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Students' view of Quantum Information Technologies, part 4

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***Abstract*—Students attending the lecture on quantum information technology are mostly at the level of completing their master's theses in the disciplines of AEEiTK or ITT. The task is to write a short essay by each student on the hypothetical addition of a narrowly applicable QIT layer to the actual implementation of the thesis, if possible. In most cases, this is possible because QITs cover a very wide range of potential technical applications. Where this is not possible, or in the case of an undefined thesis topic, students should write a more general essay or write their personal opinion on what they think about the future of QIT. The current article is another part of a series of works on this topic with subsequent student groups.**

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

I. INTRODUCTION

MASTER'S theses still relatively rarely concern directly technical applications of hardware or software for quantum information technologies. However, this will slowly change, because in many places, including the Warsaw University of Technology, we are building quantum computers. Staff will be needed to build quantum systems in the areas of computing, transmission, metrology, and simulation. Currently, there are very few of these staff. Encouraging students to actively think about what would happen if they had added a practical quantum layer to their currently mandatory research work, partially opens up such staff potential, but at a very early stage. Students can format their essay, even touching on technical dreams. After all, their hard duty is to complete the best possible master's thesis, without which they will not receive a diploma of graduation. If possible, they add a potential quantum layer to such work that is actually being done. Completing such a task requires studying at least several source works on narrow topics closely related to the subject being completed by the individual student. Writing your own essay on adding a quantum layer to your own research work is preceded by a half-hour seminar with a discussion for each student where the theses of such research and technical work are presented. An important part of the seminar is the discussion, because the topics of different theses are quite scattered and include, for example, integrated circuit technologies, electronic and photonic sensors, system software, component simulations, biomedical applications, DNA computing, etc.

II. QIT IN BIG DATA

The advent of quantum technologies has the potential to revolutionize the analysis of vast data sets, commonly referred to as "big data." One area where this is particularly evident is in the context of genetic data. The rapid advancement of sophisticated technologies, including next-generation sequencing (NGS) and whole-genome association studies (GWAS), is resulting in the generation of large quantities of data that can markedly enhance our comprehension of the human genome [1]. Quantum computers, through the utilisation of quantum algorithms (e.g., Grover or optimisation algorithms) that facilitate parallel processing, have the potential to markedly enhance the efficiency of analysing such data.

Grover's algorithm is one of the most frequently referenced quantum algorithms in the context of analysing large data sets. It is particularly useful in searching unstructured data, offering a quadratic improvement in performance over classical methods [2]. In the context of genetic data, which is characterised by a vast number of records and high complexity, Grover's algorithm could prove invaluable in rapidly identifying specific patterns or genetic mutations in datasets, obviating the necessity for prior organisation into structured formats for efficient searching. Nevertheless, implementing this algorithm in a practical setting is not straightforward, even when considering the necessity for a sophisticated quantum computer. One of the primary challenges is the loading of data into the quantum computing memory. Genetic data, which is often stored in tabular or sequential form, must be transformed so that it can be represented as qubits [2] and then loaded into the quantum register. This process requires a significant amount of resources, particularly a large number of qubits and low noise in the quantum system. It is essential that this process is carried out efficiently to ensure that the additional overhead of converting and loading the data does not negate the benefits of the quantum algorithm usage.

A significant constraint on the application of quantum technologies in Big Data analysis is the current stage of their development. The present generation of quantum devices are

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predominantly prototypes, exhibiting a restricted number of qubits and substantial decoherence issues (for further details, please refer to Chapter XI). Furthermore, contemporary classical algorithms, despite not always being optimal, frequently employ partitioning and optimisation techniques that enable them to operate effectively with large data sets. To illustrate, relational databases employ tree indexes, enabling the searching of records in logarithmic time. However, rebuilding is required when editing or inserting new data, which impacts performance. Using Grover's algorithm, data could be stored in an unstructured manner with no loss of performance. Nevertheless, in view of the previously mentioned practical implementation issues and the limitations of the Grover algorithm, it is reasonable to question the rationale and benefits of its use, which should be the subject of future research.

The introduction of quantum computers also raises significant data security concerns. Modern encryption algorithms, such as RSA, rely on the complexity of the natural logarithm problem, or the decomposition of large numbers into prime factors. This is a problem that is effectively unsolvable using classical computational methods. The most effective heuristic algorithm currently known to solve this problem is the General Number Body Sieve (GNFS) [3], which is capable of solving it in time $e^{c+o(1)\cdot(\log n)^{\frac{1}{3}}\cdot(\log\log n)^{\frac{2}{3}}}$ (still exponential). However, Shor's algorithm [4], when run on a quantum computer, makes it possible to solve this problem in a polynomial time, which will make current asymmetric encryption standards obsolete. In the context of genetic data, which is particularly sensitive and requires a high level of privacy protection, it is necessary to develop and implement new encryption methods resistant to quantum computer attacks (post-quantum cryptography).

Quantum technologies have the potential to transform the way data is processed and analyzed. However, this presents a number of significant technological and theoretical challenges. From data conversion issues to limitations on the number of qubits, through security concerns to the necessity of developing new algorithms and cryptographic standards, the future of these technologies requires further research. Nevertheless, quantum computers have the potential to become an invaluable tool in the field of Big Data, offering breakthrough capabilities in genetic data analysis and beyond.

III. QUANTUM SENSING

Quantum sening is an area of dynamic development of quantum technologies, characterized by great diversity and a wide range of applications. Progress in this field might have a significant impact on improving the quality of life for society.

