical seismicity density. Then, the spatio-temporal features are ground deformation rates (from GPS), seismic wave velocities, and noise levels from cultural activities and ocean microseisms across the network. These adapted features would serve as inputs to the QINN fusion module. QSTIN's architecture has three key mechanisms as described in the paper [21]. In the proposed QSTIN for car-sharing prediction uses rental patterns (temporal), Point of Interest (POI) distribution (spatial), and weather conditions (spatio-temporal). Meanwhile, for seismic, the temporal inputs are past earthquake magnitudes (at daily, weekly, and monthly intervals) and event frequency. The spatial inputs are station locations, Network geometry, fault line locations, and historical seismicity density. Then, the spatio-temporal features are ground deformation rates (from GPS), seismic wave velocities, and noise levels from cultural activities and ocean microseisms across the network. These adapted features would serve as inputs to the QINN fusion module. Below are the three mechanisms of QSTIN [21].

First, QINN involves the transformation of the real-valued feature set, X_{cocat} into a complex-valued representation

$$X_i = X_{real}^{concat} + i.X_{image}^{concat} \tag{22}$$

where X_{real}^{concat}, enabling to catch spatial, temporal, and spatio-temporal. Then, it utilises the modeReLU activation function,

$$modeReLU\ (z) = ReLU(|z| + b).\frac{z}{|z|}, \tag{23}$$

preserves nonlinear relationship and spatio-temporal inputs, followed by a fully connected dense layer to project the features into a higher-dimensional representation space,

$$z_{out} = w_Q\ .\ modReLU(X_i) + b_Q \tag{24}$$

The next step is the QINN fusion module will convert the complex-valued output Z_{out} into the final prediction. Last, QPSO is selectively used in the final regression layer

$$(x_i(t+1) = p_i \pm \beta.|m_{best} - x_i(t)|.\ln\left(\frac{1}{u}\right)) \quad (25)$$

to avoid the local minima that often trap in traditional optimisation.

This integration of complex-valued feature learning (QSTIN) with QPSO increases the ability to achieve [20] high-level spatio-temporal dependencies while maintaining computational effectiveness. However, the framework is suitable for earthquake forecasting in Indonesian high-noise conditions.

VIII. TRAINING OF WORFORCE FOR IQT

Forbes predicts that there is a risk in leading IQT industries of slowing down the race for an operable full scale quantum computer due to the talent shortage. The IQT industry needs to break the NISQ boundaries and speed for multi-qubit fault-tolerant quantum processors. Currently operating NISQ systems, as well as the future FTQC, will always be embedded in a classical ICT environment. The bigger will be the quantum system, including the computing and networks, the more massive support is required from the classical infrastructure. More precisely, the FTQC infrastructure contains pure quantum, quantum-classical interface and classical ICT.

It seems that the industry is not yet fully prepared for transition to the more extensive quantum level. Market analysts estimate that the gap reaching tens and hundred thousands of quantum engineers could not be filled during the next five years. A lot of technical universities around the globe run quantum classes, but only a few have recently opened dedicated, full size quantum departments/faculties. Simple classes in IQT are not addressing the issue.

A quantum engineer requires training in quantum physics, understand quantum no-go laws, control theory, cryo-technology, microwaves, understanding of various technologies of cubits/qudits, building quantum networks, programming quantum circuits at hardware and upper layers up to logical ones, and many more. This is quite a teaching material for the full size engineering course.

At WUT we begin this path of engineering training at faculties of electronics engineering, telecommunications, technical physics, and ICT. This lecture and publication workshop is an example of a way to familiarize Ph.D. Students with the IQT via asking them what would happen if they are asked to add the IQT layer to the research work they are currently doing for their individual theses.

IX. DISCUSSION, CONCLUSIONS

This article has brought together several representative topics that illustrate the current state and future potential of Quantum Information Technology, spanning foundational theory, enabling infrastructure, learning paradigms, and real-world applications. By combining contributions from multiple authors, the work highlights how quantum concepts increasingly influence diverse areas of science and engineering, while also revealing the practical constraints that currently shape their development.

At the foundational level, studies of quantum nonlocality demonstrate how innovative experimental designs, including large-scale human participation, can strengthen empirical tests of quantum theory. Although certain loopholes and philosophical assumptions remain unavoidable, such experiments represent meaningful progress in validating nonclassical correlations and illustrate the value of interdisciplinary collaboration supported by modern communication technologies.

In precision measurement, quantum-enhanced metrology shows how nonclassical states of light can extend beyond classical performance limits. While highly entangled states such as NOON states offer theoretically optimal precision, their fragility under realistic conditions restricts practical deployment. In contrast, squeezed-light-based techniques already provide measurable improvements using existing technology, making them a realistic near-term solution for high-precision angular calibration.

Quantum computing infrastructure, particularly cloud-based access to quantum processors, emerges as a critical enabler in the NISQ era. Despite ongoing challenges related to hardware noise, limited qubit counts, and ecosystem fragmentation, early standardization efforts and strong open-source communities provide a foundation for interoperability and sustainable progress. Cloud platforms thus play a central role in experimentation, education, and algorithm development while mitigating technological risk.

Advances in quantum neural networks further demonstrate both promise and limitation. At present, only relatively simple models can be implemented effectively on available quantum hardware, while more complex architectures remain beyond practical reach. Hybrid quantum–classical approaches therefore represent a feasible compromise, allowing partial exploitation of quantum resources while remaining compatible with current devices. As quantum hardware matures, such approaches may enable increasingly sophisticated learning models.

The exploration of quantum agents and quantum reinforcement learning highlights particularly strong theoretical potential alongside significant practical constraints. Current quantum hardware remains noisy, limited in scale, and lacking fault tolerance, raising doubts about near-term deployment in realistic project environments. Challenges related to data encoding, empirical validation, and integration into human-centered, iterative Agile processes further emphasize that existing approaches should be regarded as research prototypes rather than deployable solutions. Progress in this area will require benchmarking on realistic datasets, user studies with development teams, improved interpretability, risk assessment under uncertainty, and investigation of quantum-inspired heuristics that may yield partial benefits before fully scalable quantum hardware becomes available.

Finally, quantum-inspired spatio-temporal inference networks illustrate how quantum concepts can already be applied to complex real-world problems such as earthquake forecasting in high-noise environments. By combining complex-valued feature representations with advanced optimization techniques, these models demonstrate improved capacity to capture nonlinear and spatio-temporal dependencies, offering practical advantages even without reliance on fully quantum hardware.

Taken together, the contributions presented in this article show that Quantum Information Technology is best understood not as a single unified solution, but as an evolving ecosystem of theories, methods, and tools. While fully fault-tolerant quantum systems remain a long-term goal, meaningful progress is already being achieved through hybrid, quantum-inspired, and cloud-accessible approaches. Continued advances across hardware, algorithms, and application-driven validation will determine how effectively quantum technologies transition from experimental promise to reliable and impactful tools across scientific and engineering disciplines.

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