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Sensibility about Sensing: A Socio-Technical Evaluation of Quantum Sensing Implications for Nuclear Deterrence

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Executive Summary

The question of when and how new technologies could disrupt nuclear deterrence has generated a lot of literature in the security studies field, though consensus around disruptions that should be anticipated and appropriate policy responses remain elusive. Piecemeal methodological approaches that inconsistently consider technical characteristics, recognize underlying strategic debates, and assess social factors that shape perceptions around the new technologies result in misguided or incomplete evaluations. In addition to impeding attempts to forecast the pace and consequences of technological change, the limited scopes imposed by these narrower analytic lenses hinder the identification of a diverse set of meaningful policy options for governing military innovation and crafting corresponding adjustments to nuclear force structures. This brief presents a more integrated, sociotechnical analytical approach to evaluate how technological innovation impacts deterrence and strategic stability requirements (and vice versa). It urges for consideration of key technical factors to reduce uncertainty inherent in technological innovation and argues the importance of examining underlying disagreements in deterrence theory and social factors that contribute to competing perceptions of technology effects and foster disagreement over necessary policy responses. Leveraging a contemporary case study, quantum sensing, the brief demonstrates the value of a more integrated analytical framework to inform policymaking under conditions of technological uncertainty. In doing so, it critiques assumptions and informs misperceptions about the development and deployment of "emerging technologies" in existing policy and academic literature.

Introduction

Conjectures about the consequences of technological innovation have become a prominent feature in nuclear deterrence literature in recent years.[1] Across academic and policy analyses, many caution that the rapid pace of innovation in areas like artificial intelligence (AI),

[1] This policy brief is based on the author's dissertation, *Schrodinger's Technology is Here and Not: A Socio-Technical Evaluation of Quantum Sensing Implications for Nuclear Deterrence,* (University of Maryland, 2023). Research for the dissertation was made possible by generous support from the Carnegie Corporation of New York.

hypersonics, and quantum sensing could reshape the nature of nuclear deterrence in sudden and unexpected ways. Yet assertions of what these disruptions may entail range dramatically, from implying that new technologies could herald the demise of deterrence to arguing that they could critically bolster strategic stability.

Despite the overwhelming interest in the intersection of technological innovation and nuclear deterrence, analyses are often siloed across disciplines and stakeholders. Security studies analysts commonly ignore key technical aspects of innovation that could inform more realistic development timelines and illuminate constraints that will limit operability upon deployment. Furthermore, the attempt to establish some positivistic answer about whether an innovation is “stabilizing” or “destabilizing” often ignores internal disagreement. Competing deterrence theories have different conceptions of vulnerability, which lead to divergent perspectives on appropriate policy responses. Lastly, social factors that shape innovation and provide a broader scope of policy options are often overlooked. Making predictions about how emerging technologies will affect strategic stability without a nuanced consideration of the underlying technologies, strategic perceptions, and social dynamics behind innovation fosters misperceptions about the process through which technologies are likely to emerge and impedes efforts to explore the full array of potential policy responses.

Recent analyses of quantum sensing implications for nuclear deterrence illustrate this problem. Some scholars and policymakers have warned that new sensing technologies may render second-strike capabilities vulnerable by making submarines easy to locate and intercontinental ballistic missiles silos destroyable by precision conventional or low-yield nuclear weapons.[2] Others have questioned the technical likelihood of such scenarios.[3] These diverging assessments create conflicting views on the impact quantum sensing could have on deterrence and how policymakers should respond. A core assertion of the recent Bipartisan Strategic Posture Commission is that technological change provides an impetus for unfettered military innovation and force structure buildup to avert risks of an adversary achieving an asymmetric advantage.[4] Others, although far fewer, argue in favor of technological restraint and agreements to constrain nuclear force buildup to avert arms racing risks.[5] Disagreement over the requisite policy response is made more contentious by the geopolitical backdrop of renewed technological competition

[2] Rose Gottemoeller, “The Standstill Conundrum: The Advent of Second-Strike Vulnerability and Options to Address It,” *Texas National Security Review*, Vol. 4, No. 4 (Fall 2021), pp. 115-124; Keir Lieber and Daryl Press, “The New Era of Counterforce: Technological Change and the Future of Nuclear Deterrence,” *International Security*, Vol. 41, No. 4 (Spring 2017), pp. 9-49.

[3] Katarzyna Kubiak, “Quantum Technology and Submarine Near-Invulnerability,” *European Leadership Network* (December 2020).

[4] “America’s Strategic Posture: The Final Report of the Congressional Commission on the Strategic Posture of the United States,” 2023, https://armedservices.house.gov/sites/republicans.armedservices.house.gov/files/Strategic-Posture-Committee-Report-Final.pdf.

