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Students review of innovations in quantum technologies, part 8

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***Abstract*—This collective work compiles essays written by graduate students at the Warsaw University of Technology, aiming to bridge the gap between established engineering disciplines, such as Electronics, Telecommunications, and Computer Science—and the emerging field of Quantum Information Technology (QIT). The pedagogical core of this project challenges authors to identify a hypothetical or practical "quantum layer" that could augment their standard Master's thesis topics. This exercise serves to demonstrate that QIT is not merely an abstract physical theory but a versatile toolkit ready for cross-disciplinary application. The current 2025Z edition presents a diverse array of such hybrid concepts, ranging from environmental monitoring in Agriculture 5.0 and novel generative AI architectures, through robust cryptographic defense strategies and room-temperature biomedical sensors, to the fundamental hardware control stacks (Microwaves, ARTIQ/Sinara) required to operate quantum systems.**

***Keywords*—quantum information technology, QIT, teaching of QIT, Ph.D. students view on QIT, QIT implementation in ICT theses, ICT, QIT, Agriculture 5.0, Machine Learning, Quantum Security, OPM, ARTIQ, Sinara, Microwaves, Quantum Sensing**

THE engineering landscape is currently witnessing a paradigm shift, where quantum mechanics is moving from the realm of theoretical physics to practical application. This transition poses a unique challenge for future graduates in Electronics, Telecommunications, and Computer Science. It is no longer sufficient to master classical systems; the ability to integrate quantum components into existing technological frameworks is becoming a critical skill.

The essays presented in this collection (ITK25Z) are the result of a thought experiment conducted by students at the Warsaw University of Technology. The core objective was to identify potential "quantum upgrades" for their standard engineering theses. This approach encourages a pragmatic view of Quantum Information Technologies (QIT), treating them not as isolated phenomena but as modular enhancements to classical systems—whether in signal processing, data security, or control theory.

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This edition showcases a remarkable breadth of applications, demonstrating that QIT is becoming a pervasive technology stack:

- **Precision Agriculture:** Leveraging quantum sensing to achieve unprecedented accuracy in environmental monitoring for Agriculture 5.0.
- **Hybrid AI Architectures:** Enhancing generative models by fusing classical neural networks with quantum circuits, specifically in the context of Normalizing Flows.
- **Next-Generation Security:** Confronting the quantum threat to RSA with a dual strategy of Quantum Key Distribution (QKD) and algorithmic Post-Quantum Cryptography (PQC).
- **Advanced Diagnostics:** Replacing bulky cryogenic systems with room-temperature Optically Pumped Magnetometers (OPMs) for functional cardiac imaging.
- **Control Infrastructure:** Implementing deterministic, nanosecond-precision control for quantum experiments using the open-source ARTIQ and Sinara ecosystems.
- **Microwave Engineering:** Exploring the precise microwave pulse techniques required for high-fidelity qubit manipulation and readout.

Collectively, these works illustrate that the barrier between classical and quantum engineering is blurring. The following sections provide detailed insights into these specific intersections, offering a glimpse into the future of hybrid technological solutions.

I. Quantum Security Systems

A. Introduction

Modern information security is based mainly on classical cryptography. Public-key algorithms such as RSA and elliptic curve cryptography assume that certain mathematical problems are computationally hard. However, quantum algorithms, such as Shor's algorithm, can break these systems in polynomial time [1]. As a result, new security approaches are required. Quantum security systems follow two main directions. The first uses the laws of quantum physics to guarantee security, while the second develops classical algorithms that are resistant to quantum attacks. These approaches are complementary and can be combined in practice.

B. Quantum Key Distribution

Quantum Key Distribution allows two parties to generate a shared secret key using quantum states, typically single photons. The BB84 protocol is the most well-known QKD scheme [2]. Any attempt to intercept the quantum channel introduces detectable errors due to the disturbance caused by quantum measurement. Entanglement-based protocols, such as E91, use correlated measurement outcomes of entangled particles [3]. Security can be verified by observing a violation of a Bell inequality. QKD provides information-theoretic security, but practical systems are limited by transmission distance, key generation rate, and hardware cost [4]. Bell tests are experiments used to distinguish between classical and quantum correlations. They are based on Bell inequalities, which must be satisfied by any local realistic theory [5]. In device-independent QKD, security is guaranteed by the observed violation of a Bell inequality, even if the internal workings of the devices are unknown [6]. This approach provides very strong security guarantees, but requires high detection efficiency and low noise, making it difficult to implement outside laboratory environments.

C. Quantum Random Number Generators

Random numbers are essential for cryptographic systems. Classical random number generators are often pseudo-random and predictable. Quantum Random Number Generators use fundamentally random quantum processes, such as photon detection or quantum phase noise, to produce true randomness [7]. QRNGs can be certified using device-independent or semi-device-independent models. They are already used in high-security applications and can be integrated into hardware security modules and communication devices.

D. Post-Quantum Cryptography

Post-Quantum Cryptography focuses on classical cryptographic algorithms that remain secure against quantum attacks. These algorithms are based on mathematical problems believed to be hard for both classical and quantum computers, such as lattice-based and code-based problems [8]. The National Institute of Standards and Technology (NIST) leads the standardization of PQC algorithms. Schemes such as CRYSTALS-Kyber and CRYSTALS-Dilithium are already being implemented in real-world systems [9].

