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A conceptual framework for describing the future impacts of quantum sensors to national security

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Abstract

This research aims to describe the potential impact of quantum sensors on the Department of Defense and the Intelligence Community using a conceptual framework derived from an extensive literature review. The goal is to provide senior science and technology professionals and advisors with an architecture to discern the tangible impacts of quantum sensing systems on national security. The review consists of open-source scholarly publications and open-source datasets from Statista. Using this literature review, six variables were identified as having the highest potential to impact the development and application of quantum sensing systems. These variables are technical innovation, sensor application, national development, resource availability, human capital, and capital investment. This framework allows for the assessment of various categories of quantum sensors, such as atomic clocks, quantum electromagnetic sensors, quantum gravimeters, and quantum inertial sensors, in terms of their potential impact on national security.

Keywords: *quantum sensors, conceptual framework, technical innovation, sensor application, national development, national security*

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1. Introduction

The advancement of quantum sensing systems is likely to impact military assets, delivering strategic and tactical advantages in position, navigation, and timing (PNT). Moreover, quantum sensing's potential to revolutionize various domains aligns seamlessly with U.S. national security strategy with respect to gathering crucial information, assessing threats, and delivering decision advantage [1]. Quantum sensors, leveraging the delicate and precise nature of quantum states, will likely enable military and commercial enterprises to develop tools that enhance sensing capabilities far beyond the limits of traditional PNT sensors.

To meet emerging national security goals, the scope of this research was guided by four factors: military application, quantum technology type, quantum sensor viability, and quantum sensor design. While this research focuses on the military application of quantum sensors, the results can also be applied to other organizations, such as the Intelligence Community, due to shared mission sets. Additionally, discussion of advancements and needs in the private sector is necessary to provide context for military applications because of the symbiotic relationship between government- and private-sector research [2]. The research effort discussed in this article is founded on the assumption that quantum sensors will outperform classical sensors with respect to improvements in size, weight, and power—cost (SWaP-C) criteria.

The advent of quantum sensing necessitates that the U.S. military create and adopt a coherent collection management strategy to maintain awareness of related technologies being developed worldwide. Most quantum sensors are being developed with two primary goals. The first is to match the performance of traditional sensors but with lower SWaP or greater reliability [3]. The second is to develop quantum sensors with sensitivity and resolution that exceed what are possible with conventional or current technology, potentially at the cost of SWaP-C [3]. Various countries, including the United States, have made rapid advancements in quantum clocks, gravimeters, gyroscopes, and magnetometers that address at least one of these goals [4]. Despite these advancements, there seems to be a lack of concerted efforts for targeted quantum sensor development across the U.S. government compared to other quantum research areas, such as quantum computing [4]. As a result, the U.S. military, through the Office of the Under Secretary of Defense for Research and Engineering, has outlined four areas of quantum sensing systems research currently being conducted by various government entities: electromagnetic sensors, clocks, accelerometers and gyroscopes, and gravimeters [5]. These four areas will also set parameters for the scope of this research.

Current quantum sensing research efforts have various military applications. Quantum electromagnetic sensors aim to impact radio frequency (RF) detection through Rydberg atoms and their delocalized position from the nucleus, making them sensitive to electric fields. These sensors will likely provide a better alternative to the sensitive, wideband, portable RF sensors currently

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available through traditional sensing methods [5]. Atomic clocks have tactical applications in unmanned assets and classical PNT equipment [5]. Picosecond atomic clocks can be integrated into strategic assets, such as large, stable ground or naval platforms, for timing in global navigation satellite system–denied environments, while sub-nanosecond, atomic vapor cell optical clocks can be used for surface and subsurface timing in operational scenarios [5]. Quantum accelerometers can provide strategic-level inertial navigation for space, naval, and air assets, contributing to mission sets in Global Positioning System (GPS)–denied territories [5]. Paired with quantum accelerometers, quantum gyroscopes are poised to replace fiber-optic gyroscopes through thermal atomic beam sensors, which provide deep-space and underwater inertial measurement at a strategic level in GPS-denied locations [5]. Lastly, quantum gravimeters are being developed for alternative navigation, sensing, and guidance on subsurface and underground platforms due to their ability to use gravity fields to map specific regions [5]. With the Earth's gravitational map largely standardized, with the exception of minor natural interferences, alternative means of mapping and guidance can be achieved for missile assets and intelligence, surveillance, and reconnaissance capabilities [6].

Despite current quantum research efforts, concerns and gaps remain regarding the probable capabilities of quantum sensors for military applications. For instance, as the Laboratory of Physical Sciences at the National Security Agency states, it is unlikely that Rydberg communication receivers will surpass conventional RF sensors due to their bandwidth range limit of 10 MHz [4]. Currently, there is a lack of academic reporting on military-grade ruggedized sensors and internal communication among U.S. government agencies regarding quantum sensing research, development, testing, and evaluation due to conflicting assessments of fielded needs and current research efforts. This framework aims to serve as a standardized method of analysis for assessing quantum sensing capabilities and the likelihood of their development and implementation in military environments.

2. Quantum technology—a global analysis

Analyzing the data from a 2023 study, it is projected that quantum information technology will command a market ranging from $11 billion to $106 billion by 2040 [7]. This span underscores the significant uncertainty inherent in forecasting quantum technology's future market impact. Within this framework, quantum sensing is poised to become a key player, as it is currently positioned as the second-largest segment in the quantum technology market after quantum computing. The global market revenue for quantum sensing is forecasted to reach between $1 billion and $7 billion, indicating both its growth potential and the conservative estimates regarding its market size compared to its counterparts (**Figure 1**).

In addition, the distribution of quantum technology patents is an indicator of technological leadership. China has secured an unequivocal lead, possessing 56.6% of quantum sensing patents and 52.3% of all quantum technology patents globally from 2000 to 2022 [8]. The United States, while not at the forefront, holds a substantial 15.4% share of quantum sensing patents, ranking second in this domain [8]. Japan follows with a notable 13.6% share in quantum sensing [8]. While the number of patents recorded does not necessarily equate to the viability or innovative quality of the technologies presented, the volume of patents filed serves as a more objective quantitative measure, reflecting China's dominance in the quantum technology patent landscape and its ambition to lead the world in quantum sensing efforts (**Figure 2**).