[5] For example, in Europe: Ryan Swan and Haig Hovaness, “The arms race in emerging technologies: A critical Perspective,” *European Leadership Network*, February 9, 2021, https://www.europeanleadershipnetwork.org/commentary/the-arms-race-in-emerging-technologies-a-critical-perspective/; Lindsay Rand, “Reducing Strategic Risks of Advanced Computing Technologies,” *Arms Control Today,* January/February 2023.

among multiple major powers.[6] Current literature fails to resolve this debate, or even to articulate the source of such fundamental disputes.

This paper presents a socio-technical analytical approach to evaluate the interconnection between technological change and deterrence, focusing on the quantum sensing case study. First, the paper evaluates the treatment of emerging technologies in existing literature. It then outlines a framework that incorporates consideration of technical characteristics, recognizes points of contestation over strategic stability requirements, and emphasizes actors and social mechanisms that drive technology development and deployment. The paper then demonstrates the framework's utility by applying it to evaluate a contemporary case study: quantum sensing. Integrating each of these analytical dimensions contributes to a more complete understanding of the interconnectedness between technology development and strategic stability, providing better insight on possible avenues for policy mediation. The analysis finds that quantum sensing is unlikely to render some unambiguously disruptive capability. Rather, new sensors will afford iterative improvements, resulting in marginal strategic effects that are subject to interpretation. Although adherents to damage limitation logic may perceive any marginal improvement as disruptive, the analysis concludes that quantum sensors are unlikely to undermine conditions of mutual vulnerability that underpin the assured destruction logic for deterrence. Acknowledging the latter fosters a greater appreciation of arms control and technological restraint policies.

Emerging Technology Treatment in Existing Literature

Many analyses have sought to detail the complex nature of "emerging technologies" and estimate the implications for nuclear deterrence, viewing the problem through different analytical lenses. Some articles focus on individual technologies, attempting to identify all possible strategic implications.[7] Others focus on certain aspects of strategic stability, approaching disruption from a technology-agnostic angle.[8] A smaller group have attempted to develop categorical frameworks to map out how technologies broadly alter various aspects of deterrence and strategic stability.[9] However, the existing literature suffers from three key methodological and conceptual gaps that constrain policy insight.

First, many security-focused analyses lack technical depth which could reduce some of the uncertainty that plagues assessments around technological innovation.[10] Omission of technical detail is often justified under the argument that emerging technologies are characterized by uncertainty. While more accurate technical detail cannot reduce uncertainty entirely, it can inform where uncertainty arises from and indicate areas for which there is a high degree of

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[6] For example: Caitlin Lee, "Winning the Tech Cold War," *The RAND Blog*, August 2023, https://www.rand.org/pubs/commentary/2023/08/winning-the-tech-cold-war.html.
[7] For example: James Johnson, "Artificial Intelligence: A Threat to Strategic Stability," *Strategic Studies Quarterly*, Vol. 14, No. 1 (2020), pp. 16-39.
[8] For example: Rupal Mehta, "Extended Deterrence and Assurance in an Emerging Technology Environment," *Journal of Strategic Studies*, Vol. 44, No. 7 (2021), pp. 958-982 and Jane Vaynman, "Better Monitoring and Better Spying: The Implications of Emerging Technology for Arms Control," *Texas National Security Review*, Vol. 4, No. 4 (Fall 2021).
[9] The example most relevant to the proposed framework is Christopher Chyba, "New Technologies and Strategic Stability," *Daedalus*, Vol. 149, No. 2 (Spring 2020), pp. 150-170.
[10] For example: Lieber and Press, "The New Era of Counterforce," *International Security*, pp. 9-49.

consensus on roadblocks and opportunities for success. It also provides greater clarity on a technology's innovation trajectory, which is often longer than assumed in mainstream emerging technology narratives which assert that the pace of innovation is accelerating rapidly.

Second, the treatment of a strategic assessment as a positivistic evaluation of a technology as stabilizing or destabilizing ignores the fact that there are long-standing disagreements in deterrence and security theories.[11] These theoretical disagreements act as refractive lenses, effectively viewing the same information on technological innovation as producing different consequences for constructs like "deterrence" or "strategic stability." Failure to recognize the dissonance across these stakeholder perspectives ignores likely roadblocks to reaching consensus in strategic analyses, and on policy and governance approaches.

Third, most emerging technology analyses treat technological artifacts as the primary instigators of disruption, ignoring the human actors that drive innovation. [12] This curtails consideration of social factors that are neither technical nor strategic in nature, but which shape innovation and thus also affect deterrence and the technology innovation process. This is exacerbated by the fact that many analyses ignore historical case studies which could empirically inform social factors that have historically influenced decision-making regarding technological innovation and deterrence, and which provide insight on precedents for certain innovations.

Proposal of a Socio-Technical Framework

To address these insufficiencies in the existing literature, I developed a socio-technical framework that applies three distinct analytical lenses to provide clarity on the likely trajectories for technology development and deployment. I tested and refined the framework by applying it to five case studies of decision-making about strategic technologies considered "emerging" in years past: hypersonics, ballistic missile defense, stimulated isomer energy release, remote vision, and satellite imagery.[13] The framework prescribes consideration of:

1. Technical characteristics that affect the challenges and opportunities associated with developing, manufacturing, and deploying a new technology. These factors should guide a technical analysis to shrink, if not eliminate, uncertainty around a technology's timeline for development and ease of acquisition. They should also indicate how a certain technology differs from alternative counterparts to indicate important areas of disruption.