E. Conclusion

Despite their advantages, quantum security systems face several challenges. QKD systems are vulnerable to implementation attacks, known as quantum hacking, which exploit hardware imperfections [10]. PQC algorithms often require larger keys and higher computational resources. Standardization, interoperability, and cost reduction are important goals for future research. Quantum security systems represent a major shift in information security. By combining quantum physics and advanced cryptographic techniques, they offer protection against future quantum threats. Hybrid systems integrating QKD, QRNG, and PQC are likely to play a key role in future secure communication infrastructures.

II. Quantum Optically Pumped Magnetometry

A. Introduction

The quantitative measurement of weak magnetic fields generated by biological systems—biomagnetism—stands as one of the most sophisticated challenges in modern physics and biomedical engineering. The human body acts as an electrochemical machine; the propagation of action potentials constitutes a net electric current which generates magnetic fields. The cardiac magnetic field (magnetocardiogram or MCG) typically peaks at amplitudes of tens to hundreds of picotesla (10^{-12} T), roughly one million times weaker than the Earth's geomagnetic field ($\sim 50\ \mu$T). For decades, Superconducting Quantum Interference Devices (SQUIDs) were the only sensors capable of femtotesla sensitivity, but their reliance on cryogenic cooling restricted clinical utility. The maturation of Optically Pumped Magnetometers (OPMs), utilizing quantum spin states of alkali metal vapors (e.g., ^{87}Rb), has revolutionized this field, offering SQUID-level sensitivity at room temperature [11], [12].

B. Quantum Mechanics of Alkali Vapor Sensing

The efficacy of OPMs stems from the fundamental properties of atomic structure and angular momentum. Rubidium-87 (^{87}Rb) is the isotope of choice for many commercial magnetometers due to its favorable vapor pressure and optical transitions (D1 line at 795 nm). The magnetic properties arise from the coupling of orbital angular momentum ($\mathbf{L}$), electron spin ($\mathbf{S}$), and nuclear spin ($\mathbf{I}$). In an external magnetic field $\mathbf{B}$, the degeneracy of magnetic sublevels m_F is lifted via the Zeeman Effect. The energy shift ΔE is given by:

$$\Delta E = g_F \mu_B m_F B \tag{1}$$

where g_F is the Landé g-factor, μ_B is the Bohr magneton, and m_F is the magnetic quantum number. Macroscopically, this manifests as the Larmor precession of the atomic magnetic moment $\mathbf{M}$ around $\mathbf{B}$. For ^{87}Rb, measuring the Larmor frequency ω_L allows for precise determination of the magnetic field magnitude [13]:

$$\omega_L = \gamma |\mathbf{B}| \tag{2}$$

where $\gamma \approx 2\pi \cdot 700$ Hz/nT is the gyromagnetic ratio for the rubidium isotope.

C. Optical Pumping Mechanism

Optical pumping forces the atomic ensemble into a specific quantum state with high spin polarization. Using circularly polarized light tuned to the D1 transition, atoms absorb photons and eventually accumulate in a "dark state" where they cannot absorb further light (selection rules $\Delta m_F = \pm 1$). This creates a macroscopic magnetization $\mathbf{M}$ aligned with the light. The dynamics of the atomic polarization $\mathbf{P}$ are described by the Bloch equation, which models the evolution under the influence of the magnetic field, relaxation rates, and optical pumping rate R_{OP}:

$$\frac{d\mathbf{P}}{dt} = \frac{1}{q}(\gamma\mathbf{P} \times \mathbf{B}) + R_{OP}(\mathbf{s} - \mathbf{P}) - R_{rel}\mathbf{P} \tag{3}$$

Here, q is the nuclear slowing down factor (for ^{87}Rb, $q = 6$ at low fields), $\mathbf{s}$ is the photon spin vector, and R_{rel} represents the relaxation rate due to collisions.

D. Relaxation Regimes: SERF vs. Scalar

Sensitivity is fundamentally limited by the transverse spin relaxation rate T_2. At high atomic densities required for high sensitivity, spin-exchange (SE) collisions between alkali atoms usually dominate relaxation, causing decoherence. However, if the SE collision rate R_{SE} is much faster than the Larmor precession frequency:

$$R_{SE} \gg \omega_L \tag{4}$$

the relaxation due to SE collisions is suppressed. This is the Spin-Exchange Relaxation-Free (SERF) regime [14]. In this regime, the atoms effectively maintain the average spin state of the ensemble, narrowing the magnetic resonance linewidth. The fundamental sensitivity limit for a SERF magnetometer is given by:

$$\delta B \approx \frac{1}{\gamma\sqrt{nVT_2}} \tag{5}$$

where n is the atomic density and V is the measurement volume. SERF sensors achieve sensitivities better than 1 fT/$\sqrt{Hz}$ but require near-zero magnetic fields to satisfy the condition $R_{SE} \gg \omega_L$.

Alternatively, sensors like the Twinleaf OMG operate in the Scalar/FID mode for unshielded environments. By using pulsed pumping to achieve high polarization, these sensors can measure the scalar magnitude of Earth's magnetic field with high precision.

