



Emerging Technologies and Trade Controls: A Sectoral Composition Approach

**Position, Navigation, and Timing
Quantum Computing
Computer Vision**

Strategic Trade Research Institute

Center for International and Security Studies at Maryland

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The Strategic Trade Research Institute was founded in 2017 and is an independent, international, board-governed non-profit organization dedicated to building networks of strategic trade research and practice through leadership, research, and innovation. STRI publishes the *Strategic Trade Review*, the leading peer reviewed journal dedicated to trade and security. STRI engages in quality research and capacity-building and is committed to promoting a diversity of voices and perspectives. To learn more about STRI, visit www.strategictraderesearch.org.

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The Center for International and Security Studies at Maryland (CISSM) at the University of Maryland's School of Public Policy conducts research, education, and outreach about how powerful trends associated with globalization are affecting international security. It focuses on strategies to increase international cooperation, especially where powerful technologies—with both beneficial and dangerous uses—are becoming widely available to states and non-state actors. To learn more about CISSM, visit www.cissm.umd.edu.

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Executive Summary

The rapid development of dual-use emerging technologies has magnified the importance of reconciling technological leadership, economic competitiveness, and national security objectives. While trade controls on dual-use technology transfer can promote peace and mitigate security threats, overly cumbersome policies may impose economic burdens on the private sector that threaten competitiveness and innovation. Striking a balance between these opposing agendas has become especially challenging in the context of emerging technologies that have elicited significant interest in both the military and civilian markets. The dilemma has also been complicated by the merging of economic security discourse and policy with national security. Policymaking mechanisms should be calibrated at the level of individual technologies to avoid security and/or economic consequences of under or over-regulation. This report offers policymakers data, findings, and recommendations to strengthen the effectiveness of individual policies and to work towards a comprehensive technology strategy.

In order to develop trade policies that can achieve the intended security benefits without unwarranted damage to economic competitiveness and technology innovation, policymakers must recognize technology-specific development characteristics and the associated global sectoral composition – companies, universities, research institutes, and public-private collaborations - worldwide. This report applies a mapping methodology to three emerging technologies whose level of emergence and security relevance qualifies them as “chokepoint” technologies: position, navigation, and timing (PNT), quantum computing, and computer vision. Entities in each technology category were selected and analyzed using open source information in order to identify trends with respect to global dispersion, foreign involvement (including partnerships, commerce, and investment), and specific technology focus area. A second level of analysis was conducted to compare and contrast the key trends for each of the three sectors to determine how technology-specific factors impact innovation and market establishment and to illustrate the importance of technology-specific trade policies.

Analysis of the data shows clear differences among the three technologies that have important implications for the desirability and feasibility of strategic trade controls:

Position, Navigation, and Timing:

- Many existing PNT technologies are commercially available, but new research approaches that offer significant improvements to precision are in a more nascent development stage.
- The advanced PNT sector is concentrated in a relatively small number of countries and maintains close ties to government entities due to dual-use applicability.
- Extreme hardware requirements for new approaches, including cold atom, nuclear magnetic resonance, and other forms of quantum navigation make rapid dispersion of small, low-cost advanced PNT unlikely in the near future.
- These factors suggest that trade controls on cutting-edge technologies in the area are feasible.

Quantum Computing

- The quantum computer sector is at a relatively nascent stage of development but is expanding rapidly as newer companies seek to capitalize on the civilian applications.
- Hardware is consolidated into a narrow group of companies, with many software companies identifying creative approaches for sharing time and usability of quantum computers in order to make them more widely available to diverse industries.
- Due to the large upfront cost of quantum computing hardware, this trend is unlikely to change in the foreseeable future.
- Access to the actual quantum computers could be restricted based on user or application by targeting quantum clouds, or platforms that share access to quantum computers.

Computer Vision

- The computer vision sector already has a global commercial reach, with a large number of software companies being served by a fairly tight circle of hardware companies, and accommodates both military and civilian market demands.
- The majority of the computer vision technology innovation has already occurred, and systems are cost-effective and commercially available. This means that computer vision is likely not a suitable target for trade controls.
- However, as indicated by the BIS ruling on geospatial imagery software in January 2020, heightened security concerns over data collection and analysis methods may result in controls on applications that utilize computer vision technologies.
- Recent calls for controls on facial recognition indicate that other end uses of the technology may be ripe for politically desirable trade controls, even if technology dispersion has already occurred.