2. The capabilities which could be afforded by a new technology. Distinguishing between technologies and capabilities recognizes that development of a technology does not necessarily translate to a strategically significant effect, but rather it may afford some capability that then imparts a strategic effect. Evaluation of capabilities requires consideration of difficulties in leveraging a technology to achieve a strategic effect. The

[11] For example: Marina Favaro, Neil Renic, and Ulrich Kuhn, "Negative multiplicity: Forecasting the future impact of emerging technologies on international stability and human security." (2022): 107.
[12] For example: Michael Mazarr, Ashley L. Rhoades, Nathan Beauchamp-Mustafaga, Alexis A. Blanc, Derek Eaton, Katie Feistel, Edward Geist, "Disrupting Deterrence: Examining the Effects of Technologies on Strategic Deterrence in the 21st Century," *RAND Research Report*, 2022; Chyba, "New Technologies and Strategic Stability."
[13] Lindsay Rand. *Schrodinger's Technology Is Here And Not: A Socio-Technical Evaluation Of Quantum Sensing Implications For Nuclear Deterrence.* Chapter 4 (2023).

strategic benefits or risks of those capabilities are not self-evident; they can be interpreted differently depending on different strategic narratives, adding another source of disagreement beyond technical uncertainty.

3. Social factors that are likely to influence the actors who produce the technology and champion its development to achieve strategic capabilities. Identification of social dynamics at play in a technology's actor network informs both the drivers of perceptions around a technology and its effect as well as non-strategic and non-technical factors that influence innovation. Social factors are accounted for by considering the actors, institutions, and communities involved in a technology's production and application.

Quantum Sensing Overview

Quantum sensing is an emerging technology that has matured enough to generate a significant amount of concern regarding its potential consequences for nuclear deterrence. Quantum sensors are instruments that leverage quantum phenomena to measure physical properties, such as electric fields, magnetic fields, gravitational fields, and acceleration.[14] Because of their unique operating principles, quantum sensors may achieve higher sensitivities with lower size, weight and power (SWaP) parameters, depending on the application and the progression of innovation.[15]

In the military domain, quantum sensing technologies could yield improvements to several important strategic capabilities, including better detection and tracking of targets and greater navigation accuracy in adverse environments.[16] Potential deterrence implications include the use of quantum sensors to improve accuracy in missile navigation and to track mobile delivery systems such as nuclear submarines.[17] Dramatic improvements in these capabilities, either through quantum sensors or other technological innovations, would notably influence the survivability of second-strike forces and the feasibility of a disarming first strike against fixed targets like missile silos.[18] The advent of such capabilities could profoundly impact force structure and posture requirements, yet limited research has been performed to critically appraise claims of a looming technological disruption. Moreover, myriad unexplored social factors have contributed to exaggerated expectations around the feasibility for quantum sensors to achieve these enhancements.[19]

[14] C. L. Degen, F. Reinhard, and P. Cappellaro, *Rev. Mod. Phys*. Vol. 89, No. 035002 (2017).
[15] For example: Jens Pogorzelski, Ludwig Horsthemke, Jonas Homrighausen, Dennis Stiegekotter, Markus Gregor, and Peter Glosekotter, "Compact and Fully Integrated LED Quantum Sensor Based on NV Centers in Diamond," *Sensors*, Vol. 24, No. 743, 2024.
[16] Michal Krelina, "Quantum technology for military applications, *EPJ Quantum Technology*, Vol. 8, No. 24 (2021); and Edward Parker, "Commercial and Military Applications and Timelines for Quantum Technology," *RAND Research Report*, 2021.
[17] Sarah Gamberini and Lawrence Rubin, "Quantum Sensing's Potential Impacts on Strategic Deterrence and Modern Warfare," *Orbis*, Vol. 65, No. 2 (2021); and Katarzyna Kubiak, "Quantum Technology and Submarine Near-Invulnerability," *European Leadership Network* (December 2020).
[18] For example: Gottemoeller, "The Standstill Conundrum"; and Lieber and Press, "The New Era of Counterforce."
[19] Discussed in Frank Smith III, "Quantum technology hype and national security," *Security Dialogue*, Vol. 51, No. 5 (2020).

Quantum Sensing and Nuclear Deterrence: A Socio-Technical Analysis

This section applies the proposed analytical framework to evaluate the state of quantum sensing research and development (R&D) more rigorously, and to explore the disagreements in and drivers of dialogue on the deterrence implications of quantum sensing. First, it examines the technical characteristics for quantum sensors to evaluate the state of R&D and establish reasonable limits that can be expected for innovation. Next, it explores how this technical analysis and residual uncertainties are ignored or interpreted through the lenses of competing logics for deterrence when security experts and policymakers predict the strategic effects of capabilities that could be afforded by quantum sensing. Finally, it identifies the actors and social influences shaping the quantum sensing R&D network. The following section will draw upon this integrated analysis to highlight the value of applying the socio-technical framework and to inform policy recommendations.