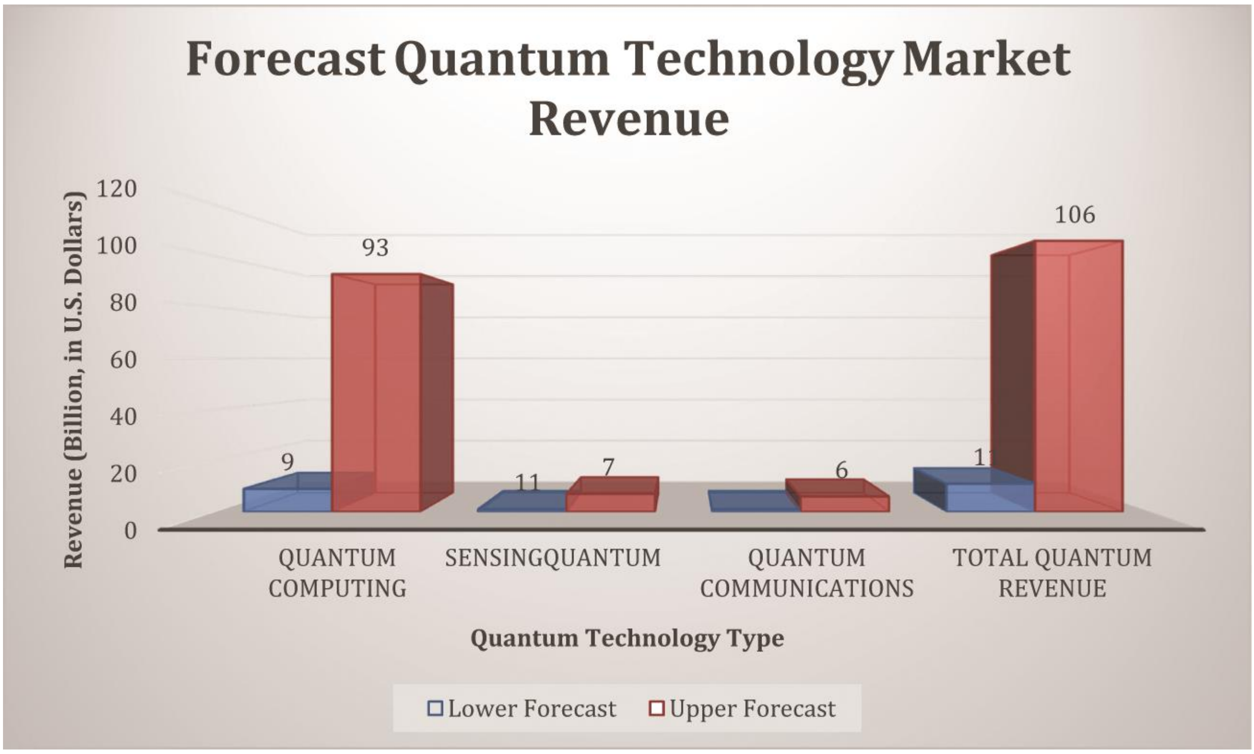

Figure 1 • Forecast quantum technology market revenue worldwide in 2040, by segment.

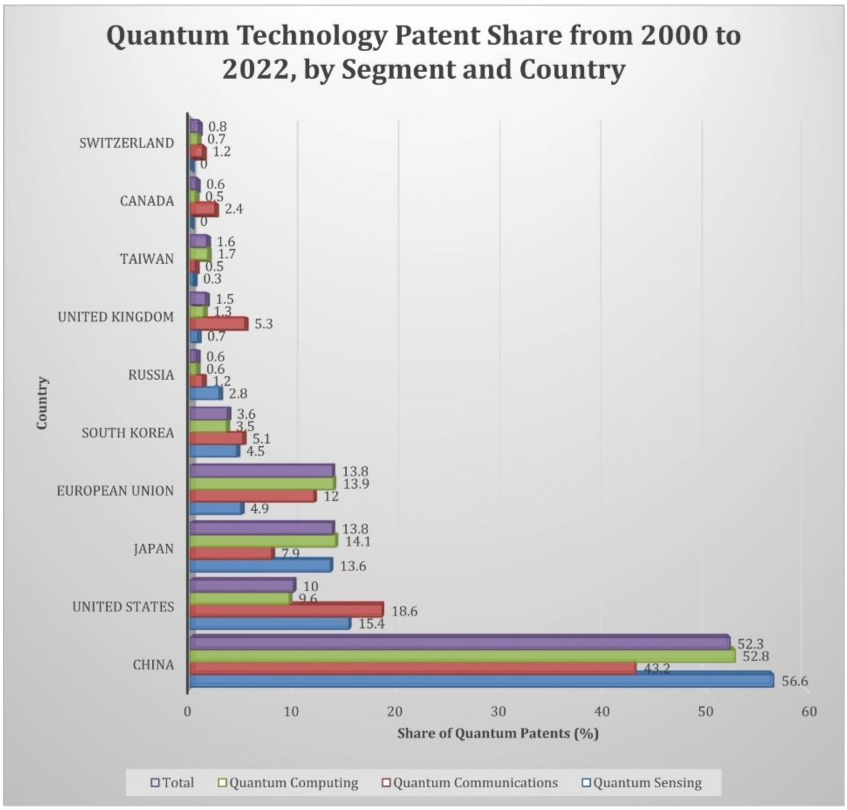

Figure 2 • Quantum technology patent share from 2000 to 2022, by segment and country.

Lastly, the expansion of quantum technology is evident in the increasing number of startup companies emerging across the globe. The data in **Figure 3** illustrate a burgeoning sector, with quantum computing leading the charge, hosting 223 startups worldwide [9]. By contrast, quantum sensing has the smallest footprint, with 23 startups [9]. This could be attributed to the maturity of quantum sensing technologies, such as atomic clocks, which have been in practical use for an extended period [10]. Consequently, innovation in quantum sensing is more likely to emerge from well-established entities, such as large corporations, research institutions, and government agencies. Overall, the total number of startups, at 318, indicates a vibrant and diverse quantum technology ecosystem.

The distribution of quantum sensing startups by country, based on current data, underscores the leading role of the United States, which reports 14 quantum startup enterprises [11]. Switzerland and Germany trail behind with five startups each [11]. Notably, China accounts for only three startups in the field—a figure that appears modest in contrast to the nation's dominant patent holdings, possibly due to the state-driven nature of its technological development and differing economic incentives compared to capitalist economies [11].

The discrepancy between the 47 total quantum sensing startups totaled here and the 23 from **Figure 4** raises concerns regarding the reliability of the data. This discrepancy may stem from factors such as multinational entities being counted in more than one country or the conflation of data where companies operate across multiple quantum technology segments. While the accuracy of the data may be subject to scrutiny, this snapshot reveals a concentrated effort within the United States to innovate and commercialize quantum sensing technologies to maintain a competitive advantage in an increasingly strategic domain.

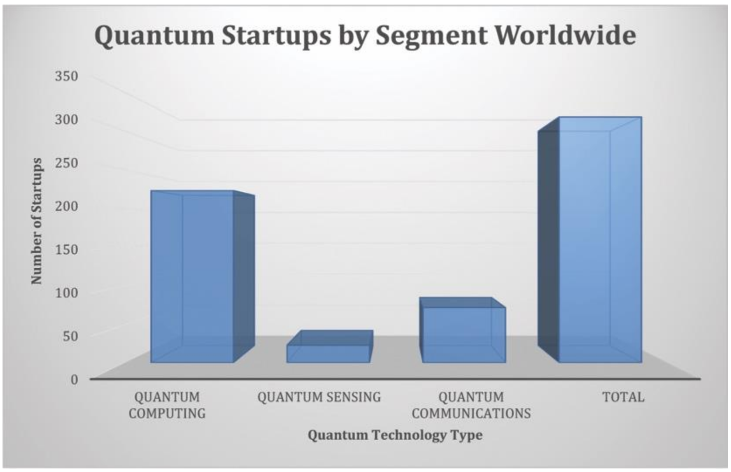

Figure 3 • Number of quantum sensing startups as of 2022, by country.