Quantum sensors, unlike sensors in use today, base their operation on the principles of quantum physics, and thus rely on the properties of qubits. In particular, three of them are used: superposition, entanglement and coherence. Superposition means that a qubit is any superposition of two quantum states: $|0>$ and $|1>$. In sensors, this property can be used to study a given physical quantity simultaneously over multiple ranges of its variation. Entanglement of qubits relies on the fact that the state of one qubit affects the state of another, regardless of the distance between them. This has a major impact on improving measurement accuracy and reducing noise. Coherence refers to the ability of maintaining superposition and entanglement over time, which is important for the precision of the measurements. As a result, the use of quantum sensors, in which quantum states and their evolutions are subjected to external forces, offers the possibility of obtaining results that are often many orders of magnitude more accurate than when making classical measurements. In reference to these properties, quantum sensors are being constructed based on atomic pairs, cold atoms and doping of materials, among others. As a result, more and more measuring devices are being created: modern magnetometers, gravimeters, clocks and quantum thermometers. Quantum technology has also found applications in imaging, medical development and IoT. The following focuses on two areas: magnetic field sensors and gravitational field sensors.

The development of high-precision quantum sensors for measuring magnetic fields is based on *NV center* technology, which comes from the occurrence of small defects in diamond, resulting in the formation of electron spins. A spin is a specific internal magnetic moment.

Diamond consists of a network of carbon atoms. In the process of making an artificial version of the mineral, successive layers of the element are deposited on top of each other. If, during this process, two atoms were removed and one was replaced by nitrogen and the other was left empty, a colored NV (nitrogen-vacancy) center with a non-zero spin S = 1 would then be formed. Such center is capable of absorbing and emitting light.

The principle of NV technology is optical excitation by irradiating the center with a 532 nm laser (green color). Then a pair of atoms is precipitated from the neutral state (m_s = 0) and goes to one of two states (m_s = ±1): *spin up* or *spin down*. This is the triplet state in which the electrons are not paired. When returning to the neutral state, a photon is emitted, resulting in the release of radiation of 600-800 nm (red light). Microwave radiation (f = 2.87 GHz) is used to affect the particle. As a result, a resonance is created, the occurrence of which is evidenced by a decrease in fluorescence intensity caused by exposure to the center. The ability to detect the resonance optically is a property of NV centers that makes it possible to use them as magnetic field measuring elements. When an external magnetic field is applied to the center along the center's axis, the states are split according to the Zeeman effect. Then it possible to observe two pairs of independent transitions induced by a resonant microwave field: m_s = 0 $\rightarrow$ m_s = -1 and m_s =0 $\rightarrow$ m_s = +1. The variation of energy levels, translates into different excitation frequencies. Their difference is directly proportional to the applied magnetic field.

The main advantages of measurements using nitrogen-vacancy centers are that they are feasible on the nanometer scale and can be performed at room temperature. As a result, more and more applications are being found for this technology. One example is the highly sensitive magnetometer, a device used to measure the magnitude, direction and change of a magnetic field. Its use of the electron spin makes it sensitive to even the smallest changes in the measured value. Such property can be used for precise navigation. The measurement from the magnetometer compared with a detailed map of the Earth's magnetic field would allow the exact location to be determined. Thus, it could be an extension or replacement for a satellite navigation system (GNSS) [5]. It would have a major impact on determining location in environments inaccessible to satellite localization, such as underwater. In addition, the operation of such a magnetometer would not be affected by any interference.

NV center-based quantum sensors would also find applications in medicine, including monitoring the brain and heart, where any change in their activity would be recorded. This would mean a much more accurate medical apparatus in MRI examinations, and would also result in a reduction in its size, which could translate into its greater availability in medical facilities, as well as a reduction in stress during the examination. This would be especially important for young patients.

The second rapidly developing group of quantum sensors are gravitational field sensors - quantum gravimeters. They use the phenomenon of cold atoms interferometry and Raman scattering to determine absolute acceleration values.

In the center of the gravimeter a chamber is placed, in which a cloud of rubidium (87Rb) atoms with a diameter of 1 mm and a temperature of about 1 μK is trapped. This is equivalent to the so-called test mass used in mechanical absolute gravimeters, based on the principle of free fall. To determine the gravitational acceleration first, the kinetic energy of the atoms, and thus their temperature, must be reduced. Lasers are used for this purpose. This will give the atoms a wave-like character and make it easier to observe their state. The next step involves the free fall of the molecules, during which they are subjected to three pulses, inflicted at equal intervals. The first one breaks the atoms into two groups with different states. Halfway through the fall, another pulse hits, so that the molecules recombine and change to the opposite state. The third pulse causes the atoms to recombine, i.e. an atomic interferometer is formed. The observed relative population of occurrences of each momentum state is directly dependent on the local gravitational acceleration.

The advantage of a quantum gravimeter over a classical one is that it has no mechanical parts subject to damage and wear, so it can work in very long measurement sessions - almost continuously (about 4 million falls are possible in a month, where for a mechanical gravimeter there are about 1 million over the course of 3-4 years [6]). In addition, it has a higher sampling rate, which improves the quality of the measurement. Thanks to the high sensitivity of the sensor, even small changes in the gravitational field can be registered. These changes can result from the presence of various geological structures below the earth's surface. Therefore, gravimeters would find use in archaeological surveys and in the search for mineral or water deposits. This is very important, especially in an era of climate change, where access to potable water is steadily diminishing. The quantum gravimeter could also be used to explore other planets, in order to search for water and other usable raw materials, so that perhaps they could be inhabited in the future.