The results from the three technology analyses highlight the importance of technology-specific trade policy development. Trade controls must be applied with consideration given to unique characteristics of each independent emerging technology sector, including the breakdown of hardware and software supply chains, the stage of development, foreign availability, and the scope of the civilian market. One of the major trends that the authors identify across the technologies is the role of software as a means to connect technologies to specific industries. But even in the context of this overarching trend, individual technology security risks and commercial benefits must guide policymakers' solutions to control intangible technology transfers or accumulated data that present security risks, without cutting into civilian applicability.

The research, data, analysis, and findings presented in this report are useful to the formulation of an effective policy approach to emerging technologies

and the development of a comprehensive technology management regime.

The report findings are relevant to:

- Formulating effective export and investment controls;
- Identifying targets for policy and industry outreach;
- Understanding potential threats to economic and national security that stem from technological competition;
- Identifying foreign partners for a global technology management strategy;
- Assessing impacts related to changes to ownership and entity structures;
- Establishing a mapping methodology that can be applied to emerging technologies.

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1. Introduction

Emerging technologies increasingly challenge policymakers with finding the right balance between technological development, economic competitiveness, and national security. Exponentially improved computing power, hyper-precise navigation systems, and mass amounts of stored personal data represent several of the key technological developments driving the need for effective emerging technology governance. However, many pivotal questions remain unanswered. At the root of governance issues lies the following: What are the most serious security concerns posed by different types of emerging technologies? Where are the most sensitive technologies being produced worldwide, and what are the patterns of diffusion? What is the most desirable approach to regulate technology development and cross-border dispersion to protect national security interests and promote economic competitiveness? What types of trade control tools are most likely to be both feasible and effective in specific emerging technology areas given their current stage of advancement?

This report provides a data-based policy analysis of these questions. It is supported by a comprehensive worldwide mapping of three emerging technologies selected as chokepoint technologies based on foreign availability, rate of cross-border diffusion, security relevance, and progress. The three technologies analyzed are: 1) position, navigation, and timing (PNT), 2) quantum computing, and 3) computer vision.

The mapping data, findings, and analysis are valuable for evaluating potential new trade controls in these various sectors, including both export and investment approaches. The sectoral composition of the three technologies studied differs significantly in ways that make some types of controls potentially feasible and others impractical. With regard to PNT, many existing technologies are already commercially available, but some new research approaches with dual-use applications are in an early enough stage that it could be possible to control dispersion. In the quantum computing sector, companies are developing creative software approaches to share time and use of limited quantum computer hardware. This means that access to the actual quantum computers could be restricted based on user or application by targeting quantum clouds, or platforms that share access to quantum computers. Finally, the authors found that in the computer vision sector, the majority of the technology development has already occurred, and technology

is cost-effective and commercially available. This means that computer vision technology is likely not a suitable target for trade controls based on those criteria. However, as indicated by recent policy trends, corporate decisions, and human rights considerations, heightened concerns over data collection and analysis methods suggest that computer vision technologies may become new targets for controls.¹

Analysis of sectoral mapping data also yields other important insights. Deciding which of the feasible trade control options are also desirable requires understanding their potential impact on economic competitiveness and national security. That will differ depending on the specific characteristics of an emerging technology sector. In addition, the mapping data is a valuable compass for private sector outreach efforts in the United States, for identifying targets for capacity-building worldwide, and for improving the effectiveness of trade policy by collaborating with international partners as part of a multilateral approach. The lens into the three chokepoint technologies analyzed in this report can also provide a roadmap for assessing the trade control governance options for other sensitive technologies.

The report begins by outlining the policy context for the authors' approach to the challenge of balancing emerging technologies and security priorities. The report then discusses the methodology used by the authors to select the three technologies chosen in this report as well as the mapping analysis. The mapping data, findings, conclusions, and recommendations for each technology form the bulk of the report. Finally, the authors apply comparative analysis to the technologies and present general patterns and trends. The report concludes with overall findings, recommendations, and pathways for future research.

2. Emerging Technologies: Policy Context

Policymakers have become increasingly aware of opportunities and risks posed by emerging technologies. They understand the potential for new technologies to accelerate productivity, growth, and economic progress, as well as to strengthen

1 "Addition of Software Specially Designed To Automate the Analysis of Geospatial Imagery to the Export Control Classification Number 0Y521 Series," U.S. Department of Commerce, Federal Register, Vol. 85, No. 3, January 6, 2020, pp. 459-462, <<https://www.govinfo.gov/content/pkg/FR-2020-01-06/pdf/2019-27649.pdf>>.

national defense sectors and improve strategic advantage. Policymakers also recognize potential risks to security and stability posed by international technological diffusion. As emerging technology risks and opportunities have increased over the last decade, they have turned to trade controls as an important set of tools for managing risks posed by dual-use technologies.