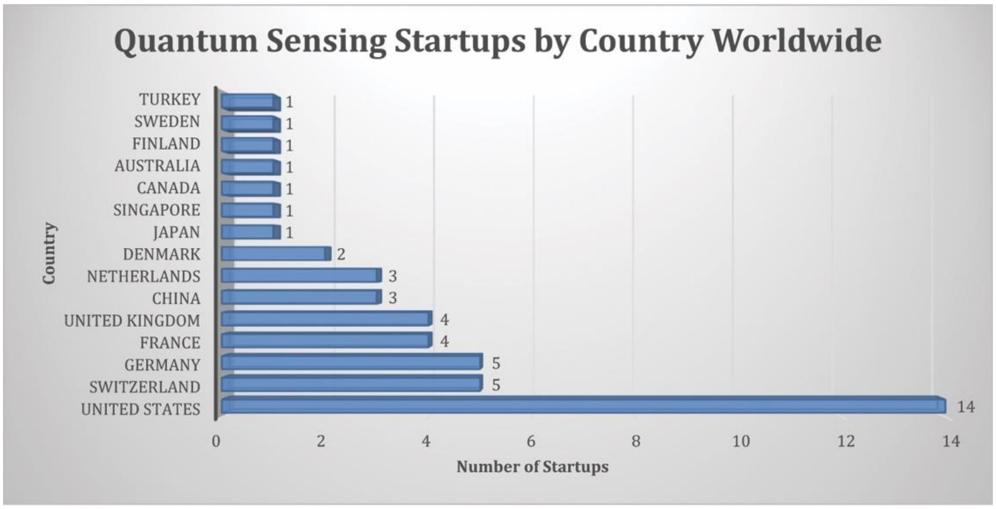

Figure 4 • Quantum startup companies by segment worldwide.

As we examine the total number of quantum sensing startups, it is also important to review the funding associated with quantum technology startups. As of December 2022, quantum computing startups have garnered the lion's share of funding, attracting $5.4 billion in investments [12]. This is significantly more than the funds allocated to quantum sensing, which stand at approximately $400 million, underscoring the heightened investor interest and perceived potential in quantum computing [12]. The distribution of funding reflects strategic priorities and market expectations within the quantum technology sector, with computing positioned as a particularly high-stakes and high-reward area of development (**Figure 5**).

The data published highlight China's strategic commitment to quantum technology, as demonstrated by its historic public funding amounting to $15.3 billion [13]. This figure notably surpasses the collective investment of European nations and significantly exceeds the United States [13] (**Figure 6**).

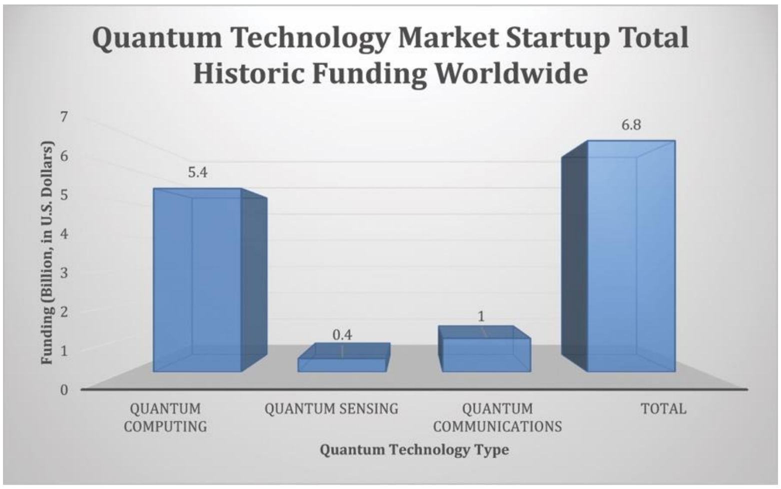

Figure 5 • Quantum technology market startup total historic funding worldwide as of December 2022, by segment.

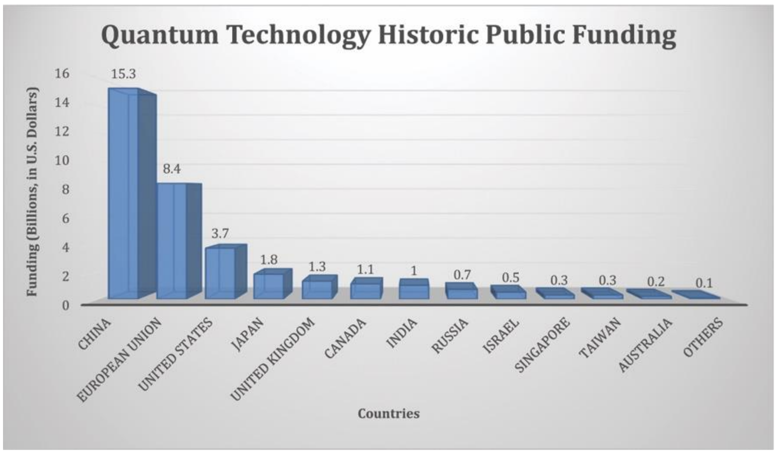

Figure 6 • Quantum technology historic public funding as of December 2022, by country.

3. A novel conceptual framework

3.1. Variable development

To establish a normalized conceptual framework for quantum sensor development, the first step was to determine independent and dependent variables. The independent variables are the types of quantum sensors being developed by the U.S. military. As previously stated, for this study, the only independent variables used are electromagnetic sensors, clocks, accelerometers/gyroscopes, and gravimeters. Dependent variables were determined through an in-depth examination of current information about each quantum sensing system type and its development. The authors documented the key factors needed for the development and implementation of each type of sensor, and then compared these factors across sensor types to identify overarching themes that became the dependent variables. The dependent variables constructed are technical innovation, sensor application, nation state (national development), resource availability (RA), human capital (HC), and capital investment (CI). The dependent variables and associated key factors can be found in **Figure 7**.

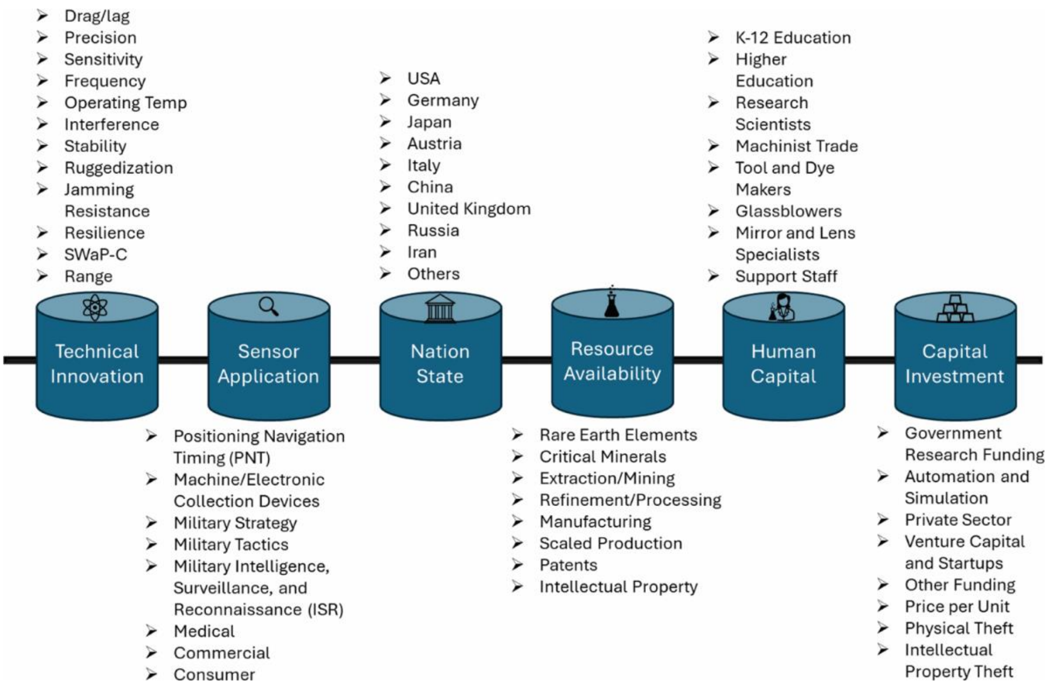

Figure 7 • Dependent variables with associated key factors.