Quantum sensors are an extremely interesting and future-oriented direction of technology development. The World Economic Forum is also paying attention to it. In *The 2030 Agenda for Sustainable Development*, a strategy for the development of the world by 2030, it recognizes quantum sensing, quantum computing and quantum communication as areas of particular importance for improving the quality of life of society, with quantum sensing currently being the fastest growing area. The report focuses primarily on the use of quantum sensors in medicine, particularly for faster and more efficient diagnosis of heart disease - one of the most common causes of death.

Despite the enthusiasm, the full use of quantum sensors is still unreachable. Although, thanks to the properties of qubits, the sensors developed from them could truly revolutionize the space we live in, their full-scale introduction is still to be seen. In its report, the WEF estimates that the introduction of quantum sensors is still several years away. The main obstacles to the development of quantum sensors are the still small, though thriving, technical base. In the construction of the measuring devices themselves, the difficulty lies in maintaining the state of the particles (coherence) and maximally limiting the effects of external forces other than those being measured. Another major impediment is the large amount of money required to develop the technology. Investing in it is still subject to certain risks and uncertainties, which discourages potential investors, especially since quantum sensors are expected to compete with sensors used today, which are also constantly being upgraded.

IV. QIT VIRTUAL REALITY

Gait analysis is an interdisciplinary research method that enables a detailed understanding of the dynamics of human limb movement. Through this analysis, it is possible to evaluate key parameters such as joint angles, speed, stride length, and limb movement synchronization. These data are invaluable for diagnosing movement disorders, monitoring therapy progress, and designing rehabilitative assistive devices. Gait analysis is widely applied in medicine, rehabilitation, sports, and ergonomics, and its importance grows alongside technological advancements. One of the critical applications of gait analysis is the identification of cerebral palsy (CP) in children. This condition often manifests as abnormal movement patterns that are challenging to detect in the early stages. Early diagnosis, however, is crucial for implementing effective therapies, making the development of advanced technologies for gait analysis particularly significant.

Human gait consists of cycles, which encompass repetitive sequences of limb movements. A gait cycle begins with the heel lifting off the ground and continues until it makes contact with the ground again. It is divided into the stance phase (approximately 60% of the cycle) and the swing phase (approximately 40%). The stance phase includes periods when the foot maintains contact with the ground and can be further subdivided into single and double support phases. The swing phase starts when the toes leave the ground and is composed of subphases such as toe-off, mid-swing, and heel strike. Analyzing these phases and their synchronization provides crucial insights into movement coordination and body dynamics [7].

Depth sensors, such as Microsoft Kinect, offer new possibilities for gait assessment due to their ability to track movement in three dimensions. These devices identify 25 characteristic points on the human body, including joints and limb centers, allowing the estimation of parameters such as joint angles, stride lengths, and movement symmetry. The main advantages of using depth sensors include accessibility, as their low cost and ease of use make the technology available to many medical and research centers. These systems are also non-invasive, requiring no markers to be placed on the body, thereby increasing patient comfort. Furthermore, their portability allows gait analysis to be performed in natural environments. However, limitations arise from measurement uncertainties in estimating characteristic points and difficulties in analyzing more complex movement patterns. Nevertheless, depth sensors represent a promising tool, particularly in the context of diagnosing CP. The ability to analyze subtle movement irregularities in children facilitates early therapeutic interventions.

Quantum virtual space (Quantum Enhanced Virtual Reality, QEVR) represents a breakthrough in gait analysis. By leveraging quantum mechanics, these systems provide the ability to create hyper-realistic simulations that track movements with unprecedented accuracy. The capacity for dynamic environmental adaptation and integration with artificial intelligence algorithms makes QEVR an extremely versatile analytical tool. The key advantages of QEVR include precise CP diagnosis, as the system tracks multiple motion markers and analyzes trajectories in real time, enabling the detection of subtle gait anomalies. The technology also allows for the creation of individualized rehabilitation models tailored to the patient's needs, with progress evaluated in dynamic environments. Furthermore, QEVR opens new possibilities, such as immersive therapies and advanced medical training simulations [8].

Despite its potential, this method also has limitations. The high production and maintenance costs of quantum computers and the need for extreme conditions (e.g., cryogenic cooling) mean the technology is not yet widely available. Additionally, quantum decoherence can affect the accuracy of analyses, posing technological challenges. When comparing depth sensors and quantum virtual space, depth sensors stand out for their affordability, ease of use, and mobility. However, their limited precision and susceptibility to errors in analyzing complex movements are notable drawbacks. Conversely, QEVR offers unparalleled accuracy, dynamic adaptability, and seamless AI integration but comes with high costs and specialized technological requirements.

Integrating gait analysis with advanced technologies such as artificial intelligence and quantum computing signals a future where movement diagnostics and therapy are more personalized and efficient. The development of cheaper and more compact quantum computers could make QEVR accessible to medical centers worldwide. In summary, while gait analysis using depth sensors is already in use and offers many benefits, quantum virtual space has the potential to revolutionize the field by providing unmatched precision and new therapeutic opportunities. However, bringing these technologies into widespread use will require further research and investments in infrastructure.

V. QIT IN HEART DISEASES DIAGNOSING

Heart diseases are among the most significant challenges in modern medicine, responsible for millions of deaths annually [9]. Major conditions include arrhythmias, heart failure, and myocardial infarctions. Effective diagnosis of these diseases requires the analysis of vast amounts of data, such as ECG signals, diagnostic imaging results, and genetic data. Traditional computational systems often struggle to process such data efficiently, limiting the potential for timely and accurate diagnosis. Quantum technologies, leveraging the principles of superposition and entanglement, offer new possibilities for cardiological diagnostics. Quantum computers can simultaneously analyze multidimensional data, accelerating diagnostic processes while enabling more precise forecasting and personalized therapy. This paper explores how these technologies can support ECG signal analysis, cardiac imaging, and treatment personalization.