<u>Technical Characteristics</u>

An evaluation of quantum sensing R&D progress is complicated by the fact that a wide variety of sensor types are being developed. The composition, production, and operability characteristics across the different sensor types varies dramatically, depending on the base material used and the target for the sensor's measurement.[20] Furthermore, each type of sensor has unique operability constraints; for example, some operate with lower precision at room temperature, while others achieve much higher sensitivities but require ultracold temperatures or other systems control conditions that heavily constrict real-world applications.[21]

The primary R&D thrust for developing widely deployable quantum sensors is finding an optimal balance where a sensor can maintain a reasonably high sensitivity while requiring limited systems control infrastructure to reduce size, weight, and power consumption and afford greater mobility. However, fundamental design limits will impede the optimization of extremely high sensitivity with minimal stabilizing components.[22] Therefore, this inherent tradeoff must be accounted for when evaluating improvements across all sensor types.

Tables 1 and 2 provide sensitivity estimates based on recently published experimental results and operability considerations for various quantum sensor platforms (and non-quantum alternatives). The two tables are categorized based on their application in measuring magnetic field gradients and rotation. These are two sensor types whose applications would be highly relevant for producing capabilities that could disrupt nuclear deterrence. As Table 1 shows, newer quantum-enabled magnetometers are not outperforming their predecessors. Though, in some cases they are more compact or have fewer operating requirements compared to extremely sensitive older sensors (SQUIDs and SERFs, i.e.). Table 2 shows a similar pattern for quantum-enhanced and non-quantum gyroscopes.

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[20] Christopher Richardson, Vincenzo Lordi, Shashank Misra, and Javad Shabani, "Materials science for quantum information science and technology," *MRS Bulletin*, Vol. 45, No. 6 (2020), pp. 485-497.
[21] Eunmi Chae, Joonhee Choi, and Junki Kim, "An elementary review on basic principles and developments of qubits for quantum computing," *Nano Convergence*, Vol. 11, No. 11 (2024)
[22] For example, tradeoffs discussed in "Bringing Quantum Sensors to Fruition," *A Report by the Subcommittee on Quantum Information Science Committee on Science of the National Science and Technology Council*, March 2022.

Table 1: Magnetometer Survey

Sensor Type	**Resolution ($T/\sqrt{Hz}$)**	**Operability and Deployment Constraints**
Optically Pumped Helium[23] [CAE]	10^{-12}	Dependent on field orientation in relation to Earth's magnetic field (would impact operability motion).
NV-Center Diamond[24]	10^{-12}	Requires better diamond fabrication and characterization techniques; decreasing the size (and diamond volume) to increase mobility could decrease sensitivity.
SQUID[25]	10^{-15}	Most systems require some cryogenic capability; susceptible to motion noise (less sensitive when moving).
Cold Atom[26]	10^{-10}	Very nascent technique; requires cryogenics.
SERF[27]	10^{-16}	Very limited bandwidth and operational range; requires temperature control.
Transmon Superconducting Qubit[28]	10^{-12}	Requires cryogenics; operability not defined in mobile setting.
Flux Superconducting Qubit[29]	10^{-11}	Requires cryogenics; operability not defined in mobile setting.