3.1.1. Technical innovation

Technical innovation (TI) encompasses the effect of scientific and engineering discoveries and limitations in the realm of quantum sensors, considering both the sharing of information and the potential theft of valuable insights. The significance of TI in the context of quantum sensing is immense, particularly in emerging technologies, where breakthroughs often occur in binary leaps rather than through gradual progress, making them challenging to reliably predict [14]. Moreover, the environment in which these discoveries occur introduces several key factors. These include whether discoveries take place in countries that practice strict safeguarding of information or in those where the common practice is to freely share information. In addition, when discoveries emerge from government-contracted research, they may be classified as government intellectual property, potentially limiting dissemination [14]. The impact of quantum sensing systems on national security will likely be heavily dependent on this variable, as TI directly influences the timeline for a sensor's deployment into the conventional military force. On a broad scale, our research finds that the fielding of quantum sensors tends to be an engineering challenge based on range and environmental considerations [15].

3.2. Sensor application

Sensor application (SA) represents the advantage each individual quantum sensor may offer to the Department of Defense (DoD), exploring how these sensors can enhance strategic military capabilities through various use cases, ranging from strategic to consumer applications. SA is tied to the strategic or tactical edge that each quantum sensor can potentially offer to the U.S. DoD, specifically within the domain of PNT. When integrated into DoD systems, these sensors, theoretically, will provide heightened precision in targeting both strategic and theater munitions, support navigation in GPS-denied environments, and enable the detection of adversary activity [3]. Advancements in these critical areas could confer a significant advantage in the event of a conflict. Furthermore, this enhanced capability serves as an additional layer of deterrence, discouraging hostile actions by adversaries. This not only delivers a strategic advantage but also mitigates an adversarial defense capability. Overall, the SA variable plays a pivotal role in shaping the development of quantum sensors, as the perceived advantages they offer guide the importance of technology development, influence investment decisions, and ultimately impact U.S. DoD interests. This variable helps properly convey the perceived impact that these emerging PNT systems will have on conventional military systems. However, according to our research, the greatest impact of quantum sensors will be within the civilian sector, as they allow for improved monitoring of civil engineering projects and environmental conditions from space [16].

3.3. Nation state (national development)

Nation state, or national development (N_{uc}), measures the impact of a nation state's initiatives and programs for developing specific quantum sensing systems. This variable measures the impact of a country succeeding in the development of a specific quantum sensor before another country while considering the profound geopolitical implications of such achievements. This variable is measured by the national initiatives and programs investing time and development capabilities into the various quantum sensing systems. N_{uc} determines if the overall quantum sensor impact will be negative or positive with respect to the perspective of one country. As an example, if the United States is the first to develop and field a quantum sensor, the impact will be positive for the United States but negative for U.S. adversaries. N_{uc} stands at the heart of the strategic competition within the quantum sensor race, as it is readily apparent that the nation to first implement these sensors will seize a significant military advantage. Using McKinsey and Company's (2023) data, countries that would be major players in the nation-state variable are the United States, China, Japan, South Korea, Russia, Taiwan, the United Kingdom, and the European Union as a whole [11].

3.4. Resource availability

RA focuses on the availability of key periodic elements essential for the research, development, testing, and evaluation of novel quantum sensors and subsequent sensor production. RA can be succinctly described by the niche materials that apply in each sensor category. These materials are not unique to each sensor, as there are heavy overlaps in the four categories of sensors that frame this research. However, the goal of this variable is to isolate a lynchpin resource, which is the chokepoint for the development of quantum sensors. Furthermore, to ensure the production of quantum sensors after development, sufficient quantities of these materials must be available. RA sheds light on the overall resources required for the development and production of individual quantum sensors while highlighting the critical resource that may inhibit or enhance the development of these sensors as they emerge into full production capacity. Ultimately, it underscores the possible resource limitations that could potentially constrain the impact of a given sensor on U.S. DoD interests. Current constraints on resources needed to develop and produce quantum sensors include a country not possessing all the required components and SWaP-C tradeoffs. The first constraint could be mitigated through intergovernmental and/or research partnerships. The second constraint, SWaP-C tradeoffs, is dependent on mission and/or user need.

3.5. Human capital

HC evaluates the influence of human expertise, including the availability of experts within the DoD, research institutions, universities, and private commercial companies, on given quantum sensing systems. Analysis of the key factors that comprise the HC variable noted a scarcity of genuine experts, as many quantum information science and technology experts pursuing military-related quantum research predominantly focus on quantum computing and quantum communication. Given this scenario, it becomes imperative for the United States, in particular, to continue investing in HC to remain competitive in the quantum sensor race. Acquiring and nurturing experts in the quantum sensing field may be one of the most pivotal variables in quantum sensor development, as it demands a substantial amount of time to cultivate individuals with the expertise required to significantly contribute to the advancement of quantum sensor technology. HC is difficult to determine for each sensor type due to the lack of granular data for each specific category of sensor. However, HC can be used as a universal variable across all sensor categories. Currently, there are two considerations for the HC variable. The first is developing a highly trained workforce able to establish and conduct the laboratory experiments required to determine technical viability. The second is developing a multidisciplinary workforce comprised of physicists, end users, raw materials experts, and others to forecast the art of the possible both now and for future endeavors.

3.6. Capital investment

CI encompasses the financial resources invested by organizations in the research, development, and implementation of quantum sensors for military applications. CI includes contributions allocated by both government and commercial sectors toward research, development, and implementation of quantum sensors for military applications. The role of financial resources in any emerging technology is pivotal, and substantial investments are anticipated from both government and commercial entities. It is theorized that as military advantages for quantum sensor development and implementation grow, the supporting government will provide research and implementation funds. Simultaneously, the investments of the commercial sector are contingent on their ability to transform quantum sensor technology into a profitable venture. It is worth noting that commercial interests may drive the development of certain sensors to a point where they have dual-use applications, including military implementation. However, the military is the primary interested party in these sensing systems until a more cost-effective development cycle for these systems is made readily available [3]. Based on our research, CI is determined by market value for the private sector and perceived military need for government budget purposes.

3.7. Data collected

The data required to develop relationships between global quantum sensing resources and their future applicability to conventional military assets was a mix of quantitative and qualitative data. The literature used highlighted areas with in-depth, ongoing data collection and revealed data relationships between our defined variables that were not currently explored. Quantitative data included metrics related to the global supply of rare earth minerals used in creating quantum sensors, government and private-sector investment into quantum sensor development, and technical research data pertaining to the development of ruggedized military quantum sensors. Qualitative data included publications on foreign and domestic national initiatives for quantum sensing development and foreign and domestic military intentions to employ quantum sensors. The qualitative data collected amplified the quantitative data collected, as the qualitative data were used to explore future implications of the trends illustrated by the quantitative data.

4. Discussion

The findings below are not all-inclusive of all quantum sensor efforts. However, the data and analysis included are meant to provide a proof of concept for using the conceptual framework for comparative analysis. An example analysis of each of the four major categories of quantum sensors with respect to the conceptual framework is showcased.