The electrocardiogram (ECG) is a fundamental diagnostic tool in cardiology, used to detect heart rhythm disorders, ischemia, and other abnormalities. Holter monitoring, which records ECG signals over 24 hours, generates vast amounts of data requiring rapid analysis. Classical computational systems process this data sequentially, which can be time-consuming [10]. Quantum computers, through superposition, can analyze many hours of recordings simultaneously, significantly speeding up the detection of subtle abnormalities, such as atrial fibrillation or ventricular tachycardias. Furthermore, quantum entanglement facilitates the analysis of interdependencies between parameters such as heart rate variability, blood oxygen levels, and blood pressure, enabling comprehensive risk prediction for heart attacks. A practical application is the early detection of ischemia in diabetic patients, who may exhibit atypical symptoms. Quantum computers can run diagnostic simulations that help physicians make faster therapeutic decisions.

Cardiac imaging, such as magnetic resonance imaging (MRI) and echocardiography, plays a crucial role in diagnosing cardiovascular diseases. Quantum technology can accelerate the processing and analysis of diagnostic images, enhancing the effectiveness of detecting pathological changes. Quantum algorithms are particularly useful for analyzing MRI images, where they can identify subtle changes in cardiac structures, such as atherosclerotic plaques in coronary arteries. Additionally, this technology enables real-time modeling of blood flow in coronary vessels, allowing physicians to better plan procedures such as angioplasty and reduce the risk of complications. Moreover, quantum neural networks can support the segmentation and classification of diagnostic images, which is essential for monitoring the progression of heart diseases. These algorithms allow for quicker and more accurate assessments of disease severity.

Personalized therapy is one of the most critical directions in modern medicine. Quantum technologies can assist in selecting the most effective treatments for patients based on their unique biomedical and genetic data. For example, quantum computing can predict patient responses to various anticoagulants, minimizing side effects and improving treatment efficacy. In patients with heart failure, quantum technologies can aid decisions regarding the implantation of devices such as cardioverter-defibrillators. Predictions based on patient data help physicians better assess the risk of dangerous arrhythmias and tailor medical interventions to individual needs [11].

Quantum technologies can support not only diagnostics and treatment but also the rehabilitation of cardiac patients. For example, quantum algorithms can analyze data from monitoring devices, such as smartwatches, that track heart rate and physical activity levels. Based on this data, rehabilitation programs can be adjusted in real-time [12]. Additionally, quantum modeling can evaluate the effectiveness of exercises and pharmacotherapy in improving heart function after a heart attack. This approach enables physicians to better monitor patient health and respond quickly to potential issues.

Despite the immense potential of quantum technologies, their development faces significant challenges. The instability of qubits (decoherence) limits the accuracy and duration of computations, and the high costs of building and maintaining quantum computers make their clinical implementation difficult. However, advancements in stabilizing qubits and developing advanced computational algorithms could significantly increase the accessibility of these technologies in the coming years. With appropriate investments and interdisciplinary collaboration, quantum technologies have the potential to revolutionize the diagnosis and treatment of heart diseases.

VI. QUANTUM TUNNELING EFFECT

Quantum tunnelling is one of the fundamental phenomena of quantum mechanics, with no analogue in classical physics. It is a process in which quantum particles, such as electrons or protons, can penetrate through a potential barrier, even when their kinetic energy is less than the energy required to surmount the barrier according to classical physics. This phenomenon arises from the wave-like nature of particles. It is described by the wave function, whose amplitude does not immediately drop to zero upon encountering a potential barrier. Instead, the wave function exhibits a gradual decrease within the barrier, leading to a finite probability of the particle being found on the other side. The likelihood of tunnelling is closely related to the width and height of the barrier, as well as the mass of the particle.

The first theoretical description of quantum tunnelling was developed in the 1920s by George Gamow, who applied it to explain the phenomenon of alpha decay in nuclear physics. This mechanism allows alpha particles to escape atomic nuclei despite their kinetic energy being insufficient to overcome the Coulomb potential barrier. The observation of this effect was one of the key confirmations of quantum mechanics as a valid theory for describing the micro-world. Quantum tunnelling is intimately linked with Schrödinger's equation, which forms the foundation of quantum mechanics. This equation describes how the wave function of a particle evolves in time and space, allowing predictions of the probabilities of various quantum states. In the context of tunnelling, the particle's wave function does not drop to zero immediately at the boundary of the potential barrier but decreases gradually within it [13]. This mathematical behavior of the wave function is critical to understanding why tunnelling occurs. For a particle with a specific energy moving in a potential field, Schrödinger's equation predicts that there is a region where the wave function is nonzero, even though the particle's energy is less than the height of the barrier. Physically, this means that the particle has a nonzero probability of being found on the other side of the barrier. This phenomenon stems from the quantum nature of particles, which differs fundamentally from classical intuitions about the motion of macroscopic objects.