[23] Jie Zhang, Yanzhang Wang, Chao Wang, and Zhijian Zhou, "Performance Enhancement by Investigating on Excitation Parameters of Helium Cell in ^{4}He Optically Pumped Magnetometer," *IEEE Sensors Journal*, Vol. 22, No. 23 (2023).
Jeffrey Schweiger. *Evaluation of Geomagnetic Activity in the MAD Frequency Band (0.04 to 0.6 Hz).* (Naval Postgraduate School Thesis, 1982). Gregor Oelsner, Volkmar Schultze, Rob Jesselsteijn, and Ronny Stolz, "Performance analysis of an optically pumped magnetometer in Earth's magnetic field," *EPJ Quantum Technology*, Vol, 6, No. 6 (2019).
[24] Jixing Zhang, Lixia Xu, Guodong Bian, Pengcheng Fan, Mingxin Li, Quming Liu, and Heng Yuan, "Diamond Nitrogen-Vacancy Center Magnetometry: Advances and Challenges," *Arxiv*, 2020, https://arxiv.org/pdf/2010.10231.pdf; John Barry, Jennifer Schloss, Erik Bauch, Matthew Turner, Connor Hart, Linh Pham, and Ronald Walsworth, "Sensitivity Optimization for NV-Diamond Magnetometry," *Arxiv*, 2019; Ryoto Katsumi, Masaki Sekino, and Takashi Yatsui, "Design of an ultra-sensitive and miniaturized diamond NV magnetometer based on a nanocavity structure," *Journal of Applied Physics*, Vol. 61, No. 82004 (2022).
[25] M Buchner, K. Hofler, B. Henne, et al., "Tutorial: Basic principles, limits of detection, and pitfalls of highly sensitive SQUID magnetometry for nanomagnetism and spintronics," *Journal of Applied Physics*, Vol. 124, No. 161101, 2018, https://doi.org/10.1063/1.5045299; Z. Song, H. Dai, L. Rong, et al., "Compensation of a Mobile LTS SQUID Planar Gradiometer for Aeromagnetic Detection," *IEEE*, Vol. 29, No. 8 (2019).
[26] Yuval Cohen, Krishna Jadeja, Sindi Sula, Michela Venturelli, Cameron Deans, Luca Marmugi, and Ferruccio Renzoni. "A cold atom radio-frequency magnetometer." *Applied Physics Letters* 114, no. 7 (2019).
[27] Jundi Li, Wei Quan, Bingquan Zhou, Zhuo Wang, Jixi Lu, Zhaohui Hu, Gang Liu, and Jiancheng Fang, "SERF Atomic Magnetometer – Recent Advances and Applications: A Review," *IEEE Sensors Journal*, Vol. 18, No. 20 (2018).
[28] N. Gusarov, M. R. Perelschtein, P. J. Hakonen, and G. S. Paraoanu, "Optimized emulation of quantum magnetometry via superconducting qubits," *Physical Review A*, Vol. 107, No. 052609 (2023); Andre Schneider, "Quantum Sensing Experiments with Superconducting Qubits," *Experimental Condensed Matter Physics*, 2021.
[29] Hiraku Toida, Koji Sakai, Tetsuhiko Teshima, Masahiro HOri, Kosuke Kakuyanagi, Imran Mahboob, Yukinori Ono, and Shiro Saito, "Magnetometry of neurons using a superconducting qubit," *Nature Communications*, Vol. 6, No. 19 (2023).

Table 2: Gyroscope Survey

Gyroscope Sensor Type	Sensitivity (°/s√Hz)	Bias stability (°/s)	Deployment Constraints
Diamond nuclear spin gyro[30]	10^{-5}	0.4	Accumulates bias quickly; will require magnetic shielding to reduce bias.
NMRG spin[31]	10^{-6}-10^{-7}	10^{-6}	Harder to entangle given characteristic defect differences.
Cold atom interferometer[32]	10^{-7}-10^{-10}	10^{-8}-10^{-10}	Large equipment requirement; low operating frequency.
Ring laser gyro (non-quantum)[33]	10^{-7}-10-^{11}	10^{-9}-10^{-13}	Bulkier size.
MEMs (non-quantum)[34]	10^{-7}	10^{-13}	Mechanical wear over time causes drift.

Capabilities and Strategic Effects

Although the technical analysis provides insight on the progression of R&D, it is difficult to predict how piecewise innovations will translate to capability improvements. This is methodologically challenging because the hurdles impeding the transition of a technology from a lab to an operational setting, and moreover to its integration into complex technological systems and networks, are often difficult to anticipate. But evaluating the suitability of a new technology for meeting a capability gap and predicting the strategic effect are also conceptually difficult because benchmarks for impactful capability improvements vary across different deterrence strategies.

First, it can be difficult to empirically estimate the capability improvement because of uncertainty over a technology's innovation to deployment trajectory and because of limited information on operational requirements. For example, Figure 1 and Table 3 estimate the ways in which quantum sensors could conceivably be used to improve submarine detection and reduce errors in missile accuracy. However, it is hard to capture the operability constraints, such as ease of deployment in a broader network, operation with lack of signal, or susceptibility to countermeasures. Furthermore, such analyses are reduced to estimates because much of the information on deployment considerations are classified. This means that such estimates will never have complete certainty in their appraisals of the suitability of quantum sensors for strategic applications. Absent this certainty, they will be unable to neatly convey some magnitude of improvement that can be achieved with quantum sensors compared to existing technologies and capabilities. Instead, policymakers and strategists will have to infer the strategic implications and make policy recommendations or decisions under conditions of uncertainty and weigh the risks of underestimating or overestimating a technology's impact.

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[30] Jarmola et al., "Demonstration of diamond nuclear spin gyroscope."
[31] Ke Zhang, Nan Zhao, and Yan-Hua Wang, "Closed-Loop Nuclear Magnetic Resonance Gyroscope Based on Rb-Xe," *Nature*, Vol. 10, No. 2258, 2020, https://www.nature.com/articles/s41598-020-59088-y.
[32] Carlos Alzar, "Compact chip-scale guided cold atom gyrometers for inertial navigation: Enabling technologies and design study," *AVS Quantum Science,* Vol. 1, No. 0144702 (2019).
[33] Scott Bezick, Alan Pue, and Charles Patzelt, "Inertial Navigation for Guided Missile Systems," *Johns Hopkins Applied Technical Digest*, Vol. 28, No. 4, 2010, https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V28-N04/28-04-Bezick.pdf
[34] Bezick, Pue, and Patzelt, "Inertial Navigation for Guided Missile Systems."