E. Engineering Implementation

Recent engineering work has demonstrated the integration of these quantum sensors into parallel acquisition systems. A prototype system described in [15] combines standard Electrocardiography (ECG) with Magnetocardiography (MCG). The setup utilizes an Arduino platform for ECG signal processing and a Twinleaf OMG sensor communicating via digital protocols for magnetic measurements. Synchronization is achieved through software-based interpolation of asynchronous streams. Results indicate that while MCG signals are detectable in subjects with low body fat, the $1/r^3$ fall-off of the magnetic dipole field poses challenges in subjects with higher adipose tissue.

F. Conclusion

The integration of quantum OPMs into biomedical instrumentation marks a shift from cryogenic SQUIDs to practical, room-temperature diagnostics. Future developments in active shielding and sensor arrays will further enhance the clinical viability of magnetocardiography [16]. Hybrid systems combining classical electrophysiology with quantum magnetometry represent a promising direction for advanced cardiac diagnostics.

III. COMPBINING QUANTUM COMPUTING WITH NORMALISING FLOWS

A. Introduction

In this section, we introduce HQCNF, which shows how normalizing flows can be combined with quantum computing.

Generative Machine Learning (ML) models are able to "generate new data", for instance generating images. These models are first fit on large dataset and then can be generate new samples, which are similar to original ones. Generated samples (should) follow the same complex distribution as original ones. There are many different types of generative architectures, like GANs [17], VAEs [18] or Normalizing Flows (NF) [19]. In all of them data is generated in similar way. Firstly a random noise is generated, then a random noise is transformed into actual data. Even though random noise to data transformation is done in completely different way in each architecture, still data is generated by transforming random noise to actual data. Random noise is usually created using very simple distributions, while data usually follows complex hard to analyse distributions.

In NF transformation is done using chain of invertible functions. (see figure 1) In NFs space of orignial data is called "the Data Space", while "space of random noise" is called "the Latent Space". An NF model allows not only to transform a point from the Latent Space to Data Space, but also to transform point from the Data Space to the Latent Space. This allows not only for sampling (data generation) but as well for density estimations, interpolation and augmentation. Details on how NFs are trained are not included in this article, the NICE paper [19] is recommended for details.

Anlei Zhang and Wei Cui, authors of paper *"Hybrid Quantum-Classical Normalizing Flow"* [20] proposed an NF architecture, called HQCNF, which combinine Quantum Computing and classical machine learning, which is outlined in this article.

B. Ammplitude Encoding

To explain idea of HQCNF, it is essentioal to introduce ammplitude encoding [21] first. Suppose $M, N \in \mathbb{N} and N = 2^M$ Amplitude Encoding allows to encode $N-dimensional$ real non-negative vector x on just M quibts, thus using full potential of a quantum computer. To encode vector x, vector x must be normalised. Then each element of vector x is encoded as amplitude of corresponding quantum state. x = $(\text{x}_1, x_2, \ldots, x_N) \in \mathbb{R}^N$

$\sum_i x_i^2 = 1$

$x = x_1 \cdot |00\ldots000> + x_2 \cdot |00\ldots001> + x_N \cdot |11\ldots111>$

Even though desired outcome is quite simple, a curcuit implementing amplitude encoding is quite complex. For the first quibt, calculate the propability that a qubit is zero $(P(q_1 = 0))$ and apply R_Y gate, roating qubit by angle $\theta_1 = 2 \cdot arcos(P(q_1 = 0))$. For every next qubit, for every possible combination of states of previous qubits, calculate the conditional propability that qubit is zero on condition that previous qubits are in that combination of states. Then apply Y rotation gate, with control on previous qubits in that combination of states, with angle θ_i equal to calculated conditional propability.

For example, for 3 quibts and 8-dimensional vector x, steps follow:

- Calculate $p_0 = P(q_1 = 0)$ and apply R_Y gate on qubit 1 with rotation angle $\theta = p_0$
- Calculate $p_0 0 = P(q_2 = 0|q_1 = 0)$ and apply R_Y gate on qubit 2, with control on zero on qubit 1, and rotation angle $\theta = p_0 0$
- Calculate $p_1 0 = P(q_2 = 0|q_1 = 1)$ and apply R_Y gate on qubit 2, with control on one on qubit 1, and rotation angle $\theta = p_0 1$
- Calculate $p_0 00 = P(q_3 = 0|q_1 = 0 q_2 = 0)$ and apply R_Y gate on qubit 3, with control on zero on qubit 1, control on zero on qubit 2, and rotation angle $\theta = p_0 00$
- Calculate $p_0 10 = P(q_1 = 0|q_0 = 0 q_1 = 1)$ and apply R_Y gate on qubit 3, with control on zero on qubit 1, control on one on qubit 2, and rotation angle $\theta = p_0 10$
- Calculate $p_1 00 = P(q_1 = 0|q_0 = 1 q_1 = 0)$ and apply R_Y gate on qubit 3, with control on one on qubit 1, control on zero on qubit 2, and rotation angle $\theta = p_1 00$
- Calculate $p_1 10 = P(q_1 = 0|q_0 = 1 q_1 = 1)$ and apply R_Y gate on qubit 3, with control on one on qubit 1, control on one on qubit 2, and rotation angle $\theta = p_1 10$

On figure 2 there is an exemplary amplitude encoding circuit. Circuits for larger number of qubits are not included, because ot their size and complexity.