The trade of sensitive goods – those intended for conventional military use as well as dual-use goods – is controlled through national and multilateral export controls. Four multilateral export control regimes – the Nuclear Suppliers Group (NSG), Wassenaar Arrangement, Missile Technology Control Regime (MTCR), and Australia Group (AG) – develop and maintain guidelines and control lists to regulate transfers of sensitive goods. Regime members generally follow these guidelines, but even non-members have an international legal obligation to implement trade controls. After United Nations Security Council resolution 1540 was adopted in 2004, all United Nations member states must regulate the transfer of goods and technologies that could be used by non-state actors for Weapons of Mass Destruction (WMD) programs.² Beyond multilateral guidelines, countries may also implement additional unilateral controls based on national security priorities.

In addition to export controls, countries also regulate the potential acquisition of sensitive goods through investment controls. Foreign Direct Investment (FDI) controls are applied to prevent the acquisition of strategic tangible and intangible assets by foreign entities. Until recently, national security reviews of FDI controls were focused on “traditional” resources (e.g., defense sector and key infrastructure). With the emergence of several countries as technology disruptors and the increased awareness that rapidly emerging technologies can be harnessed for offensive purposes, many governments are adjusting the scope of and constituent definitions for restricted sectors.

2.1 United States Policy Developments

In the United States (U.S.), the Trump Administration in 2018 articulated a “new organizing principle” for strategic policy: economic security is national security. In particular, innovative technologies are accorded priority in this new calculation

2 “UN Security Council Resolution 1540 At a Glance,” Arms Control Association, <<https://www.armscontrol.org/factsheets/1540>>.

due to their perceived revolutionary impact on economic development, driving economies into the so-called Fourth Industrial Revolution. In response, Congress enacted the Export Control Reform Act of 2018 (ECRA). Section 109 of ECRA states that: “The President shall establish and, in coordination with the Secretary, the Secretary of Defense, the Secretary of Energy, the Secretary of State, and the heads of other Federal agencies as appropriate, lead a regular, ongoing interagency process to identify emerging and foundational technologies that are essential to the national security of the United States.”³ However, ECRA did not specify emerging or foundational technologies.

In 2018, the United States Department of Commerce (DOC) Bureau of Industry and Security (BIS) published an Advanced Notice on Proposed Rulemaking (ANPRM) seeking public comment on criteria for identifying emerging technologies. The ANPRM includes fourteen broad representative categories of technology for which the government seeks input from strategic trade stakeholders on potential new entries to be added to the United States control list on certain emerging technologies.^{4,5} The technology areas are:

1. Biotechnology
2. Artificial intelligence and machine learning
3. Position, navigation, and timing technology
4. Microprocessor technology
5. Advanced computing technology
6. Data analytics technology
7. Quantum information and sensing technology
8. Logistics technology
9. Additive manufacturing (e.g., 3D printing)
10. Robotics
11. Brain-computer interfaces
12. Hypersonics

3 Export Control Reform Act, 2018, H.R. 5040, <<https://www.congress.gov/bill/115th-congress/house-bill/5040/text>>.

4 Export Control Reform Act, 2018, H.R. 5040, <<https://www.congress.gov/bill/115th-congress/house-bill/5040/text>>.

5 “Review of Controls for Certain Emerging Technologies,” Advanced Notice of Proposed Rulemaking, United States Department of Commerce, Bureau of Industry and Security, 2018, <<https://www.federalregister.gov/documents/2018/11/19/2018-25221/review-of-controls-for-certain-emerging-technologies>>.

13. Advanced materials
14. Advanced surveillance technologies

The ANPRM also includes a list of illustrative examples of the technologies for each of the above categories (e.g., computer vision and national language processing within the AI and machine learning category). It notes that the definitional process will be conducted through the interagency, private sector outreach, the Emerging Technology Technical Advisory Committee, and the Committee on Foreign Investment in the United States (CFIUS).⁶

In addition, the Foreign Investment Risk Review Modernization Act (FIRRMA) was passed as part of the 2018 National Defense Authorization Act (NDAA).⁷ FIRRMA reforms the CFIUS process currently used to evaluate and address national security concerns related to foreign investment into the United States. FIRRMA's most substantial change was to increase the scope of "covered transaction," which defines much of CFIUS's jurisdiction, to include "critical technologies." As defined in ECRA, critical technologies include "emerging and foundational technologies." FIRRMA expands the scope of transactions to businesses that produce, design, test, manufacture, fabricate, or develop one or more critical technologies (including emerging and foundational technologies) in relation to a designated industry. Designated industries are listed in the Annex of the regulation. Importantly, in the case that technologies, including those specified in the ANPRM, become controlled pursuant to ECRA, they will automatically be covered under FIRRMA's definition of "critical technologies."

