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Global Military Perspectives on Quantum Technologies

Perspectivas Globais Militares sobre Tecnologias Quânticas

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Abstract

In recent decades, a technological impactful movement on society is being visualized: the second quantum revolution; a consequence of decades of advances in nanotechnology and atom by atom assembly of materials, thus enabling to take the advantages of phenomena intrinsic to quantum mechanics, such as superposition and entanglement, to design quantum devices possessing novel or better capabilities. Alongside, a new dimension of war, a quantum domain, concerns governments worldwide, as well as private parties, especially connected to the industry sector. Managing resources to the most promising military applications in quantum technology is a subject in an ongoing discussion in terms of political and strategic planning. With that, an auspicious schedule and a favorable political-financial global plot has its origin in the present days. This article gives a global overview of the main political perspectives, American and European, on contemporary quantum technologies and their potential general and military applications.

Resumo

Nas últimas décadas, está sendo visualizado um movimento tecnológico impactante na sociedade: a segunda revolução quântica, uma consequência de décadas de avanços na nanotecnologia e montagem de materiais átomo por átomo, permitindo aproveitar as vantagens de fenômenos intrínsecos à mecânica quântica, como superposição e emaranhamento, para projetar dispositivos quânticos com capacidades novas ou melhores. Ao mesmo tempo, uma nova dimensão da guerra, um domínio quântico, preocupa governos em todo o mundo, bem como entidades privadas, especialmente ligadas ao setor industrial. Gerenciar recursos para as aplicações militares mais promissoras em tecnologia quântica é um assunto em discussão contínua em termos de planejamento político e estratégico. Com isso, um cronograma auspicioso e uma trama político-financeira global favorável têm sua origem nos dias atuais. Este artigo oferece uma visão global das principais perspectivas políticas, americana e europeia, sobre as tecnologias quânticas contemporâneas e suas potenciais aplicações gerais e militares.

I. INTRODUCTION

A technological revolution is currently happening in every branch of the social development panorama. Promptly, quantum technologies are referred to as the ultimate innovation regarding technology improvement. The expression "Second Quantum Revolution" or "Quantum 2.0" is often used to describe the ushering of quantum-based technologies that lie upon the convergence of two crucial intellectual achievements: quantum mechanics and information science, giving birth to the field of Quantum Information Science (QIS) [1].

This scenario conjectures a vast scope of opportunities associated with the development of quantum technologies, and the industry segment is not unaware of it [2]. From an industry perspective, the commercial landscape focuses on five core areas: timekeeping, sensing and measurement, imaging, communications security, and computing [2]. Alongside, this cutting-edge technology landscape has pulled the attention of powerful governments around the globe, which aim for a leading position within the global quantum technology marketplace [2]-[5]. Under a similar angle, military applications are closely related to the development of many technologies, which raises the reasoning about the main implications of military usage of quantum technologies.

Inevitably, the military usage of quantum technology became crucial for political and strategical planning of many governments. This subject points out to the establishment of different initiatives around the world with multiple parties [3] and to direct management of this subject by the government [6]. Either way, the rising involvement of various parties with this affair in recent years is notable.

This article is organized as follows: In Sec II, the current aspects of quantum technologies are overviewed, being discussed the state-of-art and capabilities. In Sec III, the American and European perspectives on the subject are analyzed. In Sec IV, the main possible military applications of quantum technologies are reviewed. In sec. V, the importance of preparing for the challenges that the second quantum revolution will bring for the armed forces is discussed.

II. QUANTUM TECHNOLOGIES

Research on quantum technology has largely been restrained to a discussion between computer scientists, physicists, engineers, and mathematicians [7]. The definition

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of quantum technology has its basis on quantum mechanics, that defines, also, its boundaries. One way of describing quantum technology is from the perspective of key concepts, which translates the theory used on the technology; including quantization, the uncertainty principle, quantum superposition, tunneling, entanglement, and decoherence [8].