C. HQCNF Architecture

There are many types of normalizing flow (NF) architectures, each relying on different invertible transformations. One popular class of such transformations is the coupling layer. A well-known example of a coupling layer is the RealNVP transformation, shown in Equation III-C. In RealNVP, the input vector is split into two subvectors. One subvector is passed through unchanged, while the other is transformed using scale and shift functions. This structure ensures that the overall transformation remains easily invertible.

$$\{ y_{1:d} = x_{1:d}$$
$$y_{d+1:D} = x_{d+1:D} \odot \exp(\mathbf{s}(x_{1:d})) + \mathbf{t}(x_{1:d})$$
$$\{ x_{1:d} = y_{1:d}$$
$$x_{d+1:D} = (y_{d+1:D} - \mathbf{t}(y_{1:d})) \odot \exp(-\mathbf{s}(y_{1:d}))$$

HQCNF developed RealNVP. In HQCF vector is split into 3, not 2, subvectors. Two of subvectors are handled just as in realnvp. The third vector is written to quantum circuit using amplitude encoding. Then, to each qubit R_Y gate is applied. A rotation angle, of Y gates, is output of a neural network (any type), which input is the first vector, which isn't modified. Later controlled not gate are applied. It is shown on figure 3. To invert the operation, it is enough to reverse orded of gates.

In HQCNF, the RealNVP idea is extended by splitting the input vector into three, rather than two, subvectors. Two of these subvectors are processed in the same way as in RealNVP. The third subvector, is written into a quantum circuit using amplitude encoding. Once encoded, an R_Y gate is applied to each qubit, where the rotation angles are generated by a neural network (of any chosen architecture) that takes the unchanged subvector as its input. Afterward, a sequence of controlled-NOT gates is applied, as illustrated in Figure 3. Because all quantum operations used in the layer are unitary, the transformation is invertible; the inverse is obtained simply by applying the quantum gates in reverse order.

D. Conclussion

HQCNF demonstrates how quantum circuits can be integrated into normalizing flows while preserving their essential invertibility. By combining classical neural networks with unitary quantum operations, the model gains access to high-dimensional quantum representations that may capture complex structure more efficiently than purely classical approaches.

IV. Microwaves in Quantum Computing

A. Introduction

Microwaves are an irreplaceable tool in the development of modern quantum information technologies, enabling precise control and readout of the state of qubits, the fundamental units of quantum information. Based on the review in [22], this section focuses on three primary platforms: trapped atomic ion qubits, semiconductor spin qubits, and superconducting qubits.

The physical basis of the light-matter interaction at the quantum level is described by the relation:

$$E = \hbar\omega \tag{6}$$

where the energy of the photon E is linked to its angular frequency ω ($\hbar$ is the reduced Planck's constant, $\hbar = h/2\pi$). This relationship allows for the resonant interaction of microwave photons with the quantum version of computer bits (qubits). A qubit, a quantum mechanical system with two energy eigenstates, $|0\rangle$ and $|1\rangle$, encodes quantum information as a linear combination of these states, called a superposition.

Conceptually, a qubit can be thought of as a nonlinear electromagnetic resonator with a high quality factor, $Q \gg 1$, where the resonant frequency ω_{01} is set by the energy difference $\Delta E = E_1 - E_0$ between the qubit states [22].

B. Physical Realizations and Frequency Ranges

Different physical realizations of qubits use microwaves across various frequency ranges and in different ways:

- **Superconducting Qubits (Transmon):** This type of qubit is a microscopic circuit composed of a Josephson junction (nonlinear inductance, L_J) and a capacitance, C_Q (operating as a nonlinear LC resonator). It encodes information in the energy states of the entire circuit. Control and readout utilize microwaves with a carrier frequency in the range of 4–8 GHz. Short pulses with

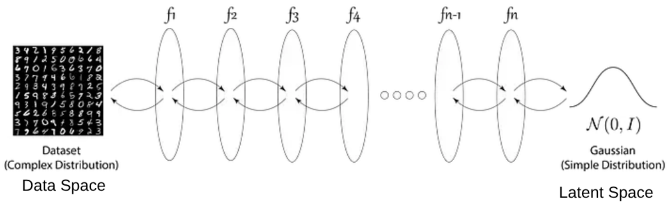


Fig. 1. Wrapped figure

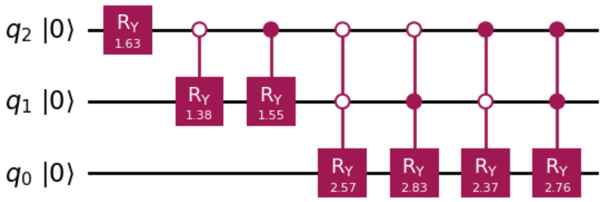
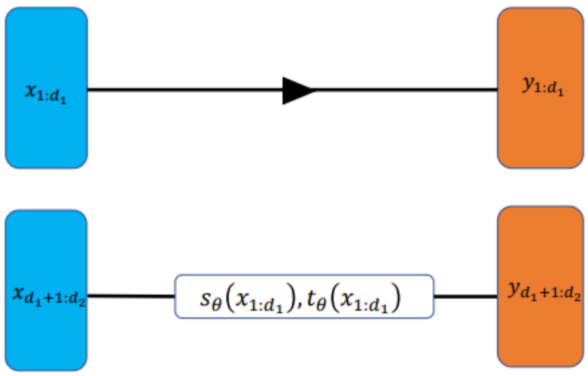


Fig. 2. Wrapped figure



(a) Classical part of the model.