The decision on how emerging technologies listed in the ANPRM will be controlled has significant repercussions for both export and investment, with an even greater potential to affect the private sector and worldwide technology flows and development. In this context, the U.S. has essentially merged its export control and FDI review regimes to confront the acquisition of emerging technologies. This underscores that emerging technologies are both defining and accelerating a

6 Interestingly, the MCTL was also intended to inform CFIUS decisions. However, according to DOD officials, the MCTL was not used to inform these decisions. Instead, DOD relied on input from technical experts in the Directorate for Defense Research and Engineering on an *ad hoc* basis. See, GAO, *Defense Trade: Enhancements to the Implementation of Exon-Florio Could Strengthen the Law's Effectiveness*, GAO-05-686, 28 September 2005, p. 22.

7 "Foreign Investment Review Risk Modernization Act," Review of Foreign Investment and Export Controls, H.R. 5515-538, 2018.

reformulation of national security, blending economic innovation with traditional definitions of national security.

2.2 Worldwide Policy Developments

Outside of the United States, it appears that policymaking to manage new technologies has gained more traction in the context of investment controls than in the realm of export controls. The international community's heightened attention to security threats posed by technological advances has led to a number of policy developments specifically geared towards managing FDI. The European Union (EU), in May 2019, adopted Regulation 2019/452 establishing a framework for the screening of FDI and subsequent guidance on implementation of the regulation in March 2020.⁸ In November 2019, the Japanese Diet passed an amendment to their Foreign Exchange and Foreign Trade Act (FEFTA) introducing new, more stringent controls on foreign investment.⁹ While most countries already have some form of controls on FDI, many have chosen to tighten these laws over the last several years.¹⁰

As new FDI legislation has increased, export controls on emerging technologies outside of the U.S. have generally been updated only subsequent to new controls within the multilateral export control regimes - and only by their members. For example, in 2019, the Wassenaar Arrangement added six new developing technology entries to its control list which were subsequently implemented in its members' national control lists.¹¹ A number of factors may be contributing to

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- 8 "Regulation (EU) 2019/452 of the European Parliament and of the Council of 19 March 2019 Establishing a Framework for the Screening of Foreign Direct Investments into the Union," <<https://eur-lex.europa.eu/eli/reg/2019/452/oj>>.
- 9 Sakon Kuramoto, Benjamin Miller, Hiroki Sugita, "Amendment to Japanese Foreign Exchange and Foreign Trade Act Regulations Expands Scope of "Restricted Businesses" to Include Some Information and Communications Technology Businesses," JD Supra, June 22, 2019, <<https://www.jdsupra.com/legalnews/amendment-to-japanese-foreign-exchange-68547/>>.
- 10 See, "Investment Policies Related to National Security and Public Order," OECD, <<http://www.oecd.org/investment/investment-policy/investment-policy-national-security.htm>>.
- 11 The technologies are: Hybrid additive manufacturing (AM)/computer numerically controlled (CNC) tools; computational lithography software designed for the fabrication of extreme ultraviolet (EUV) masks; technology for finishing wafers for 5nm production; digital forensics tools that circumvent authentication or authorization controls on a computer (or communications device) and extract raw data; software for monitoring and analysis of communications and metadata acquired from a telecommunications service provider via a handover interface; and sub-orbital craft. See: "Statement Issued by the Plenary Chair on 2019 Outcomes," Wassenaar Arrangement, 2019, <<https://www.wassenaar.org/app/uploads/2019/12/WA-DOC-19-PUB-001-Statement-issued-by-the-Plenary-Chair-on-2019-Outcomes.pdf>>.

this trend, including countries taking a “wait and see” approach while the U.S. determines the outcomes of the ECRA ANPRM emerging technologies process. In addition, many countries may desire to hold off on implementing any new controls on emerging technologies until entries are agreed upon in the multilateral export control regimes. For years, the EU, individual EU Member States, and other countries have also been analyzing groups of technologies to determine whether there is a basis for control in the multilateral export control regimes or on a state-level basis.¹² These discussions will likely continue in the regime context, with the U.S. as a principal driver of new emerging technology controls