Figure 1: Submarine Detection Range Based on Sensitivity

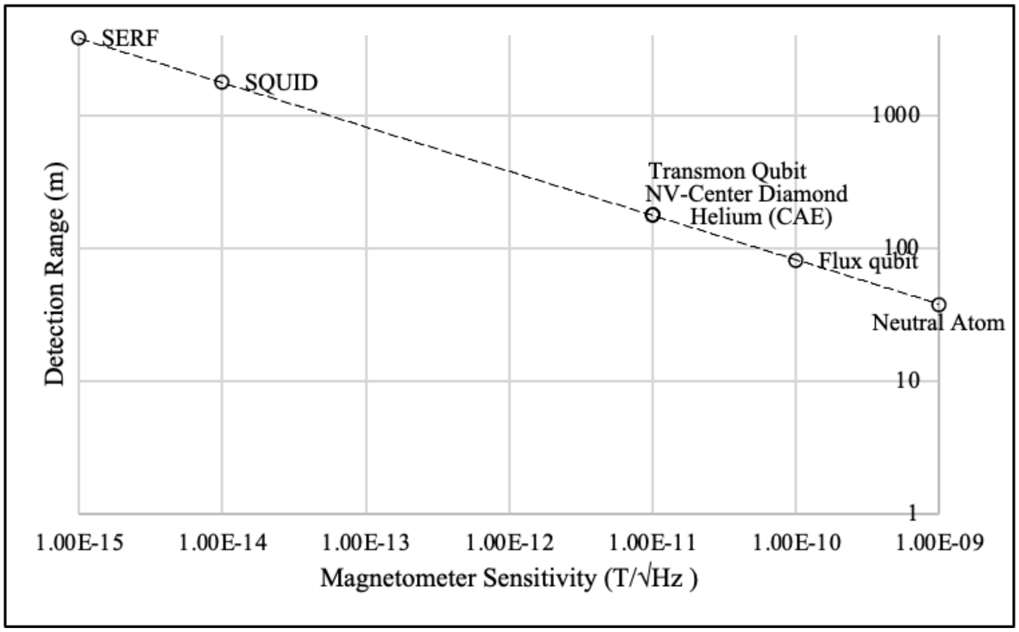

Figure 1 shows the sensitivity-detection range relationship based on magnetic signature estimates[35] and the detection ranges for the different sensor types in Table 1, assuming Columbia-class submarine parameters with 99% stealth suppression capabilities.

[35] See Rand dissertation, Equation 5.11.

Table 3: Missile Error Contributions and Quantum Sensing Application Survey

CEP Contribution	Error Source	Description	Quantum-Feasible Application?
σ_{Init}	Initiation sequencing	Initial error from positioning.	Unlikely – pre-launch errors are unrelated to navigation and are corrected later in trajectory.
σ_{Acc}	Accelerometer	Error from accelerometer bias and scale factor.	Likely – quantum accelerometers could reduce bias from drift and could be naturally calibrated (or calibrated with lower uncertainty).
σ_{Gyro}	Gyroscope	Error from gyroscope bias drift and acceleration-sensitive drift.	Likely – quantum gyros are likely to experience less drift over time and drift may be less susceptible to acceleration sensitivity.
σ_{Comp}	Guidance computation	Error in guidance computer accuracy.	Potentially – likely has already improved significantly with modern computers but may be improved slightly with improvements from quantum navigation in readout.
σ_{Thrust}	Thrust	Error from unpredictability of thrust termination.	Unlikely - unless negated by post-thrust recalibration enabled through quantum sensing.
$\sigma_{Gravity}$	Gravity	Error from gravitational variations; dependent on whether missile has a gravimetric system.	Potentially – could be improved through more sensitive gravimetry sensors and through more accurate gravity surveys afforded by quantum sensors.
$\sigma_{Reentry}$	Reentry	Error from asymmetries in reentry vehicles that create unexpected aerodynamic effects.	Potentially – cannot impede error accumulation but could correct if quantum sensing allows post-reentry navigation.
σ_{Fusing}	Fusing	Error from fusing timing for detonation; Dependent on fuse quality and timing from navigation system.	Potentially – partially dependent on navigation to determine fuse timing, which may be improved with quantum sensors.

The remaining uncertainty then translates to ambiguity when interpreting strategic effects. For example, adherents of the two most prominent logics for deterrence, assured destruction and damage limitation, would interpret the technical estimates presented here differently. Under the assured destruction logic, an emerging technology will only have significant strategic effects if it critically undermines conditions of mutual vulnerability. In this case, quantum sensors would need to afford the ability to consistently find, track, and destroy all nuclear-armed submarines to be truly destabilizing under assured destruction. Meanwhile, the damage limitation perspective would perceive any incremental improvement that could increase the vulnerability of an adversary's counterforce, including quantum sensors, as affording some strategic advantage.