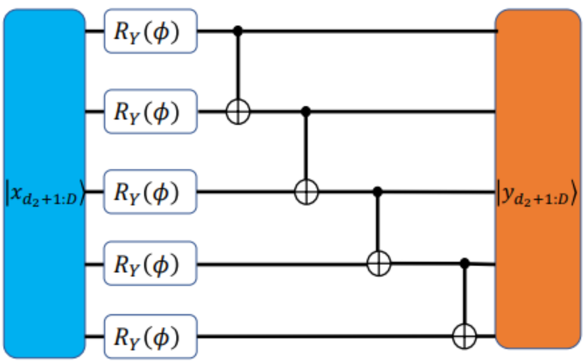


Fig. 3. Wrapped figure

a shaped envelope (e.g., using the DRAG technique) are essential for achieving high-fidelity quantum gates.

- **Semiconductor Spin Qubits:** The quantum information is encoded in the spin of a single electron confined in a nanostructure called a quantum dot. Operation typically requires a strong magnetic field. Carrier frequencies for control span a broad range, typically from 0.1 to 50 GHz.
- **Trapped Ion Qubits:** Here, the information is encoded in the electronic states of the atom, with ions held in a vacuum using electromagnetic fields (Paul trap). They are most often controlled by lasers, but microwave fields can also be used. Carrier frequencies range from 5–20 MHz to 1–12.6 GHz. They are characterized by a very long coherence time.

C. Quantum Gates and Control

The fundamental operation in quantum computation is the single-qubit operation, realized by rotating the state vector on the surface of the Bloch sphere. These operations, called gates, are implemented by applying a resonant microwave field to the qubits.

XY Gates (Rotations in the XY plane) are performed using microwave pulses. Resonant excitation of the qubit leads to Rabi oscillations, which are a cyclic change between $|0\rangle$ and $|1\rangle$. The pulse parameters, such as amplitude, duration, and phase, precisely control the rotation angle and axis, which is crucial for achieving the desired transformation.

The second type of operations are **Z Gates**. These solely affect the qubit phase (ϕ) and rotate the Z plane. They can be realized virtually (by applying a phase jump to the RF carrier for subsequent XY gates) or physically (by detuning the qubit frequency by $\delta\omega_{01}$ for a controlled duration τ) [22].

D. Advanced Pulse Engineering: The DRAG Technique

Classical, short pulses, such as rectangular or pure Gaussian, have a broad spectrum in the frequency domain. For this reason, in addition to exciting the resonant transition $0 \leftrightarrow |1\rangle$, they can undesirably excite higher energy states of the qubit, such as $|2\rangle$, which leads to loss of coherence. To counteract this phenomenon and obtain high-fidelity gates, the Derivative Removal by Adiabatic Gate (DRAG) technique is used [23].

DRAG is a quadrature modulation (I/Q) pulse technique based on the simultaneous transmission of two signals:

1) The **In-phase (I) channel** transmits a fundamental, resonant, Gaussian-shaped pulse, responsible for the main rotation of the qubit in the XY plane.
2) The **Quadrature (Q) channel** transmits a component which is the time derivative of the Gaussian pulse from Channel I, additionally scaled by a factor proportional to the anharmonicity of the qubit.

This additional component corrects undesirable effects resulting from non-zero population annihilation at the end of the pulse, effectively suppressing unwanted transitions to the $|2\rangle$ state. As a result, the DRAG pulse minimizes quantum leakage, allowing gates to be realized with fidelity exceeding 99.9% [23].

E. Dispersive Readout

A direct measurement of the qubit state would destroy the quantum state. For superconducting and spin qubits, a technique called Dispersive Readout is typically used. This involves coupling the qubit to a microwave resonator in the dispersive regime. In this regime, the qubit's state ($|0\rangle$ or $|1\rangle$) causes a slight shift in the resonator's frequency ω_r by an amount 2χ (the dispersive shift). By measuring the reflection coefficient (or transmission) of a probe tone near ω_r, the qubit state can be determined without direct interference [22].

F. Conclusion

Microwaves in quantum technologies represent a rapidly evolving field where progress is mutually driven by the demands of quantum physics and innovations in microwave engineering. The capabilities of using microwaves to perform calculations and read the state of qubit objects are integral to the advancement of platforms like transmons.

V. QID IN AGRICULTURE

Agriculture, a key sector for global food security, has undergone several stages of development over the last decades. It began with Agriculture 1.0 – where work was performed using human muscle power aided by draft animals. This evolution progressed through mechanization and internal combustion engines (Agriculture 2.0), and the 'Green Revolution' driven by genetics and fertilizers (Agriculture 3.0), leading up to the present day. The current state of affairs is referred to as Agriculture 4.0. The use of sensors to monitor crop and livestock conditions is becoming widespread. Agricultural processes are being digitized and automated, and draft animals are being replaced by autonomous or semi-autonomous machines. However, in the face of mounting food pressure driven by constant population growth, as well as ecological pressure resulting from climate change, a concept of future agriculture (termed Agriculture 5.0) is emerging on the scientific horizon, in which quantum technologies are poised to play a pivotal role. Although quantum physics is typically associated with theoretical physicists, its potential applications in agrotechnology appear vast and promising. The hypothetical integration of a quantum layer into current systems could yield benefits unreachable at this scale by any other technology.