4.1. Clocks

Though atomic clocks have existed since the first prototype was demonstrated in the early 1950s at Britain's National Physical Laboratory, they have been especially integral to DoD operations since the establishment of the Master Clock at the U.S. Naval Observatory (USNO) [17]. Various improvements in SWaP-C, both theoretical and applied, have paved the way for new generations of clocks that utilize quantum effects. The chip-scale atomic clock represented the first mobile application of quantum sensing and provided a spoof-proofing function with regard to time, reducing the need for hardware applications to rely on GPS connectivity with the USNO Master Clock. In the public sector, these technologies are being developed by the Air Force Research Laboratory, Army Research Laboratory, Office of Naval Research, and other governmental organizations, with an approximately 200-person-strong workforce. Atomic clocks tend to receive more attention from the military realm, as atomic clock programs account for over half of quantum technology funding [17].

4.1.1. Variable: technical innovation

With respect to atomic clocks, the goal of most relevant programs in the United States and abroad is to field a low-cost chip-scale atomic clock with a lower size, weight, and power profile than currently exists, as well as with day-long holdover (or much longer) of microsecond timing. Currently, costs are too high and production yields too low for most nascent capabilities, which prevents integration with GPS receivers and existing DoD PNT systems [5]. The Office of the Undersecretary of Defense for Research and Engineering (OUSD(R&E)) assesses that liter-scale atomic clocks, sub-liter clocks, rack-mounted optical clocks, GPS atomic clocks, and low-cost chip-scale atomic clocks must each typically be integrated into mobile systems for their advantage to be realized [5]. Whereas the liter-scale version has demonstrated performance in lab environments only, sub-liter, rack-mounted, and low-cost chip-scale atomic clocks have working prototypes. GPS atomic clocks stand alone both in having a fielded capability and in having an operational advantage with the highest assessed potential military impact [5].

With the notable exception of optical atomic clocks, the vast majority of currently deployed atomic clocks are considered microwave clocks due to their interrogation of microwave frequency transitions [18]. Newer microwave clocks include cold atom and ion clocks, while optical atomic clocks, also newer, rely on optical frequency transitions. Technical innovations in the capabilities of optical clocks may even see microwave clocks being replaced by 2040, especially due to advances in photonics [19]. Because of this, strategic timing may also be replaced by photonic alternatives.

4.1.2. Variable: sensor application

Though much of the promise of atomic clocks lies in improved GPS-denied environment PNT capabilities due to longer holdover times, it is important to note the potential for atomic clocks to enhance intelligence, surveillance, and reconnaissance (ISR) capabilities for similar reasons [20]. Hardware applications with demanding time and frequency requirements may be better enabled to fulfill their missions. Although many warfighting applications of these clocks may be speculative, these applications could presumably include use in platforms of every domain and with any degree of autonomy. Synchronized precise timing may also lead to enhanced imaging via large synthetic apertures; this quantum imaging, as well as other applications of timing for radar, sonar, and gravity mapping, is even more nascent than PNT capabilities and is not described in great detail here [19]. There is further informal speculation about the application of advanced atomic clocks for non-governmental purposes, such as in commercial aviation or financial markets. These applications are also not referenced in this research but rely on the same basic science.

4.1.3. Variable: nation state

The United States, People's Republic of China, the United Kingdom, and other European countries have each established themselves as leaders with respect to cold atom/ion microwave and optical atomic clocks. Whereas the United States and China have put varieties of the former into orbit, Scotland and Germany have already commercialized versions of the latter [20]. Though organizations such as USNO and the Naval Meteorology and Oceanography Command are incredibly relevant for the operationalization of atomic clocks, they are less involved in the advancement of new atomic clocks than those organizations under the National Quantum Initiative (NQI) [17]. Its overall strategy is to empower agencies using clocks, conduct other quantum technology research and development, prioritize end users, conduct feasibility studies, jointly test prototypes to identify the best clocks and sensors for each agency, develop broadly applicable components and subsystems to promote economies of scale, and streamline technology transfer and acquisition practices [21].

4.1.4. Variable: resource availability

Significant intelligence gaps also exist in identifying the resources required for advances in atomic clocks and their production. In addition to the need for raw materials such as cesium, rubidium, and hydrogen, as well as advanced microelectronics, the supply chains for atomic clocks are generally disparate and obfuscated by trade secrets and complexity. Considering this, lasers, laser systems, frequency control devices, and vacuums are each needed, although there is significant overlap between atomic clocks and other quantum technology applications in these requirements [5]. The type of atomic clock at hand also greatly affects the resource requirements; a greater degree of granularity with regard to which clocks require which resources is warranted.

4.1.5. Variable: human capital

OUSD(R&E) also found the overall priorities of quantum science initiatives to be enabling the fielding of quantum sensors and clocks, improving the industrial base and supply chain, and including fundamental research in science, technology, and engineering workforce development and utilization [5]. Beyond the STEM-based workforce that develops atomic clocks, it is important to note that programs such as the Next Generation DoD Atomic Clock program involve significant government experience as well, due to the integration of multiple agencies. Finally, there is considerable overlap in the expertise required for developing these technologies and administering relevant programs across the field of quantum technology.

4.1.6. Capital investment

Relevant programs are funded by OUSD(R&E) Quantum Science, among others, while Microchip, Teledyne, and Honeywell are considered the most relevant industry partners, particularly for low-cost chip-scale atomic clocks. For nanosecond-precision, sub-liter atomic clocks, the goal is to make them more robust—specifically, achieving a 10-year lifetime—and manufacturable at a cost of less than $30,000 per unit. Strategic clocks may also be important for large, stable platforms, as they are capable of a minimum month-long holdover [5]. The aforementioned firms play an important role in the development of atomic clocks primarily because of their fulfillment of DoD contracts. However, it will be important to track how the market develops as these technologies inevitably become more commercialized.

4.2. Inertial sensors

Quantum inertial sensors are primarily being researched for position and navigation improvements or replacements. Accelerometers and gyroscopes are two specific applications of inertial sensors. This research does not specify the particular testbeds or approaches used in each accelerometer and gyroscope program but acknowledges the existence of multiple important approaches for future considerations. The following sections describe the effort to develop quantum inertial sensors and aim to pinpoint the critical chokepoints within each of the six variables.

4.2.1. Variable: technical innovation

As highlighted by discussions with the Office of Economic Security and Emerging Technology, the primary challenges in advancing quantum inertial sensors are engineering-related rather than scientific. The scientific realm still plays a significant role in inertial sensors and offers the potential to improve theoretical values for precise navigation without GPS. Scientific research into inertial sensors is focused on achieving two additional goals. The first is identifying new approaches to developing a quantum inertial measurement unit (IMU). The second is developing an IMU that does not rely on cold atom interferometry or thermal atomic beam interferometry for accelerometers, or nuclear magnetic resonance for gyroscopes.

Therefore, the main challenge in developing military applications utilizing quantum inertial sensors lies in TI related to size, weight, and power, as they pertain to the SWaP-C of the product [5]. Reducing SWaP-C will require miniaturization of the component parts while maintaining superior performance over classical IMUs and avoiding sensor degradation due to electronic noise and platform constraints [5]. These technical challenges are further exacerbated by the demanding environments in which DoD platforms operate. The transition from lab testing to deployment in space, air, and maritime theaters presents a stark contrast in operational conditions.

