Quantum Sensing: Comparing the United States and China

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Contents

Executive Summary

The United States and China expect that quantum-sensing applications could profoundly impact on military strategy. This is based on the assumption that breakthroughs in the field could result in earlier detection of certain types of nuclear forces (such as stealth bombers or ballistic-missile submarines) which generally have a low signature. Advances in quantum sensing could also result in increased accuracy for military-surveillance systems or enhanced detectability for military targets otherwise hidden behind physical barriers.

Advanced technologies like quantum sensing are now commonly the subject of comparative national-technology assessments for the US and China at the research and development (R&D) level, and these have increasingly become central elements of international-security policy. A key purpose of such studies has been to assert national primacy or 'discovery primacy' in a given field. The idea is that the US or China can establish a clear lead in R&D in a single technology or a basket of technologies that will translate into a strategic advantage in national-security competition or war.

Such analyses have contributed to ever-tightening restrictions on technology transfer as part of the intensifying Sino-American military competition. There is no extant assessment in the public domain of the strengths of the US and China in quantum sensing that follows a comprehensive methodology of national-technology evaluation. This paper offers an initial survey relying on six broad indicators of what such a study might look at.

The report concludes that in the coming decade, Washington will likely be significantly better-placed than Beijing to achieve and deploy breakthroughs in this technology for national-security purposes. However, this assessment does not exclude the possibility that China may make militarily significant breakthroughs with little warning in one or two subfields of quantum sensing. An analysis based on sub-categories of this field is therefore essential.

A full appreciation of the strategic balance of technological power in a field like quantum sensing should also consider the clear advantages accruing to the US from the robust contributions made by several key allies and/or partners, which, depending on the subfield, include the likes of Australia, Canada, Germany, Israel, Italy, Japan and the United Kingdom.

This paper first outlines what quantum sensing is and discusses its military applications. Next, the paper offers a brief critique of methodologies of national-technology assessment and advocates an approach based on the following six indicators: governance; innovation systems; education systems; research directions; industry comparisons; and patents.

Introduction

Quantum information science (QIS) can be divided into several branches such as computing, communications and sensing.[1] The main military or national-security applications of second-generation quantum sciences are indicated in Table 1.[2]

In his confirmation hearings for the post of US defense secretary in 2021, Lloyd Austin identified quantum computing as the first of several broad technological areas where the US would need to make advances if it were to keep a military edge over China.[3] This sentiment is reflected in 24 projects related to quantum technologies that the Defense Advanced Research Projects Agency (DARPA) has undertaken.[4] The US Department of Energy (DoE) has funded a large share of US-published papers on quantum sciences in open-source journals.[5] It is clear that this is not a temporary fixation on the part of Washington as the US National Quantum Initiative Advisory Committee called in June 2023 for longer-term and enhanced investment in the quantum sciences.[6]

China is also moving rapidly to promote quantum sciences.[7] In October 2020, President Xi Jinping singled out this area as the vanguard of a new round of industrial revolutions.[8] He called for stronger policy support, more investment, training more researchers and giving scientists more autonomy in this field of research. China is very keen to exploit its edge in quantum communications, and plans to have a fully functioning global communications system that is quantum-based by 2030.[9] In 2023, Chinese media reported on major breakthroughs in quantum communications and quantum computing, even though these were not the direct results of Xi's elevated interest but rather of earlier investments.[10]

Table 1: **Military or national-security applications of QIS**

Quantum Computing	Quantum Communications	Quantum Sensing
Decryption	Secure communications	Subsurface detection
Large data analysis	Improved connectivity	Position, navigation and timing
System-optimisation processes		Timekeeping
		Target verification
		Radar and imaging

Source: Reproduced from Lindsay Rand, 'Quantum Technology: A Primer on National Security and Policy Implications', Lawrence Livermore National Laboratory, 18 July 2022, p. 7, https://cgsr.llnl.gov/content/assets/docs/Quantum-Primer_CGSR_LR_Jul18.pdf

The US–China competition over quantum technologies should also take account of the role played by other countries. In this regard, key US allies such as Australia, Canada, France, Germany, Israel, Italy, Japan and the UK make important contributions. Moreover, there are significant collaborations between the US and China as well as between US allies and China in some of these technologies. Interestingly, the US Department of Defense (DoD) and DoE have funded in part or in full some of these joint US–China initiatives.[11] Until 2023, there were very few formal restrictions on the transfer from the US to China of quantum-related technologies.[12]

However, these technologies were targeted for such action in 2023. On 9 August 2023, US President Joe Biden issued an executive order declaring a national emergency regarding technological competition with China, and this was a major escalation in the bilateral relationship.[13] The executive order mandates that US companies declare their contacts and relations with Chinese entities in various technology fields, including quantum-information technologies, because of their potential threat to US national security. The order also set in train a process of continuously reviewing developments in these technologies and a process for prohibiting US investment in certain technologies, which would be subsequently identified.

This paper addresses quantum sensing.

This field refers to a range of advanced technologies that operate at the subatomic, nanometre level to detect minute changes in the physical properties of environmental or human targets, such as their magnetic signatures. These technologies are already providing substantial improvements in how we measure, detect or navigate in military environments, and they hold considerable potential for even more breakthroughs.

Applications of this technology include improvement in sensors such as clocks, electromagnetic radiation detectors and sensors for electric or magnetic fields.[14]

The paper focuses on sensing because this area has the shortest predicted time frame for important and novel national-security uses that can be widely deployed. It is important to highlight that quantum-sensing technologies have long been studied and used successfully in civilian applications such as the Global Positioning System and in healthcare through magnetic resonance imaging (MRI).[15] In a military context, quantum sensing is fundamentally different from quantum communications and quantum computing. The latter two fields are more infrastructure-based, while sensing can provide deployable tools that will have impacts at the three levels of war.[16] However, the level of likely disruption of the technology is currently being debated.[17]

There is no comprehensive assessment of the relative strengths of the US and China in quantum sensing, though a detailed study by the RAND Corporation comparing the industrial bases of the two countries in the broader field of quantum technologies touched on many of the relevant foundations.[18] The RAND analysis will be discussed later, but it can be distinguished from this paper's approach by the latter's focus on sensing, which offers a closer look at certain additional aspects of the capabilities in quantum sensing of the US and China.

A distinguishing aspect of this paper among comparative studies is its consideration of the large diversity of subfields in scientific research on quantum sensing.[19]

The complexity of policy analysis of quantum-sensing R&D is also increased by the potential crossovers with research on artificial intelligence (AI), autonomous systems and other branches of quantum science (computing and communications). This paper does not assess these crossovers.

The first part of this paper outlines what quantum sensing is and discusses its military applications. The paper then discusses the approach to comparative national-technology assessment, underlining the importance of comprehensive approaches. Six factors are identified for analysis: governance; innovation systems; education systems; research directions; industry comparisons; and patents. The report concludes with an assessment of the relative strengths of the US and China in quantum sensing

1. Military Applications of Quantum Sensing

The most promising military applications of quantum sensing are: 1) detection and targeting; 2) positioning, navigation and timing; 3) situational awareness; 4) human-machine interfacing; and 5) operability of uninhabited platforms.[20]

One area of warfare that quantum sensing will likely most impact on is the undersea domain, since submarine forces could well be the first adopters of quantum inertial navigation and could use quantum magnetometers for detection of underwater objects (other submarines, mines and sub-surface robots and drones).[21] As an example of Chinese development in this area, the China Shipbuilding Industry Corporation signed in 2017 a funding agreement with the University of Science and Technology of China (USTC) to set up three new laboratories, including one in quantum detection and another in quantum guidance.[22] In 2018, the USTC signed an agreement with one of China's powerful military-related electronics corporations, the China Electronics Technology Group Corporation, to collaborate on quantum detection. The same year, the university revealed a prototype quantum radar.

There is considerable variation in national priorities for quantum-sensing R&D. This is in part due to the still-experimental character of much of the field, but it is also due in large part to the sheer breadth of the possible applications of this technology. States seem as interested in understanding comparative global efforts in basic-science research of quantum sensing and its exploitation as they are in their own R&D efforts. There has been more research on quantum computing or communications than on sensing. By and large, the current military applications of quantum sensing appear to be refinements of existing techniques to achieve greater accuracy or penetration, rather than completely novel applications.