2.3 Trade Control Policy Challenges

How emerging technologies are defined is context specific and in the case of the U.S., reliant on security implications based on their dual-use nature.¹³ Both the ECRA and the ANPRM state that such technologies may not yet be listed on the Commerce Control List (CCL) or in multilateral export control regime lists and therefore may not yet be evaluated for their security impacts – even though the technologies are dual-use in nature. ECRA defines dual-use items as those that “[have] civilian applications and military, terrorism, or weapons of mass destruction-related applications.”¹⁴

Importantly, the term “items” refers not just to tangible, physical goods, but also technology which can be diffused through services, training, face-to-face, physical, or digital communications, publications, and other means – so-called intangible transfers of technology (ITT). While the operations regarding the control of tangible items under trade controls are relatively clear-cut, the regulation of technology diffusion – especially where technologies are new or quickly developing – is a more difficult enterprise. ITT poses unique challenges for the application of trade controls as these technologies are more difficult to identify, track, and ultimately, control, than physical goods. It is easier to follow physical, tangible goods through traditional export control operations such as risk-assessment, enforcement, compliance, and licensing. Furthermore, whereas for tangible goods the organizations involved tend to be exporting companies, ITT

12 For a full list of FDI legislation worldwide, see the Investment Policy Hub’s website: <<https://investmentpolicy.unctad.org/investment-laws>>.

13 The 2018 U.S. Export Control Reform Act defines technology and dual-use, but not emerging.

14 Ibid, Section 2, “Definition.”

regularly takes place within university research departments, research centers, and public-private initiatives, in addition to companies. Finally, often the non-civilian end-uses of many technologies are still in development and cannot be concretely identified.

In this challenging policy context, how can a sound determination be made regarding which technologies can and should be controlled through trade controls? As one ANPRM comment stated,

“The ANPRM notes that, ‘Certain technologies, however, may not yet be listed on the CCL or controlled multilaterally because they are emerging technologies. As such, they have not yet been evaluated for their national security impacts.’ These two sentences are at the heart of the problem of defining emerging technology within an export control framework. The uncertainties and ambiguities around emerging technology make them difficult if not impossible to govern from an export control perspective, and yet this is exactly what the process to be established through this ANPRM is tasked to do.”¹⁵

3. Objectives and Methodology

As national policies evolve vis-a-vis the management and potential control of emerging technologies, the importance of understanding the characteristics of specific technology areas is more important than ever. Because the military end-use of some technologies listed in the ANPRM may not yet be clear, countries need to make prescient choices in order to be prepared for a multitude of scenarios. Additionally, the foreign availability of certain technologies - especially if they are militarily sensitive - affects the potential utility of trade and investment control tools.

Several of the broad technology groups, such as additive manufacturing and artificial intelligence (AI), listed in the U.S. emerging technologies ANPRM have been studied and scrutinized by researchers, and in various multilateral and national fora, in terms of their export control significance. However, the

15 Comment for the Department of Commerce ANPRM on “Review of Controls on Certain Emerging Technologies,” Samuel Evans, Research Fellow in the Program on Science, Technology, and Society at Harvard University’s Kennedy School of Government. Source, <t.ly/DE95l>.

subcategories within those technology sectors and others that are considered “emerging” have not been as closely analyzed.

While the military applications of each technology and subcategory are important to consider, the baseline for evaluating trade controls should also consider the composition of each sector and the technology’s geographical spread because those characteristics will affect both the types of stakeholder buy-in that would be needed for trade and investment controls and the likely security and economic effects of such measures. Composition refers to the organizations that research, develop, and produce applications of a category or subcategory of emerging technology. This report provides a novel methodology for mapping key characteristics of specific sub-sectors of emerging technologies and using that data to evaluate the potential application of trade controls on emerging technologies.

The mapping data points compiled by the report authors include information on:

- Component/technology area
- Organization name
- Type of organization (non-profit, academic, private)
- Year of establishment
- Headquarters country, city, address, and website
- Government partnerships/involvement
- Academic partnerships/involvement
- International partnerships
- International investment
- Location of distribution and production facilities
- Dual-use designation
- Target industries
- Product details

In order to highlight the characteristics of a technology’s sectoral composition, this report applies a sector-wide mapping methodology. By identifying organizations of all types involved in the research, development, and/or production of a specific technology, it is possible to construct a picture of each technology category. This report applies this mapping methodology to three distinct technology areas. The methodology takes into account the physical locations, business categorizations, external partnerships, and specific technology focus for each organization. The inclusion of these specific characteristics in the methodology allows for

the extraction of larger trends, which form the foundation for comparing and contrasting different technology areas.