4.2.2. Variable: sensor application

Quantum inertial sensors will likely have a targeted application in military systems, ranging from tactical to strategic advantage based on the IMU's parameters. It is assessed that, in the mid-term future (five to ten years), classical inertial sensors will not be replaced in consumer and industrial applications, with the exception being research and development efforts focused on lowering SWaP-C into profitable ranges [5]. Accelerometers and gyroscopes are not fully separate in some design schema, and packaged products consisting of quantum and mechanical accelerometers or gyroscopes will likely provide an intermediary stage for improvement over traditional, fully classical sensing systems [5]. The implementation of sensor packages consisting of quantum accelerometers and quantum gyroscopes is unlikely, as interferometric optical gyroscopes are currently assessed to have design space for improvement over the achieved parameters of quantum gyroscope approaches.

The implementation will likely be a combination of quantum and mechanical inertial sensors, which can provide beyond-strategic-grade navigation and positioning data with bias stability far surpassing classical systems. The other implementation case for quantum inertial sensors is to provide navigation-grade positioning with unit costs of IMUs at the tactical level. By lowering SWaP-C, more precise systems can be outfitted at the tactical and operational levels, while strategic systems begin to perform beyond strategic-grade capabilities in GPS-denied territories [5].

When discussing the specific SA variable, inertial sensors are the second-most likely sensor category to achieve commercial and industrial success behind atomic clocks, given the proper investment into research and development to reduce SWaP-C. Improvements to commercial aviation and its supporting industries are a viable avenue to increase funding for commercial use, but as these systems do not provide a revolutionary advancement over classical accelerometers and gyroscopes, this will be unlikely in the near term [20].

4.2.3. Variable: nation state

The leaders in research and development of quantum inertial sensing systems composed of accelerometers and gyroscopes are the United States and China. Allies of the United States developing quantum IMUs include Australia, the United Kingdom, Japan, and Canada, with European Union participation from France and Germany. Not all of these research and development efforts are government-driven, but all military applications identified by the authors are being driven by government and defense directives.

The United States has a vested interest in attaining quantum IMUs and precision guidance in GPS-denied territories due to the increase in electronic warfare capabilities globally and the jamming or positioning degradation occurring from natural sources. By increasing the fidelity of U.S. air and sea assets' positioning and navigation, non-wartime tactics and non-traditional warfare efforts will become increasingly viable ways of conducting operations in remote areas [20]. This capability can also proliferate the usage of autonomous underwater and aerial vehicles operating in environments experiencing heavy interference in their GPS navigation suites. The United States and its allies are investing heavily in the ruggedization and miniaturization of these systems to allow for implementation into DoD systems [20].

4.2.4. Variable: resource availability

The components of quantum inertial sensor packages are comprised of materials not fully sourced from U.S.-owned companies. Inputs from companies in France, Germany, Australia, Japan, and Italy are required due to their expertise in specific subcomponent areas. In discussions with experts at various DoD research laboratories, vacuum chambers, lasers, optics, photodiodes, and signal amplifiers were identified as the most critical elements of a quantum inertial sensor package, and not all of these components are readily available in the United States at the quality level required to ruggedize these sensors for DoD environments.

4.2.5. Variable: human capital

The authors of this article combed National Science Foundation and Department of Labor grant and program data but found no easily accessible open-source data on the number of personnel working on inertial sensors specifically. While various U.S. government documents have acknowledged research in quantum sensors, the authors are unable to assess the level of inertial sensor-specialized HC with enough granularity given the lack of available data. However, the type of HC necessary to develop quantum inertial sensors is multidisciplinary and highly trained. This is due to the material expertise and operation of sensitive laboratory equipment needed to set up lasers, optics, cryogenics, and vacuum systems to research ways to reduce the SWaP-C of quantum IMUs. While this is not necessarily granular, it is important to identify the HC for quantum inertial sensors when attempting to train and equip a workforce capable of developing engineering and technical breakthroughs.

4.2.6. Variable: capital investment

The U.S. Office of the Secretary of Defense required $75 million for quantum precision measurement system acquisition [22]. While not granular to inertial sensors, as of 2023, the free-space atom interferometers being developed for inertial navigation were documented to need $50–$100 million for subcomponent and prototype development [5]. This need could possibly be fulfilled by the FY2024 request for quantum information science systems procurement.

4.3. Magnetometers

Similar to traditional magnetometers such as compasses, quantum magnetometers utilize quantum mechanical principles to measure variations in the magnetic field of the Earth. They have applications for anomaly detection, magnetic navigation, and national defense. Like terrain following systems, magnetic navigation uses the Earth's crustal anomaly fields as a navigation signal [5]. Finally, the employment of magnetometers will likely provide the DoD with an increase in capability, agility, and assurance when receiving data in the spectrum [5].

There are three primary categories of quantum magnetometers: atomic vapor magnetometers, superconducting quantum interference devices (SQUIDs), and nitrogen-vacancy (NV) centers in diamond (NVD) [18]. Each is at a different stage of technical maturity. First, atomic vapor magnetometers use dense vapors of alkali metal atoms, allowing them to generate highly sensitive measurements of magnetic fields. By measuring the free precession of spin-polarized atoms, these magnetometers can detect changes in magnetic field strength, both in magnitude and direction [18]. Next, SQUID sensors, using small loops of superconducting wire and Josephson junctions, are able to detect changes in magnetic flux. These magnetometers are a mature technology with numerous applications for geophysical exploration and biomedical imaging. Finally, NVD is enabled by point defects in the diamond crystal lattice, where two carbon atoms are replaced by a nitrogen atom and a vacancy. As the scope of this research explores a broad overview of quantum sensors, this capstone will focus on military applications.

4.3.1. Variable: technical innovation

There are several examples of commercial quantum magnetometers in atomic vapor cells and SQUID-based sensors. The limitations of quantum magnetometers that utilize the SQUID approach involve developing cryogenic solutions that resist the environmental challenges faced by DoD platforms. Thus, they are commercially used in laboratories and are restricted in operational viability [23]. The latest technical challenge for atomic vapor-based magnetometers is miniaturization, similar to chip-scale atomic clocks. The next step in increasing sensitivity to pico-tesla levels involves approaches that exploit NVD or defects in silicon carbide (SiC). NVD and SiC approaches will be inhibited by the technical capability of their resources and the source of the materials.

4.3.2. Variable: sensor application

Due to the sources of data used in the original study and the implications for national security, this section has been omitted from this version of findings. Please contact the authors for more information.

4.3.3. Variable: national state

Based on the applications listed in previous sections, the United States is heavily interested in developing magnetometers with low enough SWaP-C and high enough performance to provide new vectors for navigation and anomaly detection. The lower the size, weight, power, and cost of a unit, the more flexible its integration into a system can be. This could provide more capabilities for mapping facilities with unmanned autonomous systems or strategic navigation on space-based assets. The application is heavily dependent on the SWaP-C of the specific magnetometer.

4.3.4. Variable: resource availability

While SQUID magnetometers have the highest degree of sensitivity, price increases in cryogenic liquids, portability concerns, and transportation obstacles have restricted SQUIDs to static facilities or industries with high profit margins [18]. Furthermore, NVD magnetometers face technical obstacles, including the achievement of higher sensitivity through increasingly pure diamond samples and the need for SWaP-C reduction in support equipment. Finally, atomic magnetometers must strike a delicate balance between entering a market that supports their growth and avoiding the proliferation of the technology to the point that unit costs become unsustainable. Securing a foundry that develops NVD and SiC samples of high enough quality for use in sensitive DoD platforms will be imperative for the United States if it wants to utilize quantum magnetometers of the highest sensitivity without a chokepoint.