2. Methodology

As the Sino-American strategic competition intensifies with critical technologies becoming an even more contentious issue, there has been a resurgence in comparative assessments of national-technology development in the two countries in key fields, such as AI, hypersonic missiles and advanced semiconductors. These assessments vary significantly in how their rationales and methodologies have been woven together. These comparisons are conducted through the prisms of various policy areas, including ethics, human rights, human security, national industry, economic trajectory and power, as well as military-strategic advantage.[23] As for methodologies, there is little consensus within governments or in academia on what constitutes an appropriate methodology for making a US–China comparison vis-à-vis the fields mentioned above.[24]

Two studies offer a good illustration of the benefits of a comprehensive integrated approach. The first is a mixed-methods analysis of 31 indicators grouped into four categories: research metrics; government activity metrics; private-industry activities; and technical metrics.[25] The second is an overview of more than 30 distinct metrics that have been used individually or in combination with one or two others for technology comparisons.[26] This study categorises these metrics into inputs, outputs and outcomes, highlighting the complex relationships between these three types of indicators that need to be considered in comparing the levels of development of national R&D ecosystems.

The methodology for this paper is to compare in six categories the strengths of the US and China in their positioning for quantum sensing for national security. The categories are:

1. **Governance**: national-level policies and structures intended to promote the growth and competitiveness of national quantum-sensing capabilities. This includes patterns of government investment in quantum sensing.
2. **Innovation systems**: the way the ecosystem of national technology policy intersects with the field of quantum sensing.
3. **Education systems**: the contours of tertiary education in quantum sensing, such as quality of education offered, the numbers of students in the field and types of job opportunities available after graduation.
4. **Industry comparisons**: the similarities and differences in the industrial bases of the US and China for quantum sensing.
5. **Research directions**: the main trends in quantum-sensing research in universities and research institutes in the US and China.
6. **Patents**: a comparison of patent data for quantum sensing in the US and China.

The first four indicators (governance, innovation systems, education systems and industry comparisons) offer a system-wide view, while the last two (research directions and patents) provide a more granular perspective.

These categories of analysis can be viewed as offering an insight into how well each country is positioned for 'discovery primacy' - the first-mover advantage that can be obtained by introducing a research concept to the market.[27]

In several places, this paper will reference the capabilities of countries apart from the US and China, because alliance capabilities and the flow of talents from other countries will affect how the two countries can exploit particular technologies for national-security purposes.

The analysis in the paper should contribute to the discourse on whether the US or China can establish a clear lead in quantum-sensing R&D or a basket of related technologies that will at some point translate into a strategic advantage for one side in national-security competition or war. However, this paper does not attempt to give a future-oriented net assessment of potential applications. It also does not analyse the likely comparative potential of the two countries in quantum sensing for military-strategic advantage during times of crisis or war.

3. Governance

The US has a powerful, highly developed and elaborate governance system for promoting quantum sensing. This government-led collaborative process began to emerge strongly between 1999 and 2009 with the first national plan for quantum sciences published in 2009.[28] This came decades after the science of quantum sensing was established. For example, the basic science underpinning modern quantum-level detection and measurement emerged in the 1930s with a US researcher making an important breakthrough in the basic science of quantum control as early as 1950.[29] In addition, the first MRI machine was used on a human patient in 1977.[30]

In 2019, the US Defense Science Board (DSB) made a series of findings about national priorities for subfields of quantum sensing.[31] The board identified accelerometers, clocks and magnetometers as the most promising applications, while offering a critique about a lack of rigor in 'tying performance to mission specifications and/or novel capability'.[32] At the same time, as one example of how different national research priorities for military purposes may be between the US and China, the DSB report deemed quantum-radar research as offering no additional value to the US. In contrast, Chinese researchers and military commentators assess it to have a high value. For example, China sees its value in potentially defeating stealth technology, electronic jamming and anti-radiation missiles.[33]

For the US, the current ambitious trajectory for quantum-sensing governance is captured in the 2022 National Science and Technology Council (NSTC) paper titled 'Bringing Quantum Sensors to Fruition'.[34] Several other policy reports and measures on QIS in general released in the past several years have shaped developments in this field. These included the National Quantum Initiative Act (2018); the National Strategic Overview for Quantum Information Science (2018); the 'Quantum Frontiers' report (2020); the National Security Memorandum on Promoting United States Leadership in Quantum Computing While Mitigating Risks to Vulnerable Cryptographic Systems (2022); and the CHIPS and Science Act (2022).[35]

The 'Bringing Quantum Sensors to Fruition' report addressed challenges associated with the commercialisation of research to produce a new generation of 'transformative sensors'.[36] The longer-term goal is to 'promote economic opportunities, security applications, and the progress of science'. One focus of this effort would be the development of cross-cutting R&D that would help bolster capabilities in quantum computing and communications. The report set metrics for the near-term (one to three years) that were mainly about mapping the field and setting priorities.[37] Its targets for the medium term (three to eight years) included fast-tracking of applications; component miniaturisation and subsystem integration; establishing new R&D consortia and production facilities; as well as devising standards for the new sensors and components.

The National Quantum Initiative Act directed government agencies to undertake a broad range of new activities in quantum science. There was a requirement for the DoE to set up research and education initiatives, such as for quantum sensing and detection.[38] These included the creation of 'at least 2, but not more than 5, National Quantum Information Science Research Centres'. The law directed the president to set up a Subcommittee on Quantum Information Science through the NSTC.[39] A National Quantum Initiative Advisory Committee was also to be created.[40] The QIS subcommittee would bring together government agencies, while the advisory committee would bring together representatives of industry, universities and federal laboratories.

The QIS subcommittee of the NSTC argued in the 'Bringing Quantum Sensors to Fruition' report that the US was ahead of all other countries in the field of QIS, including sensing, and could expect to keep that lead if it took the necessary coordination and mobilisation actions.[41] The group comprises representatives of US national-security and intelligence agencies as well as research leaders from civil coordination bodies, government departments and national-security research agencies like the Intelligence Advanced Research Projects

Activity. The main driver of the US governance system has been the QIS subcommittee, which aims to 'maintain and expand U.S. leadership in quantum information science and its applications over the next decade'.[42] US national-security agencies are directly involved in these plans, but their role and contribution to funding is not fully revealed in the public record.

Within this vibrant and nationally dispersed ecosystem, the field of quantum sensing has thrived. The US national-policy framework also places a significant emphasis on international collaboration. Its premise is that a country with greater access and a track record in utilising and aligning such alliances and collaboration will likely be better placed to dominate the quantum-sensing frontier.

In general terms, Chinese governance efforts to promote quantum sciences do not match those in the US, even though China has achieved important breakthroughs, especially in quantum communications (in which it has a world-leading position). China's governance drivers for quantum sensing are less advanced than for quantum communications. These drivers are also far less developed than those of the US. In 2011, Beijing revealed its roadmap for information technology prepared by the Chinese Academy of Sciences (CAS).[43] In the quantum-sciences field, the roadmap paid most attention to quantum computers and less to quantum cryptography.[44] In addition, there was little specific mention of quantum sensing or measurement beyond general predictions of the likely emergence of sensing applications.[45] This relative balance was a harbinger of things to come with quantum sensing consistently being at the lower end of China's science and technology (S&T) priorities compared to the other two main branches of quantum science.

China does not have a national plan for the development of QIS or quantum sensing in particular that is publicly available. Nor does it have the highly developed networks of diverse actors and legislative drivers as in the US.[46] China's most authoritative general policy statement on this matter came in the form of 'important instructions' from President Xi in October 2020 that gave 'strategic guidance' for accelerating the development of quantum science and technology.[47] China has been trying to pursue a strategic approach through a number of policy avenues, such as its 'S&T Major Projects' vehicle, which places a much heavier emphasis on industry/science linkages than the more standard funding programmes supporting basic science research.