Ultimately, the resulting analysis from this research exhibits the state of the market and potential relevance of strategic trade controls for these sectors. The mapping data and analysis brings attention to the nuances of each emerging technology area, rather than treating emerging technology developments as monolithic across the board. It is also possible to use the methodology explained here to analyze the state of the market and trends in other emerging technology categories.

3.1 ANPRM Comment Review and Technology Identification

The technology categories listed in the ANPRM, identified per ECRA as potential targets of trade controls, are at varying development stages. Because the starting point for the research team's mapping process requires the identification of each entity pursuing or developing the identified technology, the relative development stage of the chosen technology is an important determiner in the ability to map, and ultimately restrict, the dispersion of the technology.

The authors identified the three technologies addressed in this report on the basis that the technologies are at a critical juncture between the advanced research stage and early manufacturing stage of development - so called "chokepoint" technologies. By focusing on this stage of development, the report authors suggest recommendations on actionable and timely trade control policy recommendations. In order to identify technologies at this stage, the team used a variety of inputs, including:

- An initial survey of all private sector comments provided to the Bureau of Industry and Security in response to the ANPRM. These comments often provided clues to recommended technologies for trade controls and private sector insights on technology development;
- Technology literature;
- Expert feedback provided through organized dialogues and private meetings.

The three technology areas chosen based on this initial research, and which are analyzed in this report are: PNT; quantum computing (under the broader quantum

information ANPRM category); and computer vision (under the broader AI ANPRM category).

The PNT category was chosen due to its clear dual-use applicability, and an indicated surge in commercial interest noted among ANPRM commenters. PNT technologies have historically been driven by military interest, however, due to the development of civilian autonomous cars and drones, there is a projected increase in commercial demand. Although ANPRM commenters noted that trade controls on all PNT technologies could be economically detrimental, some do claim specific capabilities required to acquire sensitive information could be applicable.¹⁶ Together, the rise in commercial interest and the direct dual-use ties indicate that PNT technologies may be at an important turning point and thus merit consideration for trade controls.

Quantum computing was chosen due to the relatively nascent stage of development but the widely touted, manifold disruption potential. Although most ANPRM comments regarding quantum information technologies argued the potential harm of overarching controls, commenters did note that because the technology is still under development, progress should be monitored in an effort to identify targeted control opportunities.¹⁷ Thus, despite the general consensus that quantum computing is in too early of a development stage for immediate control implementation, the authors viewed this as an opportunity to begin mapping the technology while chokepoints are still identifiable within the young supply chain.

Computer vision was chosen due to its designation as a subcategory of AI technologies with increasing civilian applications and consisting of both hardware and software components. Computer vision has dual-use applications through its ability to collect and analyze vast amounts of data with relatively

16 For example: “Comments on the Review of Export Controls for Certain Emerging Technologies Advance Notice of Proposed Rulemaking,” Mike Gold, Vice President of Regulatory and Policy Affairs at Maxar Technologies, <<https://www.regulations.gov/document?D=BIS-2018-0024-0113>>; “Advanced Notice of Proposed Rulemaking Related to Review of Controls for Certain Emerging Technologies,” Margaret Seif, Senior Vice President at Analog Devices, <<https://www.regulations.gov/document?D=BIS-2018-0024-0076>>.

17 For example: “Comment on Advanced Notice of Proposed Rulemaking Regarding Review of Controls for Certain Emerging Technologies,” Jeff Cheek, President of The SUNY Research Foundation, <<https://www.regulations.gov/document?D=BIS-2018-0024-0135>>; “Review of Controls for Certain Emerging Technologies,” Jeffery Rittener, Vice President of Global Trade at Intel Corporation, <<https://www.regulations.gov/document?D=BIS-2018-0024-0199>>.

minimal resources. As commenters noted, while much of the algorithm basis of computer vision may be easily accessible due to open-source access, controls could potentially be applied to specific hardware components or data.^{18,19} Thus, although certain components of computer vision may be widely available, there are other components, including hardware such as processors and lenses that may be retractable if directly linked to dual-use applications; and there may also be data collected through computer vision application that could be controllable based on the ability to acquire and transmit the data.