Another way to interpret quantum technology is historically, under the scope of the emergence of concrete technologies deriving out of quantum revolutions. The first quantum revolution started in 1947 with the invention of the transistor, and went through the 50s with the laser and the integrated circuit. Nowadays, several quantum technologies are in the daily life, such as photovoltaic cells, atom clocks, medical imaging, digital photography and video LEDs, and LCD TV quantum dots [9]. Parallel to it, there are already several critical military applications relied on quantum technologies, such as GPS, missile infrared detectors and night-vision goggles.

Lastly, the definition of quantum technology concerns its core potentials, which translates the theory in practical applications. Under this perspective, quantum technology has not yet reached maturity [10]. However, several applications can be visualized: quantum computing, quantum enabling technologies, quantum telecommunications, quantum cryptography, quantum sensing [11].

The amplitude of applications of quantum physics provided by the second quantum revolution allows a didactic taxonomy in order to divide the application-based technology in groups. For this study, in order to visualize the applications on a quantum domain inside a quantum warfare [12] addressing the picturing of a global military usage of quantum technologies, the classification used will be [13]: Quantum Computing and Simulations, Quantum Communication and Cryptography, Quantum Sensing and Metrology.

A. Quantum Computing and Simulations

Quantum Computing can be defined as an alternative way to process information. In this context, the core idea is to use a basic set of quantum systems to simulate more general types of quantum systems. Since nature is ultimately quantum mechanical, it is impossible to represent the results of quantum mechanics via classical universal devices [14].

The most basic quantum system is the two-level system, and also is the fundamental unit of quantum information—they are called "quantum bits" (qubits). Due to intrinsic properties of quantum mechanics (e.g., quantum entanglement), superposition of many states can be created and used to encode information. Hence, when there is a measure of this physical system, it collapses, and the answer to the problem is achieved. Such a new information processing paradigm provides the so-called "quantum advantage" in some simulations.

After establishing the theoretical foundations of quantum computing [15], scientists worked on different approaches to building quantum computers. The most prominent proposals include trapped ions [16], cold atoms [17], superconducting qubits [18], silicon quantum dots [19], NV centers [20], Majorana fermions [21], and photonic qubits [22]. Each architecture has unique advantages and challenges regarding crucial aspects, such as scalability and decoherence.

Such challenges characterize the current state of Quantum Computing, also known as the Noisy Intermediate-Scale Quantum Era (NISQ Era) [23]. It essentially means that scientists still have to increase the number of qubits [24] and mitigate the error [25] to unlock the full potential of quantum computers.

Once progress on those problems has been made, several applications will be possible, starting with quantum dynamics simulations [26]. By scaling the number of qubits in the long term, it shall be possible, also, to obtain use cases in many areas, including financial services [27], materials and drug design [28], and aerospace engineering [29].

Nonetheless, the viability of quantum computing is challenged by the physical realization of qubits [30]. Likewise, the implementation of a multipurpose quantum computer, regardless of the objective of the cited implementation, is a subject of discussion due to the technological barriers imposed to this task. From an European Perspective, the Quantum Manifesto [3] points out on its Quantum Technologies Timeline the exceedance of computational power by a general purpose quantum computer over a classical one on 2035+. From an American Perspective, in May 2022, the Biden administration released the "National Security Memorandum on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems (NSM-10)", which notes that the Director of the National Institute of Standards and Technology and the Director of the National Security Agency are developing and expected to publicly release by 2024 technical standards for quantum resistant cryptography and additionally cites a national goal "of mitigating as much of the quantum risk as is feasible by 2035." [10].

Even with this auspicious schedule and a favorable political-financial global plot, the impact of quantum computing would be far-reaching and the cost of production would be quite high [30]. Furthermore, the inference that the feasibility of a personal quantum computer would be far off is quite reasonable.

B. Quantum Communication and Cryptography

In 2022, it is estimated that cyberattacks will cost around US$ 6 trillion globally [31]. Moreover, from the perspective of national defense, cybercrime represents a major threat to crucial systems of a country, including military facilities, the electric grid, and nuclear power plants. Therefore, it is mandatory to develop new technologies that will make communication safer.

In this context, Quantum Communication and Cryptography are approaches that might solve this problem in the future. Take, for instance, photonic qubits that transmit data in optical cables via quantum states in superposition. When a bad actor tries to steal information from that transmission line, the superposition state collapses, and the hacking activity is immediately detected. This process illustrates the core idea behind Quantum Key Distribution (QKD) [32].