At the same time, we can piece together various actions and statements on China's part to demonstrate the country's level of commitment to the development of quantum science and industry, including for national-security purposes. China is already the undisputed leader in quantum-communications research and associated applications, and it has reached this position relatively quickly after only a decade or so of serious funding.

The leading position of the USTC in quantum science in China appears to have been the result of individual contributions by a very small cohort of the institution's scientists rather than the result of a broad-ranging national plan.[48] The university enjoys a special relationship with the CAS and has operated under the latter's direct control since the USTC was established in 1958. The surge in the USTC's role in the quantum field can be traced to its establishment of a new quantum-communications laboratory in 2001. One scholar, Pan Jianwei, who completed his doctorate in Vienna in 1999, was behind this move.[49] He also established the Division of Quantum Physics and Quantum Information at the USTC in 2001.[50] Pan later conducted research at Heidelberg University between 2003 and 2008, splitting his time between the USTC and the German institution.[51] Some of his work, including the development of a research group at Heidelberg that comprised Chinese and non-Chinese researchers, was funded by the European Union. In 2023, the USTC served as the academic home of 11 other Chinese quantum researchers who returned from Heidelberg.[52]

Pan's pioneering work was complemented by the Key Laboratory of Quantum Information established by Professor Guo Guangcan, now an academician of the CAS.[53] However, neither Pan nor Guo specialise in quantum sensing, though they contribute to studies in that area.

The CAS built China's quantum efforts around Pan, including through its establishment in 2014 of the Center for Excellence in Quantum Information and Quantum Physics under his leadership. (This was the first CAS centre of excellence created as part of a plan to establish such centres in five fields, the other four being earth science of the Qinghai–Tibet plateau; particle physics; brain science; and thorium molten salt reactors.)[54]

Some of these USTC researchers are involved in research supporting defence and security companies. Pan and other researchers set up an independent company, Quantum CTeK, that supports the development of military technologies for the People's Liberation Army, including through acquisition of US research for national-security purposes.[55]

While the USTC is the main body for frontier issues of quantum technology, it also serves as the hub for efforts by various other CAS centres, such as the Shanghai Institute of Technical Physics, the Institute of Semiconductors, the Institute of Optics and Electronics as well as other domestic research institutions.[56]

Describing his journey to become a world leader in quantum communications, Pan mentioned the effort from 2003–16 to help China launch its first dedicated quantum-communications satellite. This endeavour drew on an existing quantum-sensing capability, but he had to push through managerial challenges with a level of boldness to overcome the 'incompatibility between the science and technology system and the requirements for rapid science and technology development'.[57] The implied message is that the structure and institutional weight of the Chinese Academy of Science was not really brought to bear until the creation of the Institute for Quantum Information and Quantum Technology Innovation in 2016 and the associated decision by the CAS to support the managerial style of Pan and his team of research leaders. In the same interview, Pan recognised that the system of institutional backing for quantum sensing was less developed than elsewhere, and China was not at the forefront.

In 2016, the Chinese government issued its Five-year Plan for national S&T development (as part of the 13th Five-year Plan process), which staked out new ground for quantum sciences but included only passing reference to quantum sensing or metrology.[58] While earlier strategic initiatives for national science and technology had previously made provisions for basic research and new applications in the field of quantum information, China committed only in 2016 to a national R&D plan on quantum control and quantum information (though this plan has not been published).

The 2016 initiative, called 'Science and Technology Innovation 2030 – Quantum Communication and Quantum Computing Major Project', was a multiyear and multibillion-yuan development in the 13th Five-year Plan funded in large part by the central government.[59] In addition, the local governments of Anhui province and Shanghai municipality each contributed about CNY1bn (USD150 million) to the project, with its rationale being to 'seize the commanding heights of international competition and future development of quantum technology'.[60]

In 2018, China began planning for the establishment of national-level laboratories and new technology projects. It also started further development of top-level planning in the field.[61] At the time, President Xi identified quantum information as one of five major breakthrough technologies important to China (alongside AI, blockchain, the Internet of Things and mobile).[62] His speech probably prompted the China Academy of Information and Communications Technology (CAICT) to develop a series of annual reports on quantum technology in the country.

The first of such CAICT reports, which was published in 2018, revealed the policy thinking in China at the time, especially regarding quantum sensing. It spoke of a 'large gap' with the US and of China lacking 'key technical indicators and major innovations', stating that there were deficiencies in 'industrial foundations and applications, talent introduction and training'.[63] The publication also noted that 'technology companies entered late and had limited participation', adding that there was only one start-up company. The report urged China to follow the United States' 'multiparty collaborative development model involving ... the government, technology companies, scientific-research institutions, industry, and investment forces'. The report lamented that the US 'started early and leads the technology'. It concluded that 'in terms of comprehensive strength', the US had 'traditional advantages in quantum measurement, holding world records in many sensing and measurement sub-fields'.[64]

In 2020, during a group study session of the Politburo of the Chinese Communist Party (CCP) Central Committee, President Xi reiterated that quantum S&T was at the forefront of a new round of sci-tech and industrial revolutions.[65] At the same time, he said that the country's 'quantum science and technology development still has many weak links and faces multiple challenges', and he called for study of the 'useful practices of other countries' to 'find the breakthrough point'. Xi therefore urged 'more strategic planning, policy support and investment in quantum science and technology', including talent cultivation.

His prognosis was that future advances would require the pursuit of long-term major projects, interdisciplinary integration, a 'systematic capability' for future development, and collaborative developments internationally in quantum science and technology. These would be enabled by favourable policies, investments in scientific research and the cultivation of a team of 'high-level talents'.[66] Xi assessed that China 'has basically caught up or reached the international advanced level'.[67]

The CAICT assessed in 2020 (after the Xi speech) that 'in many fields of quantum measurement, there is still a big gap between China's technological research and prototype development and the international advanced level'.[68] The academy named several subfields in which China was still lagging. In cutting-edge research on optical clocks, the accuracy index of China's prototype was 'two orders of magnitude behind the international advanced level'. The CAICT also said that the size and accuracy of China's nuclear magnetic-resonance gyroscope prototype was not competitive and that there was a gap in quantum target-recognition research and systematic integration. In addition, the CAICT spoke of a 'large gap between measurement technology research and the international leading level' and stated that the development of engineering and miniaturised products is 'still in its infancy'.[69]

China has not publicly revealed an S&T plan to its 14th Five-Year Plan (2021–25), but the outline of the general plan for social and economic development in that plan period contained important new initiatives for S&T.[70] For example, the plan announced the establishment of 'a number of national laboratories with a focus on quantum information, photonics and micro and nano electronics, network communications, artificial intelligence (AI), biotech and pharmaceuticals, modern energy systems, and other major innovation fields'.[71] Beijing added, 'we will focus our aim on AI, quantum information, integrated circuits, life and health sciences, brain science, bioengineered breeding, aerospace technology, deep earth and deep sea, and other cutting-edge fields, and carry out a set of major forward-looking and strategic national S&T projects'.[72]

For quantum sciences in general, the plan provided for setting up a national QIS laboratory, additional unspecified major projects, future industrial planning and promoting cross-disciplinary innovation.[73] On quantum metrology, there was a commitment to foster industry incubation and to accelerate 'future industries'.[74] Of special note, the plan specifically called for deepening military–civilian S&T collaboration and innovation in many fields: aerospace; AI; biotech; cyberspace; maritime; new energy; and quantum technology.[75]

Some 26 provinces and cities (including Anhui, Beijing, Guangdong, Shandong and Shanghai) included QIS in their subsidiary 14th Five-year Plans.[76] When the main Five-year Plan was published in 2021, China was tracking itself as second behind the US in scientific output for quantum sensing, followed by Japan, Germany and the UK, with the US ahead in quantum computing and China ahead in quantum communications.[77] China's technological level in an important measure of atomic clock development was 'still far behind the international advanced level'.[78] Key gaps in China's capabilities identified in 2021 included 'shortcomings in core device materials, equipment and instruments'.[79]

China's recent plans for quantum sensing appeared to be laid out in slightly more detail in the State Council's metrology development plan for 2021–35, which placed quantum sensing at the core of Beijing's ambition to become a world-leading power in metrology.[80] The rationale for this prioritisation, according to the plan, is that the field of metrology is 'fundamental for technological innovation, industrial development, national-defence construction, and is also important for building an integrated national strategic system'. Anhui, the province with most patents in quantum sensing and home to the leading quantum-science research institute, the USTC, subsequently published the provincial version of the plan.[81] Anhui has also set itself the goal of becoming the national leader in metrology with a focus on quantum sensing at the core. The two documents mentioned above provide insight into diverse policy subgoals, all of which are assigned to specific named entities in the province, but mention little in terms of useful detail for assessing current levels of development.