3.2 Sector Composition Mapping

Once the research team selected the three technology categories, organizations involved in research, development, and production were identified. The process for determining which entities fit within a given technology category's scope varied across the three technologies analyzed. In the cases of the PNT and computer vision categories, it was necessary to delineate between emerging and well-established technologies. In the case of quantum computing, it was necessary to separate quantum computing efforts from purely research-based efforts.

After the scope of each category was clearly defined, the authors consulted a variety of open source references, including academic and industry literature, business databases, government contracting data, industry expert commentary, industry websites, patent filings, technology publications, and other resources to identify relevant organizations. The scope of identification included searches to incorporate global organizations, thus producing data representing a worldwide sectoral landscape. Additionally, ANPRM comments were consulted again at this stage, as many comments provided sources for technology-related company lists and databases.²⁰

For the purpose of this research, a broad definition of "organizations" is used: academic, government, and military research groups, non-profit companies, for-

18 "Comment on ANPRM on 'Emerging Technologies,'" Keith Melchers, Export Compliance Officer at HP Inc., <<https://www.regulations.gov/document?D=BIS-2018-0024-0158>>.

19 "Comment on Review of Controls for Certain Emerging Technologies," Amir Husain, Founder and CEO at SparkCognition Inc., <<https://www.regulations.gov/document?D=BIS-2018-0024-0096>>.

20 Industry databases used in this research primarily included Crunchbase, <<https://www.crunchbase.com/>>, and Bloomberg, <<https://www.bloomberg.com/>>. Open-source government contracting data was from sources including the U.S. Small Business Innovation Research (SBIR) database, "Award Data," <<https://www.sbir.gov/sbirsearch/award/all>>.

profit private companies, and for-profit public companies were all considered as potential manufacturing base members. For the purposes of this report, “organizations,” “actors,” and “entities” refer to those actors engaged in the emerging technology field, encompassing government, non-government, and private sector work. The terms “companies” and “firms” refer exclusively to private sector organizations. These nuances are addressed in the mapping data and analyzed in the report findings.

3.3 Criteria for Assessment

In order to effectively compare and contrast organizations working in each of the technology areas, the research team developed a set of common criteria that consider the types of actors working in each sector, the global spread of the actors, and the target industries for the actors, including civilian and military applications. All chosen criteria are consistent across each technology category. This consistency also makes it possible to do a comparative analysis of the three sectors, in addition to the individual analyses of each sector. The criteria for analysis include technologies specific to the types of organizations, the characteristics and interactions of the entities themselves, and the specific work they conduct. These criteria are complemented with qualitative descriptions of industry trends and particularly interesting applications.

a) Organization Age and Type

Each technology section includes a breakdown of the identified organizations in the sector, including government, private/corporate, and non-government organizations. In addition to the types of organizations involved, each entity’s founding year is considered. This maturity metric allows for the determination of an organization as a well-established market player, a start-up or newly formed research institution entering the field, or another type of organization, and can be extrapolated at the level of the technology itself to enable identification of major trends that have changed over time.

b) Global Dispersion

After identifying the types of organizations involved, the analysis considers the geographic dispersion and international activities of each

organization. The primary traits include general geographic dispersion and specific multinational characteristics. The general dispersion is informed by the primary headquarters location of each organization and displayed on a map in each technology section. These maps provide an informative overview of where organizations are working for each emerging technology area.

In addition to the maps, this research takes into account multinational characteristics for each organization. The first category is an umbrella variable that considers whether an organization is at all multinational. In this report, the definition of multinational is broad; if an organization has any of the subcategories of international involvement, it was coded “Yes” for multinational. Multinational subcategories consider what types of international activities an organization is involved in. This includes explicit international partnerships, where an organization partners with another entity outside of its HQ country. It also includes international distribution, where an organization has the means through sales networks or direct offices to sell outside of its home country, and international manufacturing, where an organization has a physical manufacturing center in another country. The last international subcategory is international investment, which applies to private sector organizations receiving investment money from outside their HQ countries. This multi-question approach to geography makes it clear whether a company has international exposure in general and whether they work with other countries on international activities.

c) Academic and Government Involvement

For non-government entities, the criteria accounts for whether firms receive contracts or are involved in partnerships with government or academic organizations in developing the emerging technologies. These variables provide a sense of government and academic interest in each area; in the case of government involvement they may indicate possible dual-use applications. While there are limitations to this variable (not all organizations disclose their funding sources), the trends in each category are helpful in determining government interest in a particular application or form of research. The quality of information for government contracts was also surprisingly detailed, particularly

for small, privately held companies whose contracts are often listed in Small Business Innovation Research (SBIR).²¹

d) Key Industries, Applications, and Trends

The last set of criteria considers the types of applications each organization is pursuing. Organizations were coded for industries served through their technology. By using a consistent set of industries, the team is able to summarize target application trends in each technology area. In addition to getting a sense of what industries the entities are working with, there is a separate variable in the dataset for dual-use technology, which is particularly interesting for possible export control implications. Military market forces also differ from those in the private sector, which could be a significant consideration when evaluating technology control options. While some organizations heavily advertise military applications, others discuss their applications in broad terms. However, the absence of advertised dual-use applications does not necessarily mean that the technology can only be used for civilian applications.