QKD consists of transmitting data encrypted through a classical channel while using quantum bits as keys to decrypt the information. There are many ways to build such a system, the most famous one being BB84 – created by Charles Bennett and Gilles Brassard in 1984 [33]. In broader terms, BB84 has a mechanism that allows users to detect if a hacker has tried to access their data. In this case, they drop the violated key and keep generating new ones until they get a secure key [33]. That is the underlying principle of Quantum Cryptography.

Although QKD is a new technology, it has already been implemented in some regions. The largest one comprises a 2000 km fiber optic link in China, connecting the cities of Beijing, Jinan, Hefei, and Shanghai [34]. However, as QKD has some security vulnerabilities, some scientists are working on quantum teleportation [35]. By using the quantum entanglement of photonic qubits, quantum teleportation represents a more reliable way to transmit data [35]. Researchers in the USA, China, and Europe are racing to build such a network structure, which would be crucial to implementing the quantum internet [36].

C. Quantum Sensing and Metrology

Quantum sensing is about using a quantum object to measure a physical quantity [37]. Such an object might be characterized by quantized energy levels or quantum coherence, for instance. Current implementations of quantum sensors include trapped ions, neutral atoms, superconducting qubits, solid-state qubits, and Rydberg atoms [37].

Due to its high precision and sensitivity, quantum sensing might have several applications in engineering and applied physics. However, to be characterized as a quantum sensor, the system must [37]:

- have discrete and resolvable energy levels;
- be able to be initialized into a well-known energy state;
- be coherently manipulated by time-dependent fields;
- interact with a physical quantity.

Hence, given that the system fulfills the quantum sensor criteria, it has, also, to follow pre-defined steps within the quantum sensing protocol [37], which includes initializing into a known energy state, then evolving it for a specific time interval, measuring it, and repeating the process many times to estimate the signal. By following such steps, the full potential of quantum sensors can be unlocked – which already have many practical applications (e.g., magnetometers, atomic clocks, nanoscale imaging).

III. GLOBAL OVERVIEW

The scale of applications of quantum technologies has provided substantial motivation for large efforts in investment worldwide, like the United States, China, Europe, Japan, Russia, Australia, and Canada. However, these efforts are fundamentally focused on basic research at the moment. Still, the 50 most cited researchers in the fields of quantum computing, quantum sensing and quantum communication are majority from the USA or Europe. It shows that European Union’s research is just as advanced as the American [38]. Hence, it is important to analyze both perspectives and policies on quantum technology development.

A. American Perspective

The American Science and Technology policy was established by the National Science and Technology Policy Organization, and Priorities Act of 1976 to provide the President and others within the Executive Office of the President with advice on the scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, the environment, and the technological recovery and use of resources, among other topics [4]. Under this policy, lies The National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS), which aims to maintain and expand U.S. leadership in quantum information science and its applications over the next decade. In terms of political planning, the regimentation is built upon the National Strategic Overview for Quantum Information Science, a product of SCQIS, which identifies a strategic overview about the main policy opportunities on QIS in order to create a visible, systematic, national approach to quantum information research and development [6]:

- Choosing a science-first approach to QIS;
- Creating a quantum-smart workforce for tomorrow;
- Deepening engagement with quantum industry;
- Providing critical infrastructure;
- Maintaining national security and economic growth;
- Advancing international cooperation.

The United States has a vivid community in QIS by the contribution of both the U.S. Government funding system and the U.S. innovation ecosystem throughout many platforms, including Department of Agriculture (USDA), Department of Energy (DOE), National Institutes of Health (NIH), Department of the Interior (DOI), Department of Homeland Security (DHS), Department of State (State), National Aeronautics and Space Administration (NASA), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), National Security Agency (NSA), Office of the Director of National Intelligence (ODNI), Office of Management and Budget (OMB), and Office of Science and Technology Policy (OSTP), and, indeed, the Department of Defense (DOD) [6]. Moreover, SCQIS assesses the national portfolio using seven broad categories: Quantum sensing, quantum computing, quantum networking, scientific advances enabled by quantum devices and theory advances, supporting technology, future applications, and risk mitigation [6].