The focal point in China for the science and industry development of metrology is the National Institute of Metrology (NIM), which has several laboratories focusing on quantum sensing, including its crossover with applications in other fields, especially quantum communications and computing.[82]

As for military programmes, by 2012, there was evidence of funding in this area for quantum sensing. For instance, there was the National Defense Key Laboratories Fund, which supported a project by the China Aerospace Science and Technology Corporation (CASC) Second Academy analysing the characteristics of light scattering and radiation under quantum detection; another example was the CASC Fifth Academy's 508th Research Institute setting up a quantum-sensing laboratory.[83] By 2023, a US study of China's defence laboratories reported work from 2019 on the 'alleged development of a stealth-defeating quantum radar, and the anti-stealth JY-27 long-range surveillance radar'.[84]

Nevertheless, the relative position of quantum sensing in China in 2022 compared with other branches of quantum science can be seen in the output of papers, with the ratio for output of the top three provinces being approximately 17 to seven to two for communications, computing and sensing respectively.[85] Anhui, where the USTC is based, was the leading province for papers on sensing, while Beijing was in the lead for quantum computing and quantum communications.

Funding

Open-source data on funding is not comprehensive or consistent for China, but it is much more detailed for the United States.

According to the US NSTC in 2018, sensing was the field with the most funding compared to three others (computing, networking and quantum-enabled science).[86] By the end of 2022, that balance in annual spending had moved more consistently in favour of quantum computing. The US government estimated its investment to be over USD800m per year for the three years from 2021–23 in QIS (not counting DoD-administered programmes).[87] The private sector has reportedly invested at least several times as much, a funding balance not matched in China's ecosystem. The synergistic character of the US research-and-funding ecosystem has been identified as a major cause of the country's world-leading position in quantum sciences, at least as claimed by the US government.[88]

In contrast, China's total government investment was just under USD1bn for the 14 years to 2019, as shown in Table 2. (Consistent data for more recent years is not available.)

Reports that China has a USD15bn investment plan for quantum sciences cannot be supported by official Chinese sources.[89] A leading Chinese research centre has also refuted this claim.[90] The main initial Chinese source for this speculation appeared to be a news article that reflected a conversation between a journalist and academics rather than any official statement.[91]

Based on available public information, Chinese government funding for quantum sciences up to 2020 was arguably about 10–20% of the level of that in the US – though bilateral comparisons of this kind are questionable because the R&D systems of the two countries are not comparable. Private-sector investment to complement government funding of university-based research in quantum science in the US is arguably much higher than in China.

We can analyse the sources of funding within particular countries for quantum-sensing projects using data from the Web of Science database. A simple search produced a data set of 2,294 total papers, with the US clearly outpacing China (743 to 455) and the combined total of the US and its allies in the top ten for papers produced outpacing China by a factor of more than four (2,163 papers to China's 455).[92] Using that data set to identify funding agencies, we can see in Table 3 the dominance of the US and its allies in the top-ten funding agencies. However, we must note that this is

Table 2: **Funding levels in China for QIS**

Five-year plan	Amount (USD)
11th (2006–10)	150m
12th (2011–15)	490m
13th (2016–20)	~337m
14th (2021–25)	Unrevealed

Source: Data from Zhang Qiang et al., 'Quantum Information Research in China', *Quantum Science and Technology*, vol. 4, 2019, https://iopscience.iop.org/article/10.1088/2058-9565/ab4bea/meta a ranking based on numbers of papers published and funded by the top-ten funding agencies, not the total financial amounts dispersed.

The three US entities in the top-ten funders supported almost double the number of papers funded by the single Chinese entity (634 and 329), while the count for agencies of the US and its allies showed funding of almost five times the number of papers compared to China (1,536 compared to 329).

While this data is not fully reliable without more detail on the value of grants, it does suggest a greater breadth of funding sources for the US and allied countries relative to China.

Table 3: **Top-ten funding agencies for number of published papers on quantum sensing**

1	China's National Natural Science Foundation	329
2	US National Science Foundation	281
3	US Department of Defense	182
4	European Union	172
5	US Department of Energy	171
6	German Research Foundation	165
7	European Research Council	152
8	Japan's Ministry of Education, Culture, Sports, Science and Technology	146
9	Japan Society for the Promotion of Science	140
10	Japan's Grants-in-Aid for Scientific Research Program (KAKENHI)	127

Source: Web of Science Core Collection. Search using the terms 'quantum sensing' or 'quantum sensor*' in 'TOPIC' for the period 1990–2024, with the date of sampling being 24 January 2024

4. Innovation Systems

Governance at the national level for promoting quantum sensing sits within national innovation systems. These are unique to each country, and comprise a set of relationships (both enduring and dynamic) between research institutes, corporations, financial institutions, consumers, regulators and the international political economy. The previous section reveals a strong contrast between the governance approaches of the US and China to quantum sensing, and this is due in large part to the differences in their innovation systems. The analysis suggests that members of the US quantum-science community are relatively satisfied with the national innovation system in which they operate, in large part because they drive it, even as they continue to press for continuing expansion. Their Chinese counterparts have been less happy with their system mainly because they have less power over policy and less access to non-government funding, and the private-sector industry remains quite underdeveloped.[93]

A 2021 study by the International Institute for Strategic Studies (IISS) noted that the US national innovation system for information and communications technology remained the most productive and powerful in the world, as indicated by the size of the US digital economy, its leading role in global innovation, and the unmatched partnership between industry, government and academia (often called the 'triple helix').[94]

To help remedy the inferior position of its innovation system, China announced in 2023 the creation of the CCP Central Science and Technology Commission to lead a major reform. This was recognition by President Xi that the country's S&T ambitions were not being executed as quickly as they needed to be. Reforming the innovation system was seen as urgent, because compared with S&T great powers, China faced 'deficiencies in foundational and critical technologies, a lack of interaction between the educational and technical industries, and a shortage of industry members in the community for S&T innovation'.[95] The significance of setting up the new commission can be judged by two considerations: the status of the new body and the long history of attempted reform in China's high-tech industry policy over the last several decades.

The status of the new body as a high-level CCP entity is similar to that of the Central Military Commission and the Central Political and Legal Affairs Commission, historically two of China's most powerful organisations. Xi had also set up a Central National Security Commission in 2013. These commissions operate as 'political supra-ministries' to coordinate policies and channel political intent into action.[96] However, they are CCP entities under Xi's direct control rather than being under the control of the government led by the State Council and the premier as normal ministries are.

The turn in policy represented by the new commission is also an explicit recognition that Chinese reform of technology policy over the previous four decades, as successful as some efforts had been, had not been effective enough especially in the most advanced technologies. Xi must have concluded that without this additional high-level administrative change, China's innovation system would not meet the country's goal of being a leading world power by 2049. His judgement would have been influenced by increasing trends in the US toward severe export controls on China, slowing foreign investment in advanced technology, and the much higher need for national self-reliance in advanced technology demonstrated by the sharp and wide-ranging sanctions that the US, the EU and their allies have placed on Russia.

The case for better results from China's innovation system was certainly being made by its specialists in quantum sensing and quantum science. For example, a 2022 review of quantum geophysical-detection technology and equipment identified four challenges or shortcomings, all of them fundamental: R&D systems; core technology; innovation ability; and industrial application.[97] In July 2022, the Institutes of Science and Development of the CAS published a short news report that related – without further analysis or commentary – four recommendations from the US NSTC's strategy report on quantum sensing.[98] Published in this way, the US recommendations could be read as being endorsed by the CAS as acceptable goals for China.