One of the most promising innovations is the use of quantum computers to simulate biological processes. Possessing computational power unattainable by classical computers, they enable the analysis of massive datasets and, consequently, the creation of 'digital twins' of entire agricultural ecosystems. This allows for the simulation of weather scenarios and the testing of cultivation strategies in a virtual environment. Moreover, quantum algorithms can support genetic engineering, shortening the time required to identify desired plant traits from years to weeks. An equally significant breakthrough is emerging in the realm of detection. Quantum-enhanced sensors are capable of monitoring soil for moisture, the presence of pathogens, or nitrogen concentration at the atomic level. This allows for a response to changes before they become visible on a macro scale. This very ability to manipulate matter at the nanoscale paves the way for advanced materials capable of directly interacting with plant physiology. [24]

Carbon Quantum Dots (CQDs) occupy a special place in the discussion on quantum technologies in agriculture, constituting a fascinating example of the use of nanotechnology having a direct impact on plants. CQDs are particles with sizes smaller than 10 nm, exhibiting unique fluorescent properties and high biocompatibility. Their mechanism of action is based on the absorption of light from the ultraviolet range and the emission of light from the visible range. This phenomenon results from the quantum size effect. At this scale, a change occurs in the width of the energy gap between ground and excited orbitals, which affects the energy of the emitted photons.This means that the color of the emitted light depends directly on the size of the CQD – the smaller the particle size, the shorter the emitted wavelength. [25] This mechanism is extremely useful in the context of agriculture because UV light is often harmful to plants.CQDs are able to convert harmful radiation into a range useful in the photosynthesis process. The delivery of CQDs to plants can be carried out through seed soaking, root soaking, or foliar spraying. Studies conducted on Rome lettuce showed a biomass increase of 48.09% in plants treated with CQDs compared to the control group. Equally important is the production aspect. CQDs can be synthesized in an eco-friendly manner from agricultural waste, which makes them an attractive alternative to traditional chemical agents. [26]

Despite these promising prospects, significant barriers exist to the large-scale implementation of quantum solutions in agriculture. In the case of CQDs, extensive long-term research regarding the impact of these nanomaterials on soil and food chains is required to rule out potential risks prior to their mass application on crops.

Nevertheless, the integration of quantum physics into agriculture is not merely a theoretical vision but a direction in which science is actively heading. Although many solutions are currently in the experimental phase or early stages of research, their potential to transform the agricultural market is immense. From ultra-efficient simulations and sensors of unprecedented precision to nanomaterials such as CQDs that enhance the photosynthesis process—these technologies bring a new level of quality to agricultural engineering. In the near future, this vision has the potential to become a market standard rather than remaining just an academic curiosity.

VI. ARTIQ AND SINARA SYSTEMS

A. Introduction to Modern Control Challenges

Modern quantum experiments are characterized by high complexity and increasingly demanding control precision requirements. Laboratories utilizing ion traps, controlled atomic systems, or precision optics often need to perform operations with nanosecond precision across dozens or hundreds of independent channels. Conventional laboratory instrumentation typically fails to provide deterministic synchronization of multiple subsystems, hindering scalability and reducing experimental repeatability [27]–[29]. In response, two complementary open-source platforms have been developed: ARTIQ (Advanced Real-Time Infrastructure for Quantum physics) and Sinara, forming a coherent software and hardware stack dedicated to quantum technologies.

B. ARTIQ: Software Architecture for Real-Time Control

ARTIQ is an experiment control system where sequences are defined in Python, enriched with constructs for timing and synchronous operations. The execution model is divided into two distinct layers:

- **Host Layer:** Handles operations without strict time constraints via a remote procedure call (RPC) mechanism, separating experiment logic from real-time execution.
- **Kernel Layer:** Code sections marked with a kernel tag are compiled into a binary format executable directly on an FPGA. This ensures deterministic execution with nanosecond resolution [28].

A key advantage of ARTIQ is the automated management of timing. The system schedules operations to execute at precise moments without requiring the user to manually manage delays or signal propagation times [28].

C. Sinara: Modular Hardware Ecosystem

Sinara represents the hardware component of the ecosystem—a modular set of open-source electronic cards designed for seamless integration with ARTIQ [27]–[29]. Based on the EEM (Eurorack Extension Module) standard, it allows for flexible configuration tailored to specific experimental needs.

The core of the platform is the **Kasli** controller, which houses an FPGA and acts as the central communication and timing distributor [28]. Peripheral modules include:

- **Urukul:** High-speed DDS (Direct Digital Synthesis) generators.
- **Zotino:** Precision DACs (Digital-to-Analog Converters).
- **Sampler:** An 8-channel, 16-bit ADC with a low-noise differential input path and digitally programmable gain. It supports signals ranging from ± 10 mV to ± 10 V, designed to minimize self-interference [27].
- TTL/LVDS controllers and clock distribution modules.