More recently, in February 2022, SCQIS released a report regarding a Quantum Information Science and Technology (QIST) workforce development national strategic plan, which identified four critical actions [4]:

- Develop and maintain an understanding of the workforce needs in the QIST ecosystem, with both short-term and long-term perspectives;
- Introduce broader audiences to QIST through public outreach and educational materials;
- Address QIST-specific gaps in professional education and training opportunities;
- Make careers in QIST and related fields more accessible and equitable.

In March 2022, SCQIS released a report on bringing quantum sensors to fruition, which traced the implementation of four recommendations to accelerate key developments needed to bring quantum sensors to fruition in order to promote economic opportunities, security applications, and the progress of science through the development of quantum technologies in a long-term goal [39]. Parallel to it, the release by the Biden administration of the NSM-10 in May 2022 outlaid policies and initiatives related to quantum computing by identifying key steps needed to maintain U.S.'s competitive advantage in QIS [5].

B. European Perspective

The European Union has common policies in several areas such as agriculture, industry, competition and foreign trade. Likewise, scientific and technological studies are aspects of Framework Programs launched over the years, which coordinate activities of the member countries in this field. In addition, the eighth Framework Program Horizon 2020 covers the years 2014-2020 and aims to strengthen Europe's global competitiveness in terms of: excellence in science, industrial leadership and social change [40].

As a part of this Framework Programs, in May 2016, a Quantum Manifesto, endorsed by more than 3400 experts across Europe, was released calling upon Member States and the European Commission to launch a C1 billion flagship-scale initiative in Quantum Technology aiming to place Europe at the forefront of the second quantum revolution, developing Europe's capabilities in quantum technologies, creating a lucrative knowledge-based industry, leading to long-term economic, scientific and societal benefits and resulting in a more sustainable, more productive, more entrepreneurial and more secure European Union [3]. The goals of this initiative are [3]:

- "Kick-start a competitive European quantum industry to position Europe as a leader in the future global industrial landscape;"
- "Expand European scientific leadership and excellence in quantum research;"
- "Make Europe a dynamic and attractive region for innovative business and investments in quantum technologies;"
- "Benefit from advances in quantum technologies to provide better solutions to grand challenges in such fields as energy, health, security, and the environment."

This kind of policy of developing quantum technologies has an open share of investment between Member States of the European Union and the industry sector in Europe. For instance, the most notorious states in terms of investment have millionaire programs of investment planned for years to come, like the United Kingdom, that has a C270 million five-year program, and Netherlands, that has a C146 million ten-year program. Alongside, the Manifesto [3] lists that companies like "Airbus Defense and Space, Alcatel Lucent, ASML, Bosch, IBM, Nokia, IMEC, Safran, Siemens and Thales, e2v, Gooch & Housego, ID Quantique, M Squared Lasers, Muquans, Single Quantum and Toptica, occupying leading positions in their specific markets, are already investing significant amounts in quantum technology development, both inside and outside Europe".

Parallel to it, an intermediate reported was launched in 2017 designing a High-Level Steering Committee (HLSC) consisting of 12 distinguished Academic Members and 12 high-ranking Industry Members, as well as one observer. The main activities of HLSC are to deliver a Strategic Research Agenda, an Implementation model and a Governance model in order to achieve the goals determined by the Quantum Manifesto [41].

In order to follow up the ninth Framework Program Horizon Europe, which covers the years 2021-2027, the HLSC has released a Strategic Research Agenda in 2020, which includes the achievements and expected goals for near, mid and long-term future around major areas: Quantum Communication, Computing, Simulation, Sensing, and Metrology, including the milestones [41], [42]:

- "In 3 years: development and certification of Quantum Random Number Generators and Quantum Key Distribution devices and systems, addressing high-speed, low deployment costs, novel protocols and applications for network operation, as well as the development of systems and protocols for quantum repeaters, quantum memories and long distance communication;"
- "In 6 years: cost-effective and scalable devices and systems for intercity and intra-city networks demonstrating end-user-inspired applications, as well as demonstration of scalable solutions for quantum networks connecting devices and systems, e.g., quantum sensors or processors;"
- "In 10 years: development of autonomous metro-area, long distance (>1000 Km) and entanglement-based networks, a 'quantum Internet', as well as protocols exploiting the novel properties that quantum communication offers."