At the end of 2022, a leading Chinese institute stressed that China's innovation system needed to be improved in fundamental ways in 'technical communication and exchange; division of labor and cooperation between industry; academia and research; and supply-chain construction'.[99] Moreover, the report anticipated future challenges in supply-chain maintenance, international cooperation and talent training because of growing complexities in the international situation.

5. Education Systems

A country's education system serves various purposes such as individual development, knowledge transmission and being a pipeline of talent for industry. A comparison of the relative strengths of the US and Chinese education systems for producing such a talent pipeline in quantum sensing must first observe that the boundary between the two countries in terms of personnel and knowledge flow is a very porous one. (US export controls on China, which include the transmission of knowledge through education programmes, have not traditionally extended to fundamental science.)

To produce its quantum-science talent pipeline, China draws on the US system in several ways. One of the most direct means is through Chinese citizens taking up employment in China after graduating from degree programmes in the US. This, however, is not the most common nor necessarily the most productive way in which China draws on the US education system.

China's S&T sector has expanded due to growing integration with the US economy over several decades. As a result, China can harvest the expertise produced by the American education system through a number of collaborative R&D programmes, joint ventures and direct contracting - subject of course to export controls. Moreover, because of the strong trend toward integration with G7 countries, China can rely on such avenues for talent or knowledge acquisition from US allies that are particularly strong in quantum-sensing education, including Germany, Japan and the UK. As pressures in the US to decouple from China grow, and as the latter pushes for a more self-reliant education pipeline in quantum sensing, China's dependence on foreign education systems will likely decline somewhat.

However, there are at least two factors that will limit the scope of any decline. Firstly, China wants to compete in the global quantum-sensing market, not withdraw from it. This will ensure an active and relatively open transfer of non-sensitive research and commercial R&D where China will draw heavily on foreign-educated talent. Secondly, the Chinese education system will remain relatively unattractive to foreign and Chinese talent because of the system's preference for bureaucratism, its politicisation and its lower quality in several areas (as seen in manipulated citation counts).

Education outcomes are shaped by a country's research culture and structures. For example, in key countries, quantum science has not enjoyed the standing of a distinct discipline.[100] This carries with it disadvantages associated with the allocation of infrastructure resources and the potential to offer foundational courses in related fields. At another level, in competing for external resources, cutting-edge research fields must operate in an environment where existing funding streams ('silos') are most often 'aligned with traditional disciplinary boundaries' that are 'often not well matched to the reality of making progress in quantum science'.[101] China has a highly centralised system for establishing disciplines and approving relevant degrees within each discipline across its entire university network. In each emerging field of advanced technology, this process takes years to mature.

For example, the first undergraduate degree anywhere in the world in quantum engineering was offered at the University of New South Wales (Sydney) in 2011.[102] The professors involved in that initiative assessed in 2022 that 'demand for such engineers is predicted to be in the tens of thousands within a five-year timescale, far exceeding the rate at which the world's universities can produce PhD graduates in the discipline'.[103] US universities – in a liberal system of independent or state-based institutions – commenced this process of undergraduate education in quantum sciences in 2015 at the University of Chicago, followed in 2018 at the University of Maryland and 2019 at Stanford University. The enterprise of boosting educational focus on QIS is therefore a relatively recent one.

China does not have a publicly available plan for education in QIS, but it is active in this area. In 2021, China's highly centralised education system authorised an undergraduate degree in this field for the first time, with the USTC and Tsinghua University in Beijing introducing it, among others.[104] However, it must be stressed that this is not a quantum-engineering degree, but rather one addressing the fundamental science. Of note, some observers do not rank the USTC as China's leading university for education in quantum sciences. Its undergraduate degree in this field was graded as quite poor (three stars out of the maximum eight) in the 2022 rankings of the Chinese Universities Alumni Association.[105] (The USTC was ranked as an eight-star teaching university in only one discipline – general physics.) On the other hand, the university has offered elective units (single subjects) in quantum optics and QIS since the early 1990s as well as master's and PhD programmes in quantum sciences 'for some time'.[106]

An industry newsletter (outside China) has offered some indirect corroboration of the assessment above regarding the low world ranking of China's quantum undergraduate studies. In a list of the top-20 universities' (otherwise unranked) master's and PhD programmes for QIS, as listed in Table 4, the USTC was the only Chinese institution. (The methodology of this ranking was not disclosed.)

Table 4: **Top-20 postgraduate degrees in QIS**

	Name of institution (country)
1	Lincoln Laboratory, Massachusetts Institute of Technology (US)
2	University of California, Berkeley (US)
3	University of Chicago (US)
4	Joint Quantum Institute, University of Maryland (US)
5	Center for Quantum Information Science and Technology, University of Southern California (US)
6	California Institute of Technology (US)
7	Stanford University (US)
8	Harvard University (US)
9	Carnegie Mellon University (US)
10	University of Colorado Boulder (US)
11	University of Waterloo (Canada)
12	University of Bristol (UK)
13	University of Cambridge (UK)
14	University of Oxford (UK)
15	École Polytechnique (France)
16	Delft University of Technology (Netherlands)
17	Austrian Academy of Sciences (Austria)
18	USTC (China)
19	National University of Singapore (Singapore)
20	University of Sydney (Australia)

Source: Kenna Hughes-Castleberry, 'Top 20 Quantum Computing Masters & Ph.D. Degree Programs in 2022', Quantum Insider, 6 June 2022, https://thequantuminsider.com/2022/06/06/top-20-quantum-computing-masters-ph-d-programs-in-2022/

Educating a work force for quantum applications is not merely a question of setting up new degree courses. The job (technical) roles valued most by US industry in the field of quantum sciences are quite varied: application researcher engineer; experimental scientist; theorist; and technician.[107] There are also up to 11 additional specialisations needed.[108] Many of these can only be developed in an industrial enterprise or in the largest R&D labs in universities or government agencies. Thus, the challenges of organising national education systems, including on-the-job training or professional development courses, to support the commercial production of quantum devices need to account for several quite distinct and complex fields of public policy for education well beyond assessments of education needs in the fundamental science.[109]

A 2018 US-government-directed study found that while continuing investments in basic science will remain foundational to developing technical research specialists, there will be bigger challenges in the need to 'build a quantum-smart and diverse workforce' and 'provide the key infrastructure and support needed to realize the scientific and technological opportunities'.[110] The challenges included the need to establish university faculties dedicated to quantum engineering or electronics and to introduce quantum physics in the classroom starting in primary school.[111] One analysis suggested that workforce retraining would be the most viable option in the coming years, since formal education pathways would take quite some time to mature.[112] These recommendations indicate just how essential the creation of new education and training programmes for the armed forces and security agencies in quantum sensing will be in next several decades.

In 2021, the US NSTC published a report on strategic approaches to quantum-capable workforce development.[113] To maintain the American lead in quantum technologies, the report recommended a more open approach than we have seen in emerging policy on technology restrictions, an emphasis on working with allies and closer attention to workforce development.[114] Moreover, the 2022 'Bringing Quantum Sensors to Fruition' report assessed that 'many scientists conducting basic research lack expertise in vast domains where their work might eventually be applied' and there would likely need to be 'cultural shifts within agencies and academia' to address the problem.[115]

While such talent deficits do exist in the US, the situation may well be worse for other countries, including China. The following questions arise. Are there tech-savvy cohorts in sufficient numbers in discrete technologies, such as quantum-sensing, in major powers including China, to enable such countries to gain a significant technological edge? How would we assess such capabilities? Would each country need a baseline number of graduates in every emerging field, such as quantum sensing, AI or hypersonics? Beyond raw numbers of tech-savvy cohorts in specialist fields, there is a need to align these cohorts with many other factors of workforce development and structure.

6. Research Directions

This section looks first at several bibliometric assessments already undertaken and compares their conclusions with some original bibliometric analysis undertaken for this paper with regard to the general field of quantum sensing and some of its subfields. This discussion of subfields exposes the divergence in national technological preferences of the US and China within the branch of quantum sensing. It also shows the potential shortcomings of assessing an American or Chinese lead based simply on aggregated quantities of publications identified through a very broad rubric such as 'quantum sensing' and variants thereof. We can note that for many articles on subfields of quantum sensing, the term 'quantum sensing' does not necessarily appear in the title or abstract, or even in the text.)