4.3.5. Variable: human capital

Outside of the overall quantum precision measurements and semiconductor industries, quantum magnetometers aiming to achieve GPS-independent navigation will require human resources beyond the hard science of quantum physics. These include expertise within the geophysical surveillance community, the magnetic anomaly community, and a close working relationship with suppliers of high-quality raw minerals for NVD and SiC. This is a sparse section of research for electromagnetic sensors, and granular data signaling any specific HC numbers for magnetometers alone was not found through our data collection.

4.3.6. Variable: capital investment

Beginning in 2023, the United States implemented a 3- to 5-year funding plan for quantum magnetometer research. This funding consists of $35 million for solid-state and SQUID approaches to magnetometers [5]. Furthermore, there is approximately $30–$60 million of unfunded but achievable progress in optically pumped magnetometers, depending on the prioritization of higher-priority capabilities [5]. The second unallocated $30–$60 million is projected for advanced research and prototype development, with acquisition and sustainment of the sensor being achievable in five to ten years [5].

4.4. Gravimeters

Quantum gravimeters are the final independent type of sensor evaluated using this conceptual framework. Due to their high sensitivity and stability, these devices can analyze gravitational forces from the mass beneath the Earth's surface, allowing for the detection of underground voids and density variations. Such capabilities make quantum gravimeters crucial for applications in geophysics, natural resource exploration, environmental monitoring, and infrastructure health monitoring. In addition, military applications are also possible, such as navigation in GPS-denied environments and the detection of underground facilities [24].

Quantum gravimeters have the potential to significantly outperform traditional gravimeters. Traditional gravimeters, such as spring-based or superconducting gravimeters, measure gravity using mechanical or superconducting elements [25]. Although effective, they are limited in sensitivity, stability, and susceptibility to long-term drift. Quantum gravimeters, relying on quantum mechanical principles, offer significant improvements in these areas, leading to higher precision, reduced noise, and enhanced stability over time, making them superior for many scientific and practical applications [24].

Quantum gravimeters are currently in various stages of development and deployment. Research institutions and commercial entities are actively refining these devices to make them more compact, robust, and user-friendly. Several prototypes have been successfully tested under laboratory and field conditions, demonstrating their potential. However, widespread commercial availability and routine use in practical applications are still under development, with ongoing efforts to address technical and cost-related challenges [5].

4.4.1. Variable: technical innovation

As a cutting-edge technology, quantum gravimeters rely heavily on scientific breakthroughs which are often binary in nature, representing sudden leaps from theory to application [14]. These breakthroughs can drastically enhance the precision, sensitivity, and overall performance of quantum gravimeters. However, the unpredictable nature of these advancements makes the pace of development difficult to predict, and progress can occur rapidly and unexpectedly.

Today, major breakthroughs are necessary for quantum gravimeters to improve their ruggedization, size, weight, and constant application. Quantum gravimeters are produced and used almost exclusively in a laboratory environment. They will need to be ruggedized to become more transportable and resilient to external conditions [26]. This includes not only sensitivity to temperature but also to vibration. Additionally, current quantum gravimeters weigh hundreds of pounds and occupy at least a cubic meter of space. Furthermore, the cost of quantum gravimeters remains incredibly high, ranging from $500,000 to $1 million per unit. It should be noted that finding cost information on these technologies can be difficult due to the newness of commercial availability.

Lastly, quantum gravimeters require a breakthrough in application. Currently, the most advanced models, which combine both absolute gravimetry and gravitational acceleration, must be moved from point to point and allowed to process for several minutes. This means they are mostly stationary sensors, and breakthroughs are needed for integration into mobile platforms. However, implementation in moving vehicles is possible for advanced quantum gravimeters with further development [24].

4.4.2. Variable: sensor application

Quantum gravimeters, encompassing both absolute gravimeters and those measuring gravitational acceleration, support a variety of sensor applications. These applications span multiple military uses, including PNT, potential measurement and signature intelligence (MASINT) collection, and ISR capabilities. Quantum gravimeters enhance PNT systems by providing precise gravitational field measurements, improving accuracy in areas with weak or unavailable GPS signals. This is particularly valuable for submarines, underground facilities, and operations in dense urban settings or other GPS-denied environments. MASINT could be developed from or augmented by quantum gravimeters, as these devices could identify subsurface changes, hidden structures, movements, or mass variations, providing critical data for intelligence analysis. Additional strategic military applications include detecting and mapping underground bunkers, missile silos, and other strategic installations. Furthermore, quantum gravimeters' theoretical ability to detect submarines and space threats may prove strategically relevant [27]. Tactically, quantum gravimeters could be used to detect landmines, tunnels, and other subterranean threats. In ISR roles, they provide high-resolution gravitational field data, potentially enabling the detection of concealed enemy assets and movements. Quantum absolute gravimeters, when combined with conventional acceleration gravimeters, have demonstrated viability from airborne platforms, showing promise for use in moving platforms [28].

However, their greatest impact will most likely be in the civilian sector. Commercially, quantum gravimeters may prove invaluable in resource exploration, such as locating oil, gas, and mineral deposits. They are also employed in civil engineering for infrastructure monitoring, detecting subsurface anomalies, and assessing the stability of buildings and bridges. Furthermore, they play a crucial role in environmental monitoring, including groundwater detection and volcanic activity monitoring. Some of this monitoring may even be viable from space [16].

4.4.3. Variable: national state

Key nation-states making significant progress in quantum gravimeter development include the United States, China, the United Kingdom, and France [29]. The United States leads with advancements driven by government investment and research efforts [30]. U.S. allies have also leveraged their scientific expertise and technological infrastructure to make strides in the development of quantum gravimeters [31]. The United Kingdom has supported national initiatives driving research and development in quantum gravimeters [32]. France's research efforts have led to important theoretical and practical advancements in this technology. Similar to the United Kingdom, China has made significant progress through state funding and national programs [33].

4.4.4. Variable: resource availability

This research did not identify any chokepoint resources for quantum gravimeters. While these devices require specialized resources and components, they are not considered limiting factors. Essential components for quantum gravimeters, such as ultra-high-vacuum systems, cryogenic cooling systems, and specialized lasers, are widely used in multiple technologies and cannot be classified as chokepoint resources. However, the complexity of integrating these components underscores the technical challenges involved in producing quantum gravimeters [30].

4.4.5. Variable: human capital

The development and production of quantum gravimeters require highly specialized knowledge and expertise in quantum mechanics, optics, and engineering. There is a limited pool of highly trained professionals in these fields, and a shortage of skilled labor could pose a significant bottleneck. The complexity and precision required for quantum gravimetry demand extensive training and experience, which cannot be rapidly scaled. It is estimated that the field of quantum gravimetry will continue to experience increasing demand for skilled HC as quantum sensing applications demonstrate value in the energy sector [34]. This growing demand exacerbates the existing shortage of professionals with this skill set. Addressing this issue will require significant investment in education and training programs to cultivate the next generation of quantum experts, as well as international collaboration to share knowledge and resources. Without a concerted effort to expand the talent pool, advancements in quantum gravimeters could face substantial delays.