Experimental investigations of quantum tunnelling began in the 1930s, when its crucial role in atomic nucleus decay was observed. A breakthrough came with the application of quantum tunnelling to explain the emission of alpha particles in Gamow's model. Subsequent research expanded the understanding of tunnelling, especially in the contexts of semiconductors and nanotechnology. In the 1960s, the Josephson effect was discovered, demonstrating the tunnelling of Cooper pairs through a thin insulating layer between two superconductors. This phenomenon has found applications in devices such as SQUIDs (Superconducting Quantum Interference Devices), which are used for precise magnetic field measurements. One of the most significant experimental tools for studying tunnelling is the scanning tunnelling microscope (STM), invented in 1981 by Gerd Binnig and Heinrich Rohrer. The STM enables surface mapping with atomic-scale resolution, which is crucial in nanomaterial research. The tunnelling current measured between the microscope tip and the sample allows for the reconstruction of surface topography [14]. Quantum tunnelling also plays a pivotal role in semiconductor physics, enabling current flow through thin material layers, such as in metal-insulator-metal (MIM) junctions and tunnelling field-effect transistors (TFETs). In biological contexts, tunnelling of protons and electrons explains transport mechanisms in enzymatic systems and cell membranes.

Quantum tunnelling underpins the operation of many electronic devices. One of the most well-known examples is the tunnel diode, which exploits electron tunnelling through a thin potential barrier. In tunnel diodes, current can flow even at very low voltages, distinguishing them from traditional diodes. A key element of their construction is the highly doped p-n junction, which reduces the width of the potential barrier. At low voltages, electrons from the valence band of the p-type region can tunnel directly to the conduction band of the n-type region, resulting in a sharp increase in current. As the voltage increases, the tunnelling probability decreases, leading to the phenomenon of negative differential resistance. Tunnel diodes are used in oscillatory circuits, where their rapid response to voltage changes enables the generation of signals at gigahertz frequencies.

Tunnelling transistors (TFETs) also leverage the tunnelling phenomenon. In these devices, the tunnelling barrier replaces the traditional junction in MOSFETs. Tunnelling occurs between the source and the drain, allowing current to flow at very low gate voltages. As a result, tunnel transistors consume significantly less energy, making them an ideal solution for energy-efficient integrated circuits and IoT technologies.

In chemistry and biology, electron and proton tunnelling aids in understanding catalytic and biochemical processes. Enzymatic reactions often involve proton transfer through energy barriers, which can be explained by tunnelling mechanisms. A notable example is the reactions in the mitochondrial electron transport chain, where proton tunnelling plays a critical role in electron transport and energy production in the form of ATP.

Research on quantum tunnelling opens new perspectives in nanotechnology and solid-state physics. One key direction is the development of precise molecular sensors that utilize changes in tunnelling current to detect individual molecules. Such sensors have applications in chemical analysis, medical diagnostics, and environmental monitoring. In quantum computing, tunnelling plays an important role in error correction and qubit stabilization processes. In systems like superconducting quantum circuits, tunnelling enables controlled transitions of qubits between different energy states. Studies of this phenomenon may enhance the reliability and scalability of quantum computers.

In quantum biology, proton and electron tunnelling is crucial for understanding transport mechanisms in cell membranes. Research in this area could lead to the design of new drugs and biomimetic materials. Another promising avenue is the use of advanced computational simulation methods to study tunnelling processes in complex systems. Quantum algorithms enable real-time modelling of tunnelling, which is highly significant in quantum chemistry and materials science. Examples include simulations of catalytic reactions that account for hydrogen atom tunnelling through energy barriers.

VII. QIT IN TIME MEASUREMENT

Time is one of the most fundamental and mysterious phenomena of our world. Measuring time, which may seem like a simple task, is actually one of the most challenging fields of science, deeply tied to the laws of physics. Modern achievements in this field are based on quantum mechanics, the general theory of relativity, and the latest technologies. Let's delve into how atomic clocks work, why time flows differently in various locations, and how these discoveries impact science and everyday life. The history of time measurement began with primitive sundials, but a major breakthrough came with the invention of mechanical devices using pendulums. However, they were not accurate enough, especially for navigation, where determining longitude was crucial. This spurred the development of chronometers resistant to external influences. The true revolution occurred with the invention of atomic clocks. Their foundation lies in using the oscillation of particles in atoms to establish a stable frequency.

Unlike mechanical pendulums, atoms provide an extraordinary level of precision in measuring time, unaffected by temperature, humidity, or other factors. Atomic clocks use the phenomenon of electrons transitioning between energy levels within an atom. For example, in cesium-based atomic clocks, 9,192,631,770 oscillations are registered in one second, defining the length of a second in the international system of units [15]. The operation of atomic clocks is closely linked to quantum mechanics. Electrons in atoms occupy specific energy levels, and transitions between these levels occur at precisely defined frequencies, which serve as a standard. This frequency is measured using microwave radiation that excites the electrons. If the radiation frequency matches the transition frequency, the electron absorbs energy. Atomic clocks feature a closed-loop system for frequency regulation. A special generator emits microwaves, and the frequency of this radiation is compared with the resonance frequency of the atom. If discrepancies arise, an error signal is sent back to the generator, which adjusts its settings. This allows the device to maintain precision with an error margin of less than 10^-13 [15].

In the past, it was believed that time was an absolute quantity, flowing uniformly for everyone. However, Albert Einstein's theory of relativity proved otherwise. Gravity and motion affect the passage of time. On the Earth's surface, time flows differently depending on altitude and the strength of the gravitational field. The farther from the center of gravity, the faster time flows. This effect has been tested and confirmed experimentally. In Japan, atomic clocks were placed at different levels of the Tokyo Skytree: on the ground and at a height of 450 meters. The results showed that time indeed flows faster at higher altitudes, in accordance with the predictions of the theory of relativity.

Another significant aspect is the Earth's rotational motion. It is irregular and constantly changing, causing discrepancies between atomic time and astronomical time. To compensate for these differences, Coordinated Universal Time (UTC) is used. It combines atomic and astronomical time and is adjusted by adding or subtracting leap seconds. High-precision clocks are crucial in science and technology.