According to an analysis by four leading Chinese specialists on QIS, in the period before 2006 China only undertook 'minor projects mixed with other fields', when four major projects received funding for five years (the normal period for forward planning in China under its Five-year Plan system).[116] The four projects were quantum control; single quantum-state detection and interaction; long-distance communication; as well as research and verification of quantum experiments at space scale.

Few Chinese observers see their country's research outputs in quantum sensing as coming close to matching those of the US. For example, a 2022 Chinese survey accepted the findings of a US study concluding that while 'China ranks first in the world in terms of citations of quantum sensing papers, … the United States ranks first in the world in terms of influence'. The survey added, 'from 2011 to 2020, the US produced 235 highly cited quantum sensing publications'.[117] (While the total number of papers may seem low, other bibliometric studies confirm a relatively low number of scientific research papers in the category of 'highly cited' for the field described as quantum sensing or related to quantum sensors.)[118]

A 2022 CAS assessment saw the main research in quantum sensing (and measurement) as being based in China, the EU and the US, though it also mentioned Australia and Japan.[119] The mention of China together with the US and the EU was likely based on patriotic grounds rather than a firm assessment by the authors that China was of equal standing to the US and EU countries. The article seemed to suggest that China had a more project-based approach, while the US and the EU had more integrated, coordinated approaches built on large-scale cooperation between institutions and industry.[120]

The CAS paper noted that China had invested comparatively less in quantum sensing than in quantum computing and quantum communications and that in military applications, China was not at the same level as the US and some of its partners.[121] The article added that in military affairs, 'quantum-radar technology will subvert stealth technology and electronic warfare'. This subfield of quantum radar is one on which US public research output is well behind that of China, in large part because of a consensus in the US that such a capability is not viable. A RAND report also noted the differing levels of attention that China and the US devoted to subjects of military interest. According to the report, which relied on advanced searches of available data, compared to the US, published Chinese research from 2010–20 was weighted more heavily in favour of topics that the US DoD deemed as low priority.[122] For China, 41.4% of the publications fitted that category of low DoD interest compared with 16.1% for the US.

A bibliometric study by Indian scholars on the country of origin of leading research in quantum sensing from 1991–2020 reached similar conclusions about the US lead in the field, but they put China further down the rankings than Chinese sources. The scholars concluded:

- The US and Germany lead the world with a combined share of 50% of the global research output.
- The US, Germany and Italy are home to 13 of the top-15 most-productive organisations and home to 14 of the top-15 most-productive authors in the subject.[123]

Other comparisons from the Indian study showed the US and its allies in a very strong position relative to China.

Since the study reviewed the period 1991–2020, it may be seen as diluting China's relative strengths because the People's Republic entered the field more recently than other countries. This point, however, can easily be countered by the fact that the number of publications considered before 2005 was only a small fraction of the number considered after that year: 32 compared with 588.[124] Moreover, the long-term picture is important in establishing the degree to which quantum sensing has become an established field in particular countries, thereby allowing research institutions more time to build their capacity.

In checking the validity of these bibliometrics assessments, the author of this paper consulted the Web of Science database using a simple search (with the search terms 'quantum sensing' or 'quantum sensor') and more varied searches on certain subfields (using search terms like 'atomic clock' and 'quantum radar'). In all, 14 separate searches were conducted. The period covered was from 1990–2023 (to 26 April 2023), and the data was analysed according to countries/regions.[125]

In the simple search on the field of quantum sensing in general as noted above, the one using the broad rubrics, the US clearly outpaced China, and the 'US + allies' search outpaced China by a factor of more than four (1,533 papers to China's 346). For the 69 highly cited papers, 'US + allies' outpaced China 58 to six.[126]

In the subfield of quantum imaging, China and the US seemed neck and neck, but the 'US + allies' count was still heavily in their favour over China. We can therefore confirm the broad findings of the bibliometric studies cited at the start of this section. The US had a fairly commanding lead over China on a straight bilateral basis, and this lead was even greater when it came to an alliance perspective. There was also wide variation in which country led depending on the subfield of quantum sensing.

7. Industry Comparison

A specialist US assessment in 2023 compared the national industrial bases of China and the US for quantum technologies. The report concluded that for sensing, the US 'appears to be a world leader in this area – particularly in regard to actual deployment outside the lab – but Europe is strong as well, while China lags significantly behind'.[127] On the other hand, the report observed that quantum sensing was a difficult field to assess systematically because of a much smaller market size, the diversity of applications and discrete technologies as well as a relative lack of open-source reporting. That study is a highly comprehensive comparative assessment of US and Chinese industrial strengths in quantum sensing. This paper has not sought to duplicate that work.

Credible Chinese assessments largely concur with this US assessment of the relative standing of the quantum-sensing industry in both countries. One CAICT analysis concluded that American, British, German and Japanese companies dominated the upstream market, while American, Chinese and European companies dominated the mid-stream market. This analysis noted that the Chinese manufacturing scene in quantum sensing was still dominated by start-ups.[128] In an earlier CAICT report, causes given for the lack of market penetration of Chinese companies included an inability to supply commercial-scale production, product performance not meeting demand and small market scale (presumably regarding the domestic market).[129]

8. Patents

An analysis of patent trends can provide indications of the 'pace and dynamics of innovation at the invention stage' with respect to technological fields and subfields.[130] However, considerable care needs to be exercised in assigning a nationality to outcomes apparently reflected in the data. This is because patents are often filed on behalf of funding organisations that can be based in different countries from the researchers. Moreover, in some cases, the research in certain countries has not yet resulted in patents being finalised. It is therefore unwise to interpret patent data in any field, such as quantum sensing, 'as a direct measure of the level of innovation' of a specific country.[131] Assessing patent trends is nevertheless more reliable for helping make judgements about the prioritisation of investments in subfields.

A 2022 Chinese assessment of patent applications in quantum information showed the US in the lead of technological innovation in quantum computing (56% of applications) with China in second place but accounting for only 26% of applications.[132] In quantum communication and quantum measurement, China was assessed as leading for patent applications, accounting for 54% and 49% respectively, compared with the US representing 24% and 32% in those two categories.

Table 5: **Leading actors in patent applications in China, 2000–20**

	Organisation (country)	Number of patents
1	Samsung Electronics (South Korea)	63
2	Hamamatsu Photonics (Japan)	30
3	Toshiba (Japan)	26
4	Semiconductor Energy Research Institute (China)	25
5	Beijing University of Aeronautics and Astronautics (China)	22
6	Shanxi University (China)	21
7	University of Tokyo (Japan)	20
8	Sharp Corporation (Japan)	18
9	Boeing (US)	18
10	Shanghai Institute of Microsystem and Information Technology (China)	17

Source: Hu Qinglong, 'Research on International Competition Situation of Quantum Information Technology Based on Patent', *Frontiers in Business, Economics and Management*, vol. 6, no. 2, 2022, p. 207, https://drpress.org/ojs/index.php/fbem/article/view/3029/2958

While China may be far ahead of the US in patent applications in quantum sensing registered with the World Intellectual Property Organization (WIPO), and even further ahead of Japan, the top applicants for these Chinese patents are predominantly non-Chinese firms or individuals, as indicated in Table 5. Thus, patent activity in China is more extensive for firms headquartered outside China than for firms of Chinese origin. For example, a different 2022 Chinese study assessed that the US led in patent applications in China in six out of ten categories of quantum applications, while China led in three. The two countries were close to equal in the remaining category, in which both were behind Japan.[133]

Considering this broad diversity in the field of quantum sensing and noting the limitations of patent analysis derived solely in terms of quantity, the author undertook a deeper inquiry into patent numbers and their distribution.

An analysis of patent numbers for quantum sensing (using a simple search) in the PATENTSCOPE database of the WIPO, reflected in Table 6, shows the following distribution by location of patent office, while Table 7 lists the top-ten patent holders for the same search.