4.4.6. Variable: capital investment

The United States invests heavily in quantum sensors through the DoD, the National Institute of Standards and Technology, and the National Science Foundation. This support is bolstered by initiatives such as the National Quantum Initiative Act. The DoD acknowledges the strategic advantages of quantum gravimeters and actively invests in their development [35]. In addition, government-based research organizations, such as the Army Research Laboratory, fund research to enhance navigation, detection, and surveillance capabilities [30].

In the private and commercial sectors, several companies are actively developing quantum gravimeters and receiving capital for their development. For instance, U.S.-based ColdQuanta focuses on quantum atomics and cold atom technology, specifically targeting quantum gravimeters [36]. These investments underscore the significant interest and resources being directed toward the development and deployment of quantum gravimeters, recognizing their potential impact across strategic, scientific, and commercial domains.

5. Findings

5.1. Quantum clocks

There is significant diversity within this category of quantum sensors, with atomic clocks varying in their technological foundations and national security implications. Describing each relevant capability in detail is beyond the scope of this research. However, this interdisciplinary study supports and complements other efforts to describe the new atomic clock ecosystem. As reductions in SWaP-C are realized, low-cost chip-scale atomic clocks will become a reality, greatly improving the PNT capabilities of hardware applications across every domain. Chip-scale atomic clocks will also enhance capabilities at both tactical and strategic levels [19]. Though this discussion of technology readiness is informed by the nature of microwave and optical phase transitions, it focuses primarily on how the United States, China, and allied nations have advanced in their development of atomic clock capabilities. This study also recognizes the complexity of supply chains, HC, and CI in advanced atomic clocks. Each of these variables can be better understood by the DoD and should be addressed through future research and analysis.

5.2. Quantum magnetometers

Quantum electromagnetic sensors are likely the most diverse sensor category in terms of development level and intended applications. While outside the scope of PNT, anomaly detection using chip-scale atomic magnetometers could provide advancements for civil engineering and geophysical surveys. These two applications do not create a PNT advantage but could augment positioning and navigation in uncertain terrain. Magnetic navigation is likely to provide DoD platforms with an auxiliary method of wayfinding. However, its viability depends on TIs in ruggedization and miniaturization for NVD-based electromagnetic sensors.

The supply chain and CI by public and private entities can likely be pinpointed for electromagnetic sensors that have matured into commercial products, such as those utilizing atomic and SQUID-based applications. However, supply chains impacting DoD interests have not been identified in this research. This is due to the fact that miniaturized and cost-effective sensors are not yet available for DoD applications.

5.3. Quantum inertial sensors

The impact of inertial sensors on national security and traditional military sensing systems is likely to be limited in the near term. Over the next two to three years, advancements in quantum accelerometers and gyroscopes may occur if funding remains consistent with historical trends. However, this timeframe will likely not be sufficient to transition these testbeds from laboratory environments to operational use in DoD settings due to thermal and electromagnetic effects on the sensors. In the mid-term (five to ten years), innovations in engineering could enable quantum accelerometers and gyroscope packages to be introduced into maritime, air, and space platforms—provided that current limitations are overcome.

The supply chain for quantum inertial sensors is currently unestablished and is likely to remain so unless the technology becomes widely adopted for commercial and industrial applications. However, with inputs from national initiatives and taskings to various agencies, it may be possible to identify the emerging supply chain for quantum inertial sensors and assess their scalability for mass production.

5.4. Quantum gravimeters

Research on quantum gravimeters reveals significant potential, but substantial development is required before they can be widely adopted for DoD use. At present, their utilization in military applications is unlikely to have a noticeable impact on national security due to the need for further advancements to enhance their applicability. Most quantum gravimeters must remain stationary and are highly sensitive to vibrations and extreme temperatures. In addition, their bulky size and heavy weight pose logistical challenges [24]. Moreover, traditional gravimeters do not have widespread military applications, and quantum gravimeters have not yet demonstrated sufficient advantages in SWaP-C to justify significant additional CI [37]. Future research and investment may be more effectively sourced from civil and commercial sectors.

Military use cases for quantum gravimeters could be transformative if their full theoretical potential is realized. They could enhance PNT capabilities, particularly in GPS-denied environments, and may be developed to detect adversarial submarines and underground facilities. However, current quantum gravimeters have only niche applications. For example, they can detect underground facility structures but only when positioned almost directly overhead on the surface. This process requires significant setup time and extensive data analysis. Moreover, specialized personnel are needed to operate the equipment and interpret the collected data. Airborne gravimeters can detect variations in surface densities caused by mass differences, potentially identifying large tunnel systems constructed by insurgents [28]. Nevertheless, this capability requires air superiority to conduct overflights in set patterns, and the verification of this capability was not established in this research. In addition, research suggests potential uses for quantum gravimeters in space to detect space debris, but it remains unclear if they would outperform existing space debris detection sensors [27].

The most immediate benefits of quantum gravimeters to national security are likely to stem from their contributions to environmental, civil, and commercial sectors [Campbell]. In geophysics, quantum gravimeters have demonstrated potential in detecting magma movement and providing early warnings for potential earthquakes. They may also be useful in monitoring polar ice variations and changes in sea levels [16]. Civilian applications include detecting underground voids beneath construction sites, measuring soil subsidence, and monitoring infrastructure health [16]. However, the most significant impact of quantum gravimeters is likely to be in the energy sector. These sensors could be used to detect underground natural resources, including fossil fuels, offering substantial benefits to national and global energy strategies [30].

6. Conclusions

As research and development on quantum sensors continues, it becomes increasingly vital to assess a nation's efforts in a normalized and systematic way. As part of the proof of concept for this conceptual framework, the authors conducted a qualitative comparative analysis between two countries, which will be published separately, as some findings are highly sensitive. The proof-of-concept analysis supports the use of this conceptual framework to generate a holistic view of the impact on national security as each quantum sensor system reaches maturity. When fully analyzed, the six variables—technical innovation, SA, national development, RA, HC, and CI—will provide insights into the most significant challenges to fielding these systems, as well as justification for continued funding for programs aimed at enhancing a nation's warfighting capabilities in an increasingly asymmetric warfare environment. While this framework presents a simplified, non-exhaustive view of a complex system, it nonetheless offers a succinct overview of the pivotal factors contributing to the realization of a quantum sensing advantage for a given nation. This research serves as a technological forecast, suggesting that quantum sensing systems are the quantum technology closest to impacting national security. It provides national security and science and technology advisors with concrete evidence to inform far-reaching defense decisions.

6.1. Recommendations

The recommendations generated from this conceptual framework are tied to national policy issues. While the current iterations of U.S. national strategy documents do not explicitly mention quantum sensing, other published documents related to U.S. national security—such as President Biden's Executive Order 14105, which focuses on U.S. investment in certain national security technologies and products in countries of concern—imply the need for quantum science applications. One recommendation is to explicitly state which emerging technologies, particularly in the realm of quantum sensing, should be safeguarded by U.S. military and commercial entities [38]. In addition, a policy or method for measuring quantum technological readiness from a military perspective—assessing both the potential military impact and operational readiness of a given sensor category—is necessary. This may have significant implications for how programs are structured.

6.2. Future research

Future research should apply the current conceptual framework to perform comparative analyses of other countries conducting quantum sensor research. Secondly, the authors aim to develop a weighted quantitative method to standardize analyses among entities assessing quantum sensor impact. This would enable more consistent comparisons across different assessment entities. Lastly, the authors intend to apply the conceptual framework to other emerging quantum technologies to determine whether it is universally applicable or needs modifications based on the specific technology being studied.

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