In terms of research, according to The Quantum Insider [43], Europe has 4 of the 12 best Quantum Computing Universities and Graduate Programs of the World in 2022: The Institute for Quantum Computing – University of Waterloo; University of Oxford; Quantum Applications and Research Laboratory at LMU Munich (QAR-LAB); and University of Innsbruck – Quantum Information & Computation.

C. Remarks on China

Another important player in the global plot of quantum technology development is China. Although it is hard to estimate how much the Chinese government has already invested, it has begun to invest extremely rapidly after 2010 [44]. With eminent success in some fields and with companies and institutions patenting aggressively, China's quantum technologies program is well advanced [2]. Especially, the field of quantum communications has received a recent seven billion US dollars investment program [45]. In addition, China even claims the development of a spy satellite that uses ghost imaging technology, though the spatial resolution it has is unclear [46].

Besides that, China's quantum technology funded subjects include quantum information research, quantum control, quantum sensing, quantum materials, quantum dots, quantum cryptography and quantum chips [47]. Under the analysis of open source documents, it is estimated that there has been, at least, an investment of 25 billion US dollars by Chinese government in quantum technology, without including private investment, from mid-1980s to 2022 [47].

IV. MILITARY APPLICATION OF QUANTUM TECHNOLOGIES

A. Quantum Warfare

In modern times, especially from World War II until now, the purpose of the utilization of technology on war is studied by military leaderships. In recent decades, the investment in military technology by the states is increasing significantly, as well as the amount of academic research on this topic [48]. To explore this recent scenario, it is important to know that quantum technology has not yet reached its peak when it is taken into account the second quantum revolution. Nevertheless, its potential holds significant implications for the future of military sensing, encryption, and communications, as well as for political oversight, authorizations, and appropriations [10]. In order to visualize the main implications of quantum technologies on a hypothetical warfare, Fig. 1 suggests the military applications and mentions the probable capabilities and performances:

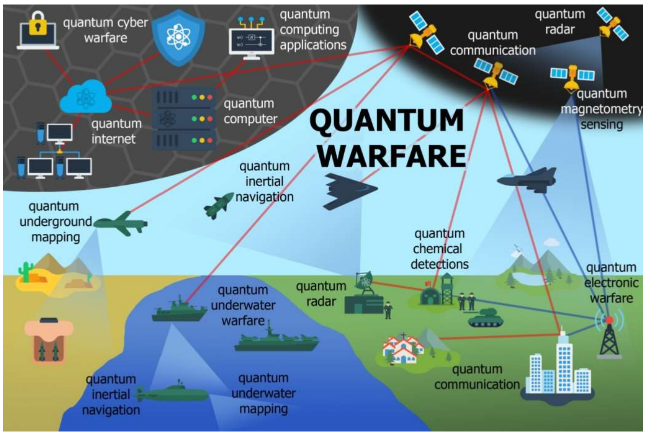

Fig. 1. Hypothetical quantum warfare utilizing various quantum technology systems [13].

From this point on, it is important to point out the leading advantages of each possible quantum military application [13]:

1) Quantum Cybersecurity: Encryption algorithms and approaches, as well as quantum key distribution, can provide vectors of attack on current symmetric and asymmetric encryption due to the effectiveness of quantum processing. This leads up to machine learning and artificial intelligence usage for cyber warfare [49].

2) Quantum computing capabilities: Since Shor's algorithm [33], the concept of quantum advantage, i.e., a computational problem that cannot be solved classically with reasonable resources [50], gained force. From this, complex problems that rely on high-performance computing can be strongly benefited from the development of quantum computing. Military problems could be solved more precisely and quickly: battlefield or war simulations; analysis of radio frequency spectrum; logistics management; supply chain optimization; energy management; and predictive maintenance [51].

3) Quantum communication network: Combinations of optical fiber and free-space channels would connect several nodes such as vehicles, command centers, ships, planes, soldiers, etc [45].