An analysis of patent numbers for a simple search on quantum imaging in the PATENTSCOPE Database shows the following distribution for the top-eight countries and

Table 6: **Number of patents for quantum sensing granted by location of patent office**

	Location of patent office	Number of patents
1	China	449
2	US	108
3	Patent Cooperation Treaty (in multiple locations)	64
4	European Patent Office (in multiple locations)	35
5	Japan	23
6	South Korea	15
7	Australia	13
8	India	11
9	Russia	10
10	Canada	8

Source: WIPO PATENTSCOPE database, simple search on front page (using the term "quantum sens*"~1) conducted on 17 January 2024

Table 7: **Top-ten patent holders for quantum sensing**

	Organisation (country)	Number of patents
1	Beijing Information Science and Technology University (China)	26
2	California Institute of Technology (US)	21
3	Wuxi Institute of Quantum Sensing (China)	18
4	Merck Patent GmbH (Germany)	18
5	State Grid Corporation of China (China)	16
6	Beijing University of Aeronautics and Astronautics (China)	15
7	Electric Power Science Research Institute, State Grid Anhui Electric Power Co Ltd (China)	15
8	Wuxi Quantum Sensing Technology Co Ltd (China)	15
9	Anhui Guosheng Quantum Technology Co Ltd (China)	13
10	SomaLogic Inc (US)	13

Source: WIPO Datascope database, simple search on front page (using the term “quantum sens*”~1) conducted on 17 January 2024

two multinational registration offices out of a total of 307 patents granted by the offices indicated (refer to Table 8).

Broken down by subfields of quantum imaging, Table 9 shows the count per office according to the top ten subfields.

Table 9 shows that in eight of the top ten subfields (cells shaded in grey), there are significant differences between China and the US. Notably, the United States' count is much higher than China's in the subfields G01T (measurement of nuclear radiation or X-ray), B82Y (specific uses or applications of nanostructures) and H01L (semiconductor devices). In contrast, China's count is much higher than that of the US for G06T (image data processing), G06N (computing arrangements based on specific models), G02B (optical elements or apparatuses), H04L (transmission of digital information) and G01S (radio direction finding). Also notable is that for three of the top-ten CPC codes (cells shaded in blue), other countries (mostly US allies) combined have more patents than either China or the US, showing that in these subfields, productive research in quantum imaging is somewhat decentralised.

The sharp divergence of priorities between the US and China is further revealed in a patent-data search that the author conducted on quantum radar (using the search term “quantum radar*”~1), which showed that China accounts for 63 of 73 results, while the figure for the US is only four. In contrast, a search on nanostructures and quantum optics (with the term “nanostructure*” and “quantum optic*”~1) shows 37 results. Out of these, 16 results are for the US with none for China.[134]

In assessing quantum technologies in general, one 2022 study concluded that even if one could argue that China was on par with the US, ‘this does not yet translate into a higher number of USPTO/EPO patents, or higher patent quality, when compared to US companies and universities’.[135] That said, as of 2021, China was second, ahead of Europe and Japan in patent filings according to this study.

Table 8: **Patents granted for quantum imaging by patent office**

Patent office	Number of patents
China	165
US	62
European Patent Office	27
Patent Cooperation Treaty	26
Japan	8
South Korea	6
Canada	4
Germany	3
Australia	3
UK	3

Source: WIPO Datascope database, simple search on front page (using the term “quantum imag*”~1) conducted on 17 January 2024

Table 9: **Quantum-imaging patents granted by patent office**

Cooperative Patent Classification (CPC) categories	Total number of patents	China	US	Others
G06T	73	57	11	5
H04N	59	22	21	16
H01L	54	10	21	23
G06N	53	35	7	11
G02B	31	22	3	6
H04L	26	19	4	3
G01T	25	1	11	13
H01S	23	5	5	13
G01S	20	11	3	6
B82Y	19	3	8	8

G06T Image data processing or generation, in general; **H04N** Pictorial communication, e.g. by television images; **H01L** Semiconductor devices not covered by class H10; **G06N** Computing arrangements based on specific computational models; **G02B** Optical elements, systems or apparatus; **H04L** Transmission of digital information, e.g. telegraphic communication; **G01T** Measurement of nuclear or x-radiation; **H01S** Devices using the process of light amplification by stimulated emission of radiation (laser) to amplify or generate light; devices using stimulated emission of electromagnetic radiation in wave ranges other than optical; **G01S** Radio direction finding; radio navigation; determining distance or velocity by use of radio waves; locating or presence detecting by use of the reflection or reradiation of radio waves; **B82Y** Specific uses or applications of nanostructures.

Source: Cooperative Patent Classification, ‘Table’, undated, https://www.cooperativepatentclassification.org/cpcschemeanddefinitions/table

9. Conclusion

Comparisons of US and Chinese standing in quantum sensing are likely to be of greatest value when they are more comprehensive (taking account of all main factors) and when they focus on the subfields of quantum sensing of most relevance to the strategic balance of military power and other aspects of national security. Such a study would be a substantial exercise requiring scientific, defence industry and military expertise and does not yet exist in the public domain.

Nevertheless, this report suggests strongly that in the coming decade, Washington will be significantly better placed than Beijing to achieve and deploy breakthroughs in quantum sensing for national-security purposes. At the same time, this assessment does not exclude the possibility that China could make militarily significant breakthroughs with little warning in one or two subfields of quantum sensing to the severe detriment of the other side.

There is an important policy question arising from this focus on subfields. What should the balance be between, on the one hand, policies that have a laser-like focus on distinct military or security breakthroughs in a small number of specific subfields and, on the other hand, policies that are based on broader geo-economic or even techno-nationalist assumptions, advancing the claim that in essence all Chinese critical technology development undermines US national security? This latter approach appears to be represented very well in President Biden's August 2023 declaration of a national emergency in technology policy. It will certainly promote a sweeping and less targeted mindset, even though it foreshadows mechanisms for review of individual technologies. It is not clear just what methodology will be used under the executive order to designate work in certain subfields as subject to further restrictions.

Another element for US intelligence agencies to consider is the risk of failing to discover breakthroughs by China in narrow subfields due to putting too much effort into broader, perhaps unachievable, generalised strategies of export control.

The case of quantum sensing and the accumulating number of other advanced or frontier technologies (such as AI) reveal serious challenges for the knowledge limits of policymakers. Only a few people involved in the decision-making processes will have an adequate understanding of the technologies for the types of budget and regulatory choices to be made. There is a risk that the more complex a scientific field is in both knowledge content and social construction (especially international linkages), the greater the temptation for government officials will be to resort to simplistic mechanisms based on very broad approaches. Such export controls may damage the international collaborative infrastructure essential for fundamental research.

The workforce deficit in key technologies, such as quantum, AI and even basic information security, remain profound and are not especially tractable to policy interventions. Even if constructive education and workforce policies at the national level can be devised, these will for the most part take one or two decades to mature. Foreign specialists will remain key to the national security of all states in the field of quantum sensing at the technical and policy levels.

An undue focus on compliance under the broader approach, or even the goal of decoupling, might indirectly weaken the necessary and fundamental activity of the transnational flow of basic science. This is to the detriment of fostering alliance strengths in science and industry. In the long run, this could also hinder developments in the US in the most promising new technologies.

One of the most significant elements of Sino-US competition in quantum sensing, as in other technologies, is the role that other countries play in strengthening or weakening the position of either. Washington can call on various close allies, such as Australia, Germany, Italy, Japan and the UK, whose capabilities taken together with those of the US far outweigh those of China. This consideration could usefully have even greater weight within US policy even if it runs counter to basic techno-nationalist impulses among some policymakers and political circles.

Notes

1 Some sources distinguish between the three broad fields of sensing: passive systems involving measurement of external elements; metrology (sensing of devices created for the purpose, such as atomic clocks); and active systems, which are based on a generated signal and usually rely on photons. Some studies identify quantum cryptography or quantum simulation as separate subfields, yet others identify quantum networking or the quantum internet as major subfields.