Taken together, the remaining uncertainty in technical estimates and the refraction through competing deterrence logics suggest that emerging technologies will rarely, if at all, confer some clear, unambiguous strategic advantage. The quantum sensing technical and capability analyses presented here suggest that quantum sensors will only afford incremental improvements to nuclear deterrence-relevant capabilities. Whether or not those improvements are strategically significant will be perceived differently by different stakeholders.

Actors and Social Influences

Historical case studies of emerging technology development show that policymakers are not guided purely by technical assessments and strategic evaluations; social and parochial interests also influence both actor decisions and technology development in ways that are rarely captured in the current literature.[36] Also prominent in the case of quantum sensing, these factors contribute to inflated expectations and fractured dialogue across technical and non-technical audiences, producing inflated perceptions of a technology's disruptive potential.

Among the technologist epistemic communities, shifting science communication norms and lack of consensus on innovation potential or clear metrics to evaluate quantum technology development have fostered vague assertions that are difficult to critically appraise. Recent science communication literature highlights various influences that have contributed to steadily inflating rhetoric when conveying science "breakthroughs."[37] Many of these influences are already employed in quantum technology narratives, including promises of an imminent "quantum supremacy" over non-quantum technologies or a forthcoming (second) "quantum revolution."[38] Furthermore, lack of consensus on which type of quantum platform will be most suitable for a particular application and fundamental differences across system types that make it difficult to establish uniform metrics foster vague assertions meant to treat categories of quantum technologies as a whole, despite vast variation within in each category.

Among capability-seeker epistemic communities, numerous factors incentivize technology procurement despite great uncertainty about technical feasibility or strategic value. As technology competition becomes more prominent in the current geopolitical context, innovation in and of itself is becoming a marker for power and influence. Furthermore, knowledge barriers that impede the flow of information between security practitioners and technical experts limits the ability to share information that could shed light on operability constraints. Finally, the codevelopment of measures and countermeasures has long incentivized the cyclical development of a measure to gain a strategic advantage and the subsequent innovation of a countermeasure to diminish the advantage.[39] Synergy between communities that produce or procure measures and countermeasures incentivizes continual development in both spheres.

At the same time as technologist and capability-seeker communities face greater pressure to promote new technologies, actors seeking to exert oversight and critique exaggerated claims face significant resource constraints. Few organizations exist outside of the technologist and capability seeker spheres to critique assertions made by each epistemic community.[40] Those that do also have limited access to complete information on either the capability requirements or

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[36] For example: Donald MacKenzie, "Missile Accuracy: A case study in the social processes of technological change," *The social construction of technological systems: New directions in the sociology and history of technology* (1987), pp. 195-222. For historical case studies, see Rand dissertation, Chapter 4.

[37] Kristen Intemann, "Understanding the Problem of 'Hype': Exaggeration, Values, and Trust in Science," *Canadian Journal of Philosophy*, Vol. 52, No. 3, 2022, pp. 279-294.

[38] On quantum supremacy, see: John Preskill, "Quantum Computing and the Entanglement Frontier," *WSPC-Proceedings*, 2012. On the second quantum revolution, see: Jonathan Dowling and Gerard Milburn, "Quantum Technology: The Second Quantum Revolution," *Philosophical Transactions of the Royal Society*, Vol. A, No. 361, pp. 1655-1674. For more social dynamics, see: Rand dissertation, Chapter 7.

[39] See Rand dissertation, Chapter 7.

[40] For example: "The Office of Technology Assessment: History, Authorities, Issues, and Options," *Congressional Research Service*, Updated April 29, 2020, https://sgp.fas.org/crs/misc/R46327.pdf.

technology development. Furthermore, organizations and researchers capable of providing independent reviews often face pressure from government and private funders to discuss, and therefore accept, the disruption of emerging technologies, despite significant evidence that many misperceptions plague emerging technology research and rhetoric.

Insights and Implications of a Socio-Technical Analysis

Evaluating the case of quantum sensing through the socio-technical framework demonstrates how an interdisciplinary analytical approach provides important insights on strategic implications and policy opportunities. First, the quantum sensing case provides an alternative narrative that contradicts the mainstream assumption that rational policymakers must hedge against the threat of a "technological surprise." The threat of some vague "technological surprise" is often paired with calls for greater technology R&D funding, and counterintuitively is used to argue the imperative of rapid, unfettered technological innovation.[41] Yet, as this analysis shows (along with other historical case studies surveyed[42]), technology development timelines have historically extended much longer than the current emerging technology narrative implies. Furthermore, innovation progress *can* be monitored through evaluating key milestones that have been reached (demonstrated in the technical analysis component of the framework). Finally, even after a technology is acquired, additional measures are required to transition it to an operational setting with high assurance and to achieve iterative qualitative improvements that would be capable of satisfying significant strategic advantages.