Navigation systems, such as GPS, rely on time synchronization between satellites and ground stations. Even the slightest error in time calculations can lead to significant deviations in determining locations [16]. Furthermore, time measurement allows for the creation of gravitational field maps of the Earth.

Differences in the rate of time flow between two points are used to identify gravitational anomalies, aiding geology, resource exploration, and the study of tectonic plate movements. Ultra-precise atomic clocks have shown that time is not an absolute concept. It depends on gravity, speed, and even position relative to sea level. These discoveries are transforming not only science but also our perception of reality. Modern technologies, such as atomic clocks, have ushered in a new era in understanding time. They are not only a benchmark of precision but also a tool for testing the fundamental laws of physics. Measuring time has become not just a part of science but a key to understanding the structure of the universe. These clocks have become not only practical tools but also symbols of scientific progress, demonstrating how far humanity has come in understanding the world around us.

VIII. QIT IN ENVIRONMENTAL CONTROL

Quantum sensors, quantum cryptography, and the Quantum Smart Grid are the cornerstones of a technological revolution in the Internet of Things (IoT), referred to as Quantum IoT (QIoT). Technological innovations based on quantum mechanics are bringing new possibilities to home automation, offering remarkable measurement precision, unprecedented data transmission security and more efficient energy management.

Quantum sensors take advantage of quantum mechanics phenomena such as superposition, entanglement, and tunneling to achieve measurement precision unavailable to classical technologies. Thanks to these properties, they are revolutionizing home automation, finding applications in areas such as HVAC (heating, ventilation, air conditioning) systems, where they enable precise regulation of temperature and humidity, improving user comfort while optimizing energy consumption. Magnetic quantum sensors track current flow in real time, identifying energy losses and detecting anomalies in home electrical networks. Gravity sensors, on the other hand, monitor the condition of buildings, allowing for early detection of minor structural changes and preventing potential structural disasters.

One of the key elements of QIoT is quantum cryptography, which offers an unprecedented level of security in data transmission. Using the phenomena of quantum entanglement and photon polarization, it enables the creation and transmission of cryptographic keys in a way that resists interception attempts. This technology, based on the quantum key distribution (QKD), eliminates the risk of eavesdropping, as any attempted interference changes the state of transmission, which automatically alerts the system. This is particularly important in systems such as smart locks, monitoring, or alarms, where user security is a priority. In addition, quantum cryptography provides effective protection against future threats, such as quantum computers that can break classical encryption methods. [17].

Quantum Smart Grid, as another key component of QIoT, enables precise management of energy flow in home energy networks. These grids integrate quantum sensors and QKD technologies, enabling the efficient use of renewable energy sources such as solar panels and wind turbines. With advanced energy management systems, it is possible to optimally integrate them into the home's infrastructure, improving efficiency, and reducing the risk of overloads. Quantum Smart Grid also minimizes the risk of failures through the early detection of problems such as overloads or energy losses. All data transmitted on these networks are protected by QKD, providing the highest level of security to both users and energy providers [18].

Despite the huge potential of QIoT, the implementation of this technology faces numerous challenges. High infrastructure costs, the need to work in controlled environments, and the difficulty of integrating with existing classic IoT systems are significant barriers. Developing efficient quantum gateways for data conversion between classical and quantum systems remains a key problem. However, experts predict that in the coming decades, technological advances and gradual cost reductions will accelerate the adoption of QIoT, making it a standard in home automation.

IX. ALD TECHNOLOGY

Quantum technologies have become a key part of science and industry over the years, driving the technological momentum. Fields of science such as quantum computers, sensors and quantum communication currently require high precision in the manufacture of each element of the device, in particular the production of their ultra-thin layers. The technology enabling the deposition of such layers is Atomic Layer Deposition (ALD). The high precision and ability to control the sputtering of layers at the atomic level plays a significant role in the creation of advanced material layers used in all kinds of advanced quantum devices.

Atomic Layer Deposition is an advanced chemical process that allows for the deposition of thin, uniform layers of materials with significant control. The process consists of stages in repeated cycles, through the alternating of pumping in and pumping out of precursors. Properly selected precursors can only combine with the substrate or with the atomic layer of a previously introduced precursor, but atoms of the same precursor cannot overlap [19]. This provides us with layer growth at the atomic level.

High precision in controlling the thickness of the sputtered layer is not the only advantage of the ALD technology, which also allows the deposition of layers on surfaces with complex geometries, such as nanostructures and on three-dimensional surfaces. The ability to use various precursors allows technologists to create complex material layers such as oxides, nitrides and sulfides.

Due to its significant advantages, the ALD process has found wide application in quantum technologies. The first of such fields are quantum computers for which superconducting qubits of high purity and stability are produced. ALD allows the creation of ultrathin layers of oxides or superconductors such as NbN or Al_2O_3, which are used as tunnel barriers or insulating layers. For qubits based on ion trapping, it is crucial to produce electrodes with high surface smoothness and high-class material stability. The use of ALD allows the application of such metallization layers, increasing the reliability of the device.

ALD technology is also used in devices based on Quantum Dots [20]. Thanks to the ALD process, it is possible to deposit protective coatings on the surface of Quantum Dots to protect them against oxidation and degradation. Due to the high precision of ALD, it is possible to add nanometer structures to Quantum Dots in order to change their size, composition, but also physical properties, affecting their energy bands. Another application of ALD in the production of Quantum Dot-based devices is the creation of core-shell structures such as CdSe/ZnS, significantly improving the yield and efficiency of the devices. Currently, in order to produce devices such as QLED (Quantum Dot LED) displays, solar cells or quantum sensors, it is necessary to use ALD technology [21].