2 The first generation led to the development of x-rays and nuclear weapons.

3 Mallory Shelbourne, 'SECDEF Nominee Austin Affirms Threat From China, Will "Update" National Defense Strategy', USNI News, 19 January 2021, https://news.usni.org/2021/01/19/secdef-nominee-austin-affirms-threat-from-china-will-update-national-defense-strategy.

4 See the list of projects at the following URL: https://www.darpa.mil/tag-listtag=Quantum. The projects are found on the tab called 'Programs'.

5 For example, in July 2023, the Office of Science in the Department of Energy announced setting aside USD11.7 million in funding six new projects on 'whether, when, and how quantum computing might advance the frontiers of computational science'. See US Department of Energy, 'Department of Energy Announces $11.7 Million for Research on Quantum Computing', 27 July 2023, https://www.energy.gov/science/articles/department-energy-announces-117-million-research-quantum-computing. See also the Web of Science database for information on many other funded projects.

6 See National Quantum Initiative Advisory Committee, 'Renewing the National Quantum Initiative: Recommendations for Sustaining American Leadership in Quantum Information Science', June 2023, https://www.quantum.gov/wp-content/uploads/2023/06/NQIAC-Report-Renewing-the-National-Quantum-Initiative.pdf.

7 See Physics World, 'Quantum Teleportation Moves Into the Third Dimension', 7 August 2019, https://physicsworld.com/a/quantum-teleportation-moves-into-the-third-dimension/.

8 Zhang Zhihao, 'Xi Highlights Crucial Role of Quantum Tech', *China Daily*, 19 October 2020, https://www.chinadaily.com.cn/a/202010/19/WS5f8cc996a31024ad0ba7f62e.html.

9 Yang Sichen, '*Zai tan junmin ronghe, beihou de shenyi ni dong ma*?' [What's the Reasoning Behind Military Integration], www.81.cn, 15 March 2018, http://www.81.cn/2018zt/2018-03/15/content_7973046_2.htm.

10 See, for example, Xinhua, 'China's 176-qubit Quantum Computing Platform Goes Online', 31 May 2023, https://english.news.cn/20230531/0946675301284c1786b4ee27251c89a3/c.html.

11 See, for example, Liu Nana et al., 'Client-friendly Continuous-variable Blind and Verifiable Quantum Computing', *Physical Review A*, vol. 100, no. 6, December 2019. According to the Web of Science, the research was jointly funded by Brazil, Singapore and the US Air Force.

12 Kevin Klyman, 'The U.S. Wants to Make Sure China Can't Catch Up on Quantum Computing', *Foreign Policy*, 31 March 2023, https://foreignpolicy.com/2023/03/31/us-china-competition-quantum-computing/.

13 The White House, 'Executive Order on Addressing United States Investments in Certain National Security Technologies and Products in Countries of Concern', 9 August 2023, https://www.whitehouse.gov/briefing-room/presidential-actions/2023/08/09/executive-order-on-addressing-united-states-investments-in-certain-national-security-technologies-and-products-in-countries-of-concern/.

14 Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology* (Santa Monica, CA: RAND Corporation, 2022), p. 11, https://www.rand.org/content/dam/rand/pubs/research_reports/RRA800/RRA869-1/RAND_RRA869-1.pdf.

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16 One RAND paper, for instance, argued that sensing may be 'closest to useful commercial deployment but the least potentially disruptive', in Edward Parker, *Commercial and Military Applications and Timelines for Quantum Technology* (Santa Monica, CA: RAND Corporation, 2021), p. 1, https://www.rand.org/pubs/research_reports/RRA1482-4.html#download.

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31 See Defense Science Board, 'Applications of Quantum Technologies', October 2019, https://dsb.cto.mil/

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36 National Science and Technology Council, 'Bringing Quantum Sensors to Fruition', p. vi.

37 *Ibid*., p. 14.

38 Congress, 'H.R.6227 - National Quantum Initiative Act', Title 4.

39 See *Ibid*., Section 103.

40 See *Ibid*., Section 104.

41 According to the 'Bringing Quantum Sensors to Fruition' report, the Subcommittee on Quantum Information Science was set up under the National Quantum Initiative Act and coordinates federal R&D in QIS as well as related technologies in order to 'maintain and expand U.S. leadership in quantum information science and its applications over the next decade', in National Science and Technology Council, 'Bringing Quantum Sensors to Fruition', p. i.

42 *Ibid*.

43 The CAS is a government-directed body that serves similar purposes to the US National Academy of Sciences (NAS). The latter is a completely private enterprise charged with providing independent and objective advice to the government on science-and-technology matters. The CAS operates many of China's leading research laboratories, while its US counterpart carries out public-policy activities around science. The CAS also sets funding priorities for science research in China's state-run university system, while the NAS advises on research agendas for the United States' mostly private universities or those operated by the states.

44 See Li Guojie (ed.), *Information Science & Technology in China: A Roadmap to 2050* (Heidelberg: Springer, 2011), pp. 76–80 (for quantum computing) and pp. 140–142 (for quantum cryptography and communications). There is also reference to some underlying technologies (such as photonics) that could emerge as highly relevant to quantum sensing (pp. 67–75).

45 *Ibid*., pp. 60, 63, 104.

46 In China, the equivalent of legislative drivers might include formal statements of Communist Party leaders or policy statements from leading S&T organisations, such as the CAS or the Ministry of Education.

47 CAICT, '*Liangzi xinxi jishu fazhan yu yingyong yan jiu baogao*' [Quantum Information Technology Development and Application Research Report], 2021, p. 5, http://www.caict.ac.cn/kxyj/qwfb/bps/202112/P020211224561566573378.pdf.

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60 *Ibid*.

61 CAICT, '*Liangzi xinxi jishu fazhan yu yingyong yan jiu baogao (2018 nian)*' [Quantum Information Technology Development and Application Research Report (2018)], 2018 p. 3, http://www.caict.ac.cn/kxyj/qwfb/bps/201812/P020181221551983008723.pdf.

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63 *Ibid*., pp. 10–11.

64 *Ibid*. pp. 33–34.

65 Zhang Qihao, 'Xi Highlights Crucial Role of Quantum Tech', Qishi, 19 October 2020, http://en.qstheory.cn/2020-10/19/c_548156.htm.

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72 *Ibid*., p. 12.

73 *Ibid*., Preface, page un-numbered.

74 *Ibid*., p. 24.

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76 CAICT, '*Liangzi xinxi jishu fazhan yu yingyong yan jiu baogao (2021 nian*)', p. 5.

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108 *Ibid*., pp. 7–8.

109 See Clarice D. Aiello et al., 'Achieving a Quantum Smart Workforce', *Quantum Science and Technology*, vol. 6, no. 3, 2021, https://iopscience.iop.org/article/10.1088/2058-9565/abfa64/pdf. Within each country, there are many sets of actors who will need specialist technical education if they are to shape military technological outcomes in a given field. These include researchers and their institutions; research funders; engineers and designers to assemble prototypes; corporations or firms able to produce a new capability in numbers; a military testing-and-evaluation system; as well as a responsive military procurement system. In addition, there needs to be a doctrinal and operations mindset in the armed forces attuned to the new technologies, alongside operators in the field who can use the new capability. While this is a normal set of gateways through which any novel technology must pass to become militarily significant, the burdens of educating all these actors, especially government decision-makers, in the various relevant aspects of quantum sensing are not only daunting, but also growing in number and complexity.

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121 Yang, Xu and Tang, '*Guoji liangzi chuan gan yu celiang lingyu zhanlue bushu yu yanjiu redian*'.

122 Parker et al., *An Assessment of the US and Chinese Industrial Bases in Quantum Technology*, pp. 37, 77.

123 Brij Mohan Gupta, Surinder M. Dhawan and Ghouse Modin N. Mamdapur, 'Quantum Sensing Research: A Scientometric Assessment of Global Publications During 1991–2020', *International Journal of Knowledge Content Development & Technology*, vol. 12, no. 3, September 2022, p. 31, https://journals.sfu.ca/ijkcdt/index.php/ijkcdt/article/download/691/51.

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135 *Ibid*., p. 879.

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