4) Quantum positioning, navigation and timing: The increasing of performance of time standards and frequency transfer would usher from the combination with optical atomic clocks in quantum networks, which would enable new applications on a real warfare, like quantum sensing and imaging [52].

5) Quantum intelligence, surveillance, target acquisition and reconnaissance: This subject is related to the capability of improvement of situational awareness of multi-domain battlefields, which would be possible due to new instruments on quantum sensing: quantum gravimeters, quantum magnetometers, quantum radars and imaging devices, etc. This data would be processed quickly by quantum computers of high processing power [38].

6) Quantum electronic warfare: Classical electronic warfare could be enhanced by quantum computing and timing, as well as new devices could be conceived and effectively used, like quantum antennas of few micrometers capable of intercepting low-frequency signaling.

7) Quantum radars: Quantum radars are highly resistant to noise, jamming, and other electronic warfare countermeasures. Also, the output signal is invisible to electronic warfare measures due to its low power.

8) Quantum underwater warfare: Quantum technology could improve magnetic detection of submarine or underwater mines. Also, submarines could adopt quantum inertial navigation.

9) Quantum space warfare: Satellites could be key spots for placing quantum sensing and communication technology. As well, quantum radars and electronic warfare devices would be deployed in space.

10) Chemical and biological simulations and detection: With quantum computers, defense-related research on new drugs and chemical substances based on quantum simulation would be possible, which would perform as a useful tool for detecting explosives and chemical warfare agents.

11) New material design: The development of new materials would provide camouflage, stealth, ultra-hard armor, and high temperature tolerance material for the defense industry.

12) Brain imaging and human-machine interfacing: Magnetoencephalography scanners could be present on soldier's helmets for continuous and remote medical monitoring. Thus, human-machine interfacing and communication could be improved with autonomous systems.

B. Projections

According to a technical report made by the US Army Research Laboratory [44], these are the main possible breakthroughs in a military ground warfare directly related to quantum technology until 2050:

- Intersection of artificial layered semiconductor materials, near-field electromagnetics, and quantum optics that enable infrared sensors that would be dramatically smaller, cheaper, and more sensitive and multifunctional than what is available today;
- Ways to measure, distribute, and exploit quantum entanglement that enable ultra-precise timing and time distribution, improved sensing, faster information processing, and new security in communications that are impossible by any other means.

Aside from that, the possibility of a quantum arms race between China and United States, that will transform the nature of warfare, is already under debate [53].

V. CONCLUSION

It is notorious that the improvement of QIST holds an inherent potential to all sources and participants of the global political panorama. It converges to the engagement of public and private resources from various parties and governments around the globe, which are working to star the upcoming events as vanguard.

In terms of military usage, the managers of military quantum technologies of the future have to deal with concern about the investment of time and resources. The global conception on this subject is to build a quantum ecosystem composed of industry, academic institutions and the defense sector. It leads up to the decision makers dealing with the identification of the most advantageous and disruptive quantum technologies, its research and development and the reaching of the full operational capability, which includes modification or creation of new military doctrines, preparation of new military scenarios, strategies, and tactics fully exploiting the quantum advantage [13]. Thus, a new dimension of war, a quantum domain, is visualized, in which the comprehension of time, space, and matter are different from the classical and, therefore, the classical warfare is disrupted from whatever existed before [12]. This concern is fundamental for the development and management of military power across the world from now on.

Due to the complexity of the challenges of the quantum warfare, it is most important than ever a close collaboration between military forces, public and private research institutes, universities, and industry. Brazil already has a success story in the development of another complex and critical technological area with the building of the Departamento de Ciência e Tecnologia (DCTA) complex [54]. At the national level, the main coordinated effort is the Conselho Nacional de Desenvolvimento Científico e Tecnológico / Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (CNPq/FAPERJ) funded Instituto Nacional de Ciência e Tecnologia de Informação Quântica (INCT-IQ), that aims the development of basic research which leads to the development of quantum computing and communication technologies. This Institute has 120 researchers of 29 universities and institutes across the country. The possibility of Brazil being a player in quantum technologies will depend on reenacting the same environment that created the Brazilian Aerospace industry.

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