A big challenge is the integration of quantum devices with classical electronics. The use of ALD enables this process by producing thin insulating layers and connections that enable the integration of systems and their miniaturization.

In conclusion, ALD technology is crucial in the development of quantum technologies. High precision and repeatability allow the production of quantum devices with high reliability and stability, such as quantum computers, quantum optics systems and devices using quantum dots. Observing technological trends, it can be noticed that manufacturers of quantum devices such as Google, IBM and Intel are investing heavily in the development of ALD in order to further develop quantum technologies. This shows how important this technology is in the context of the development of quantum technologies, and research on ALD and its development may contribute to another technological breakthrough, significantly accelerating the development of computers and quantum devices.

X. QIT IN MEDICINE

Contemporary medicine constantly seeks new tools and technologies to enable faster and more accurate diagnostics, as well as more effective treatments for diseases. Quantum sensors, which rely on quantum phenomena to measure physical quantities, offer modern medicine unprecedented opportunities. Thanks to their sensitivity and spatial resolution, they have the potential to revolutionize diagnostics and treatment at the molecular, cellular, and whole-organism levels.

Among the promising quantum sensor technologies, optical pumping magnetometers (OPM) and nitrogen-vacancy (NV) centers in diamonds deserve special attention. OPMs measure magnetic fields using ensembles of alkali atoms (e.g., rubidium). Operating at room temperature and with long coherence times, they are attractive for biomedical applications. One notable use is magnetoencephalography (MEG) based on OPMs, offering significant advantages over conventional SQUID-based methods. OPMs, which function at room temperature (unlike SQUIDs), allow the development of lighter and more comfortable helmets for measuring brain activity. This enables studies on patients who cannot undergo traditional MEG, such as children. For example, OPM-MEG has been used to diagnose drug-resistant epilepsy in school-aged children. [22]

On the other hand, NV centers in diamonds are point defects near nitrogen atoms in the diamond crystal lattice (known as nitrogen-vacancy centers) with spin properties. These phenomena can be used to measure magnetic fields, temperature, electric fields, or pressure, offering subcellular resolution. Nanodiamonds containing NV centers can be introduced into cells and tissues, facilitating the study of biological processes. For this purpose, NV-based magnetic microscopy has been used to detect cancer biomarkers and analyze malaria hemozoin nanocrystals in blood, which serve as malaria biomarkers. A promising application appears to be the use of NV centers in nuclear magnetic resonance (NMR), enabling the study of single molecules and cells, including determining the structure of transmembrane proteins or cellular metabolism. Such studies can be used to track drug distribution within the body, potentially revolutionizing the pharmaceutical industry by allowing direct analysis of drug effects. Another intriguing application is NV thermometry, which allows temperature measurements in cells and small organisms. For instance, this technology has been used to study the temperature threshold that induces the death of HeLa cells—human cervical cancer cells. This makes it possible to identify the appropriate temperature sufficient to effectively destroy HeLa cells in the context of cancer therafor. [23]

Despite their impressive potential, quantum sensors still face many challenges. Further sensitivity improvements could enable faster measurements and open new possibilities, such as real-time imaging of neuronal activity. Miniaturization of sensors and the development of portable measurement systems would increase their accessibility and facilitate their use in clinical settings. Further research is also required to understand the effects of diamond nanoparticles on living organisms to ensure their safety in biomedical applications.

Financial considerations cannot be overlooked. At their current stage of technological development, the costs are high. This is due to the complexity of production processes, the need for advanced materials (such as diamonds with NV centers), and the requirement for highly skilled personnel to operate and maintain the equipment. For example, although producing optical pumping magnetometers (OPMs) does not require the low temperatures needed for SQUID-based devices, it remains expensive due to the precision manufacturing and advanced electronic and optical systems involved. Similarly, the production of nanodiamonds with NV centers possessing specific properties is costly. Additionally, developing methods for delivering them to cells and tissues involves significant expenses. These financial barriers may limit access for certain social groups, raising questions about equality in healthcare access. Another societal concern relates to the safety of using nanodiamonds in living organisms. Although they are generally considered biocompatible, their long-term in vivo effects are not fully understood. Therefore, further studies should focus on their potential toxicity, accumulation in organs, and ability to provoke immune responses.

It is also essential to remember that quantum phenomena are delicate and challenging to observe directly, making such sensors susceptible to disturbances. This requires specialized expertise for their operation, necessitating investments in the education of professionals who would manage them. For example, NV centers in diamonds require precise control of parameters such as temperature, magnetic fields, and pressure to function optimally. Furthermore, the human body generates numerous signals that can additionally interfere with NV center operation.

Despite the challenges and associated costs of quantum medical sensors, the future undoubtedly belongs to them. They are a groundbreaking tool in biomedicine, offering unmatched sensitivity and resolution. Their further development and miniaturization open new perspectives in diagnostics and treatment, and their integration into medical systems could revolutionize healthcare. In the policies of many nations, healthcare requires substantial financial investment to improve quality and accessibility, making the adoption of quantum technologies seem unrealistic at present. However, efforts to develop these technologies should be intensified, beginning with greater investments in educating future quantum technology specialists, improving the performance of quantum sensors, and optimizing costs. This would enable these technologies to become a fundamental part of medical diagnostics in the near future.

XI. QUANTUM COMPUTERS

The modern world is on the threshold of a technological revolution, the epicentre of which are quantum computers.