Technical documentation highlights the platform's modularity and ease of reconfiguration for diverse research applications [28], [29].

D. Ecosystem Integration and Scalability

Together, ARTIQ and Sinara form a complete ecosystem designed for deterministic, synchronous, and scalable operation. The DRTIO (Distributed Real-Time Input/Output) protocol enables the distribution of modules over long distances while maintaining stable clock synchronization, supporting systems with hundreds of modules.

The open-source nature of these designs has led to their adoption as standard infrastructure in laboratories worldwide. By replacing custom, ”disposable” control solutions with a standardized stack, researchers can significantly accelerate progress, improve result repeatability, and reduce infrastructure costs.

E. Conclusion

As quantum technologies evolve, the demand for flexible control systems capable of strict timing operations grows. ARTIQ and Sinara meet these requirements, establishing themselves as foundational tools for modern quantum experiments. Their versatility supports advancements in quantum computing, precision metrology, and advanced measurement systems.

VII. Extending fields of QIT applications

What are the main factors influencing the expansion of QIT application areas? Current practical applications of quantum information technologies are determined by the capabilities of available NISQ hardware – noisy intermediate-scale quantum devices.

A. The NISQ Era and Error Resilience

We are currently in a transitional NISQ era, which, at the research and implementation levels, is moving towards computing, generating, and distributing information using quantum error-tolerant methods. This resilience can be of various nature and can be built at the physical, logical, and intermediate levels.

At the physical level, it will involve the selection of robust technologies for the specific application, as well as the topology of qubits and their systems. Unfortunately, such topologies are currently highly redundant. Building error tolerance at the physical level is inevitable. Only with redundant physical resources can quantum error tolerance be further developed at the logical level. Physical redundancy is implemented at the logical level through:

- Prediction and tolerance;
- Symptom detection;
- Code interaction with error classes;
- On-the-fly correction, and more.

The NISQ era deliberately forgoes many of these possibilities, allowing for the technological feasibility of quantum components and their application in test systems and even market applications.

B. Transition to Fault-Tolerant Solutions (FTQC)

The NISQ era paves the way for applications and serves as a sandbox for building a quantum market. Further application development will require abandoning the NISQ concept and moving to fault-tolerant FTQC solutions. Perhaps this will also be an intermediate era toward a full quantum computer that handles inevitable errors in yet another way.

Highly integrated low-photon technologies, as well as some others, already hold some promise in this direction. Photons are less susceptible to quantum errors. Unfortunately, optical components can introduce errors resulting from their thermodynamics, so quantum system solutions are moving toward the photonic version of VLSI. In low-photonic VLSI photonic systems, the influence of thermodynamics and randomness can be minimized.

It is to be remembered that indistinguishability at the quantum level is also a resource. Indistinguishability concerns equally qubits as well as quantum circuit components. Natural qubits are indistinguishable, synthetic qubits are not, like the circuit components. Synthetic qubits require offsets.

C. Application Areas and Resources

The main application areas of quantum information technologies are listed as:

- Computing;
- Network transmission and distribution;
- Sensors and telemetry;
- Synchronization.

Within these broad fields, specific application areas are listed. In the field of computing, these will be completely different applications of gate-based computers, i.e., quantum nondeterministic Turing machines. A quantum Turing machine most closely resembles classical computing systems and most quickly allows for the utilization of significant experience in micro- and nanoelectronics. Other applications are envisaged for adiabatic quantum computers, quantum annealers, and simulators.

D. Advanced Quantum Resources: Contextuality and Qudits

Quantum computing can utilize continuous values of quantum states by using vacuum squeezed states defined by the shape of the Wigner function for calculations. Measuring squeezed states reveals quantum contextuality, a fundamental and rich resource in potential applications. The goal is to master such resources at a technical level. We discuss the fundamental resource position of contextuality in a similar way to entanglement. Both of these resources allow for the full application utilization of the power of multidimensional Hilbert space for mapping multi-parameter classical problems from Euler space.

The qudit, with its multilevel energy and multilateral entanglement, is a natural object of Hilbert space. We know that multiplexing of energy and space domains is possible. An ideal qudit is a photon possessing degrees of freedom in the primary domains of:

- Space (spin, polarization, orbital spin);
- Energy (frequency, envelope).

We are increasingly realizing the application potential of entangled photon qudits through the development of single-photon engineering.

REFERENCES

[1] P. W. Shor, "Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer," *SIAM Journal on Computing*, vol. 26, no. 5, pp. 1484–1509, 1997.

[2] C. H. Bennett and G. Brassard, "Quantum cryptography: Public key distribution and coin tossing," *Proceedings of IEEE International Conference on Computers, Systems and Signal Processing*, pp. 175–179, 1984.

[3] A. K. Ekert, "Quantum cryptography based on bell's theorem," *Physical Review Letters*, vol. 67, no. 6, pp. 661–663, 1991.

[4] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, "Quantum cryptography," *Reviews of Modern Physics*, vol. 74, pp. 145–195, 2002.

[5] J. S. Bell, "On the einstein podolsky rosen paradox," *Physics*, vol. 1, pp. 195–200, 1964.