Recognizing that technological surprise is unlikely has important implications for existing policies to reduce strategic risks, such as the hedging strategy. While hedging may seem like a cautious policy approach – a way to appease actors concerned about a technology's potential while also respecting skepticism voiced by others – it inevitably fosters actor networks and fuels misperceptions. By creating actor networks invested in a technology, even if only at low funding levels, policymakers create advocates for the technology, and likewise may send signals to adversaries that the technology is being pursued for strategic purposes. This then creates an action-reaction cycle that can be difficult to stymie. In the case of quantum sensing, the newly announced Defense Innovation Unit solicitation, which calls for quantum sensors that could be used to improve precision weapons and perform magnetic anomaly detection invokes this risk.[43] Policymakers should more carefully consider the intent of such solicitations, the effects, and how such actions could be perceived.

Second, the case study shows that even though a technical analysis reduces uncertainty about how much capability enhancement can be achieved in the near and medium term, different interpretations of risk and disagreement over an appropriate policy response will arise from competing deterrence theories. Although the technical analysis provides greater clarity on the

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[41] For example, see: David Vergun, "DOD in Search of Disruptive Technologies that Will Enable the Warfighter," *Department of Defense News*, March 8, 2022, https://www.defense.gov/News/News-Stories/Article/Article/2959378/dod-in-search-of-disruptive-technologies-that-will-enable-the-warfighter/.

[42] See Rand dissertation.

[43] "Defense Innovation Unit Launches First CSO Under New Emerging Technology Portfolio," *Defense Innovation Unit*, May 8, 2024, https://www.diu.mil/latest/defense-innovation-unit-launches-first-cso-under-new-emerging-technology.

improvements that could conceivably be expected for quantum sensors, significant uncertainty clouds the transition to operability in a real-world setting to confer a strategic capability. When this ambiguity is refracted through different strategic lenses, such as assured destruction and damage limitation, different strategic implications are perceived. While an assured destruction logic may perceive remaining uncertainty around a technology as reinforcing the credibility of an assured retaliatory capability, damage limitation advocates may view uncertainty as an opportunity for an adversary to gain a strategic advantage through technological surprise. This means that the infusion of emerging technologies into security debates will not resolve underlying disagreements over the best way to reinforce deterrence and strategic stability.

Finally, beyond strategic and technical considerations, actor networks impose added pressure to sustain financial support for R&D efforts without clear strategic value or technical viability, thereby biasing policymakers' perceptions. Often, policymaker decisions are not entirely driven by estimations of technical feasibility or evaluations of strategic effects. They are also informed by more parochial interests, and perceptions of technological innovation that are driven by various social factors. For example, policymakers may decide to pursue quantum sensors as a method of funding longer-term quantum technology research.[44] However, this then reinforces an artificially positive feedback loop in favor of quantum sensing development that has the potential to propagate misperceptions over its applicability. Moreover, technologists who claim that quantum sensors could theoretically afford better detection and navigation capabilities but ignore important operability requirements in strategic settings further stoke misperceptions.

Recognizing that technological innovation is driven by human actors and that actors are guided by considerations beyond the purview of technical feasibility and strategic rationale affords a new avenue for policy governance. Policymakers should examine how broader technology strategies and industrial policies, like the National Quantum Initiative or the National Science Foundation Regional Innovation Engine, influence technology actor networks and incentivize certain behaviors and narratives among actors. Furthermore, policymakers should seek to address the lack of unbiased technology reviewers by devoting more resources or establishing institutional capacity to perform critical oversight of emerging technology acquisition viability and strategic value.

Conclusion

Taken together, these findings shed light on how "emerging technology" and deterrence vulnerability narratives create a synergistic feedback loop in favor of both more rapid technological development and expansion of nuclear arsenals. This dynamic has been fostered by interest in emerging technologies among policymakers and funders. Ultimately, this feedback loop increases the difficulty of pushing for policies of technological restraint and incentivizes arms racing dynamics. Such narratives are aided by the fact that the literature is often fragmented methodologically, hampering critical interdisciplinary analyses that could be used to quell hype over the feasible scale of disruption that should be expected and interrogate the drivers of hype.

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[44] Referenced in: "Bringing Quantum Sensors to Fruition," A Report by the Subcommittee on Quantum Information Science Committee on Science of the National Science and Technology Council, March 2022, https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf.

As the geopolitical landscape increasingly shifts towards a technological competition, policymakers must actively seek ways to counter pressure to engage in arms racing. While the easiest solution may seem to be hedging against surprise, such policies have only promoted cyclical concern over nuclear vulnerability and urges to innovate new technologies to offset new vulnerabilities. Rather, policymakers should invest in opportunities to increase socio-technical awareness. Technical expertise should be leveraged to monitor technological development and abate fears of surprise, while social science expertise should be used to rein in exaggerated claims and address incentive and power structures that foster miscommunication.

About the Author

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