These extremely advanced devices, based on the principles of quantum mechanics, have the potential to revolutionise computer science, science and industry. Quantum computers can solve problems that are practically impossible for classical computers. This new technology not only introduces advanced infrastructure, but also opens up new research possibilities.

Quantum computers are based on two fundamental principles of quantum mechanics: superposition and entanglement. In traditional computers, data is stored in the form of bits that take on the values 0 or 1. In quantum computers, however, data is stored in qubits, which can exist in the state 0 and 1 at the same time thanks to the phenomenon of superposition. This ability allows for the simultaneous processing of many states, which drastically increases computing power. Entanglement allows qubits, even those far apart, to share information instantly. Thanks to these properties, quantum computers can perform calculations that would be impossible to achieve in a traditional way. Although this technology is still in the early stages of development, companies are already presenting prototypes capable of performing complex calculations. It is worth noting that one of the biggest challenges is precise control of qubits and minimizing computational errors. The stability and isolation of qubits from external influences are key aspects in the further development of this technology.

Cryptography, one of the most important areas that can be revolutionized by quantum computers. Algorithms such as Shor's allow for lightning-fast factorization of large numbers, which threatens current RSA encryption systems. At the same time, quantum cryptography methods are being developed, which, thanks to the Heisenberg uncertainty principle, provide absolute data security. Quantum computers can break classical encryption in much less time than any supercomputer [24]. Work on security based on quantum mechanics is carried out in parallel to meet the challenges related to digital security. Quantum computers can be both a threat and a solution to future problems in the field of data protection. In the future, this technology will require the creation of completely new encryption standards, resistant to quantum attacks.

Quantum computers can also bring huge benefits to economics and medicine, changing the way economic research and analysis are conducted, as well as the treatment process. In economics, this technology enables modeling more complex market scenarios, taking into account variables that were previously ignored. Quantum analyses can significantly improve financial forecasting and the prediction of economic crises. In medicine, quantum computers help with biomolecular simulations, which speeds up the drug discovery process. Simulating drug interactions at the molecular level, previously limited by the power of traditional computers, opens up new possibilities for treating diseases such as cancer, diabetes, or Alzheimer's. Quantum computers will enable the simulation of chemical reactions with unprecedented accuracy [25]. Additionally, they can personalize therapies, adapting treatment to the needs of individual patients, which will revolutionize precision medicine.

Another area of application of quantum computers is optimization problems, occurring in logistics or materials design. Thanks to the rapid processing of huge amounts of data, quantum computers can find optimal solutions to complex problems. For example, tests can be conducted for quantum applications to optimize delivery routes. In particular, problems that previously required huge computational resources can now be solved much faster. It is expected that in the future, the use of quantum computers in data analysis will affect almost every sector of the economy.

Another area where quantum computers are used is optimization problems, such as in logistics or materials design. Thanks to the rapid processing of huge amounts of data, quantum computers can find optimal solutions to complex problems. For example, logistics companies such as DHL or FedEx are testing quantum applications to optimize delivery routes. Additionally, in the financial sector, quantum optimization can help manage investment portfolios or model risk. This technology is also useful in creating advanced mathematical models that help in making business decisions. In particular, problems that previously required huge computational resources can now be solved much faster. It is expected that in the future, the use of quantum computers in data analysis will affect almost every sector of the economy.

Despite their enormous potential, quantum computers still face many technological challenges. One of the biggest challenges is their scalability. Current prototypes, although impressive, have a limited number of qubits. In addition, qubits are extremely sensitive to interference, which leads to errors in calculations. Work on increasing the resistance to decoherence is crucial for the future of this technology. The development of quantum computers also requires huge amounts of energy and money. Another challenge is developing the right software that will fully utilize the capabilities of the new machines. As technology advances, it will also be necessary to consider the ethical aspects related to the potential impact of this technology on society.

The applications of quantum computers are also associated with ethical aspects. On the one hand, they can bring unimaginable benefits, on the other – their uncontrolled use can threaten privacy and data security. In the future, it will be necessary to develop global regulations regarding the use of quantum computers. It is crucial that the development of this technology is monitored and regulated to avoid potential abuses. The use of quantum computers can also affect the labor market, changing the demand for specific skills. It will be necessary to increase awareness in society about the possibilities and risks associated with this technology. Quantum computers are not only a chance for technological development, but also a challenge for future generations.

Quantum computers, still in their early stages of development, have the potential to completely change the modern world. Their ability to solve problems in ways unimaginable for classical computers makes them the subject of great interest in both the world of science and economy. However, the development of this technology must be conducted in a responsible manner, taking into account ethical and social aspects. In the future, quantum computers may become the foundation of a new technological era in which the boundaries of what is possible will be pushed even further. The future of quantum computers is not only technological progress, but also a redefinition of our approach to global problems [26].

XII. DISCUSSION, CONCLUSIONS

Quantum Information and Technology (QIT) applied in various areas of science and technology presents both tremendous challenges and unprecedented opportunities. In this paper, guided by the perspectives of diverse engineering students engaged in specialized research areas, a complex interplay between QIT and domains such as biomedical engineering, electronics, nonotechnology, cybersecurity, software and metrology has emerged. Specifically, medical quantum equipment may revolutionize the field with its new perspectives on medical examinations and innovative medical equipment.

Furthermore, the auspicious development of quantum computers and quantum sensors create new possibilities for advanced calculations, dataset analysis and measurements, as well as for Big Data, Internet of Things and cryptography. Quantum technologies with a proper amount of time and resources could have a promising and wide-reaching impact on different branches of knowledge, as well as living conditions of society. So for the IT may be confirmed in the fact that year of 2025 will be an International Year of Quantum Science and Technology.

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