[6] A. Acín, N. Brunner, N. Gisin, S. Massar, and S. Pironio, "Device-independent security of quantum cryptography against collective attacks," *Physical Review Letters*, vol. 98, p. 230501, 2007.

[7] X. Ma, X. Yuan, Z. Cao, B. Qi, and Z. Zhang, "Quantum random number generation," *npj Quantum Information*, vol. 2, p. 16021, 2016.

[8] D. J. Bernstein, J. Buchmann, and E. Dahmen, "Post-quantum cryptography," *Springer*, 2017.

[9] National Institute of Standards and Technology, "Post-quantum cryptography standardization," 2022. [Online]. Available: https://csrc.nist.gov/projects/post-quantum-cryptography

[10] V. Makarov, "Controlling passively quenched single photon detectors by bright light," *New Journal of Physics*, vol. 11, p. 065003, 2009.

[11] D. Budker and M. Romalis, "Optical magnetometry," *Nature Physics*, vol. 3, no. 4, pp. 227–234, 2007.

[12] S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L.-A. Liew, and J. Moreland, "A microfabricated atomic clock," *Applied Physics Letters*, vol. 85, no. 9, pp. 1460–1462, 2004.

[13] Twinleaf LLC, *OMG: Optical Magnetometer Gradiometer Operation Manual*, Twinleaf LLC, 2024. [Online]. Available: https://twinleaf.com

[14] I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis, "A subfemtotesla multichannel atomic magnetometer," *Nature*, vol. 422, no. 6932, pp. 596–599, 2003.

[15] M. Broczkowski, "System do równoległej akwizycji sygnałów mkg i ekg z wykorzystaniem platformy arduino," 2025.

[16] Y. Yang *et al.*, "A new wearable multichannel magnetocardiogram system with a serf atomic magnetometer array," *Scientific Reports*, vol. 11, p. 5564, 2021.

[17] I. J. Goodfellow, J. Pouget-Abadie, M. Mirza, B. Xu, D. Warde-Farley, S. Ozair, A. Courville, and Y. Bengio, "Generative adversarial networks," 2014. [Online]. Available: https://arxiv.org/abs/1406.2661

[18] D. P. Kingma and M. Welling, "Auto-encoding variational bayes," 2022. [Online]. Available: https://arxiv.org/abs/1312.6114

[19] L. Dinh, D. Krueger, and Y. Bengio, "Nice: Non-linear independent components estimation," 2015. [Online]. Available: https://arxiv.org/abs/1410.8516

[20] A. Zhang and W. Cui, "Hybrid quantum-classical normalizing flow," 2024. [Online]. Available: https://arxiv.org/abs/2405.13808

[21] N. Munikote, "Comparing quantum encoding techniques," 2024. [Online]. Available: https://arxiv.org/abs/2410.09121

[22] J. C. Bardin, D. H. Slichter, and D. J. Reilly, "Microwaves in quantum computing," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 403–427, 2021.

[23] F. Motzoi, J. M. Gambetta, P. Rebentrost, and F. K. Wilhelm, "Simple pulses for elimination of leakage in weakly nonlinear qubits," *Physical Review Letters*, vol. 103, no. 11, p. 110501, 2009, see also arXiv:0901.0534v3.

[24] M. F. Taha, H. Mao, Z. Zhang, G. Elmasry, M. A. Awad, A. Abdalla, S. Mousa, A. E. Elwakeel, and O. Elsherbiny, "Emerging technologies for precision crop management towards agriculture 5.0: A comprehensive overview," *Agriculture*, vol. 15, no. 6, p. 582, 2025.

[25] W. You, W. Zou, S. Jiang, J. Zhang, Y. Ge, G. Lu, D. W. Bahnemann, and J. H. Pan, "Fluorescent carbon quantum dots with controllable physicochemical properties fantastic for emerging applications: A review," *Carbon Neutralization*, vol. 3, no. 2, pp. 245–284, 2024.

[26] T. L. Tan, R. Nulit, M. Jusoh, S. A. Rashid *et al.*, "Recent developments, applications and challenges for carbon quantum dots as a photosynthesis enhancer in agriculture," *RSC Advances*, vol. 13, no. 36, pp. 25 093–25 117, 2023.

[27] G. Kasprowicz, T. Harty, S. Bourdeauducq, R. Jördens, D. Allcock, D. Slichter, D. Nadlinger, J. W. Britton, and A. Sotirova, "Sampler – open-source data acquisition module for quantum physics," *International Journal of Electronics and Telecommunications*, vol. 68, no. 4, pp. 761–766, 2022.

[28] G. Kasprowicz, P. Kulik, M. Gaska, T. Przywozki, K. Poźniak, J. Jarosiński, J. Britton, T. Harty, C. Ballance, W. Zhang, D. Nadlinger, D. Slichter, D. Allcock, S. Bourdeauducq, and R. Jördens, "Artiq and sinara: Open software and hardware stacks for quantum physics," in *Quantum 2.0 Conference*. Optica Publishing Group, 2020, p. QTu8B.14.

[29] G. H. Kasprowicz, D. Allcock, S. Bou Habib, S. Bourdeauducq, J. W. Britton, T. Filipek, M. Gaska *et al.*, "Sinara: open source modular hardware for quantum physics," 2017, poster presentation.