3.4 Challenges/Limitations

A number of challenges and limitations were identified in conducting the sectoral composition mapping and subsequent assessment. Selective data omission, with respect to entire organizations, funding amounts, international ties, and specific research scopes can skew the general trends identified. The relative abundance of information about entities and government involvement in the United States and the European Union could potentially bias the data from these geographic areas. However, even with the likelihood of certain amounts of omitted data, the mapping of general trends can still provide an overview of actors that could be impacted by trade controls and policies. The extent to which certain challenges and limitations were relevant to the specific technologies will be identified in the respective technology sections of this report.

21 U.S. Small Business Innovation Research (SBIR) database, "Award Data," <<https://www.sbir.gov/sbirsearch/award/all>>.

4. Position, Navigation, and Timing

4.1 Introduction: The Reach of PNT

Positioning, navigation, and timing (PNT) technologies are an important component of advanced civil and military platforms, and efforts to develop next-generation PNT systems are underway globally. The U.S. Department of Transportation defines positioning as “accurately and precisely determin[ing] one’s location,” navigation as determining “current and desired position,” and timing as acquiring a time signal and maintaining timing accuracy.²² These categories encompass numerous technologies that enhance the capabilities of civilian and military platforms. While the PNT category includes many well-established technologies, including ubiquitous navigation platforms that use the global positioning system (GPS), emerging technologies in this area respond to demand for smaller, less power-hungry sensors that provide accurate data in increasingly difficult and novel use cases, such as in space and underwater.

Cutting-edge PNT research is attempting to apply quantum technology to the field, including advanced atomic clocks and quantum approaches to navigation systems. While some of these advanced applications have been commercialized, many remain in a strictly research and development phase. This early development phase means there is an opportunity to engage key stakeholders on emerging PNT risks and possibly apply additional controls prior to the new systems becoming fully commercialized.

This section introduces the PNT category, delineates “emerging” from legacy PNT, summarizes major emerging PNT areas, analyzes the dispersion of advanced PNT research and development around the world, and details how export control outreach could be developed in the PNT sector. It argues that while many PNT systems are well-established, there are emerging aspects of PNT in the research and development phase. These emerging PNT technologies have dual-use implications and could be the subject of export and other trade controls before they are fully commercialized.

22 “What is Positioning, Navigation and Timing (PNT)?” U.S. Department of Transportation, <<https://www.transportation.gov/pnt/what-positioning-navigation-and-timing-pnt>>.

4.2 Security Implications

Many eye-catching, modern platforms with possible dual-use applications—autonomous vehicles, unmanned underwater and aerial vehicles, satellites, and more—will require specialized PNT sensors that can be miniaturized and/or function in difficult environments.

Emerging PNT technologies may be an important chokepoint technology because they have the potential to enhance advanced dual-use platforms with air, land, sea, and space applications. In contrast to stand-alone platforms, emerging PNT technologies are sensors that can enhance other systems. Without PNT, many other emerging civilian and military hardware could not operate properly, including satellites, underwater vehicles, and drones. Existing PNT systems allow different platforms to accurately navigate, including jamming-resistant navigation systems for military land vehicles.²³

As new civilian and military platforms are introduced for use in space, underwater, or in difficult environments, new PNT systems will likely be needed. Another emerging category, AI, has been described as an “augmentation system” for existing digital platforms.²⁴ In a similar fashion, some emerging PNT systems may become key augmenting factors in physical platforms. Since they provide navigation and timing, they are crucial elements of advanced systems, and thus become an important components of other emerging technologies. The litany of applications for PNT makes it of interest to military technology development communities, and there is evidenced government interest in developing advanced PNT. The next few years may signify a key transition period for emerging PNT, as research into some of the most advanced systems continues and additional commercialization opportunities appear on the horizon.

23 An example of land vehicle PNT is produced by KVH, “Battle-Proven Tactical Navigation for All Platforms,” <<https://www.kvh.com/military-and-government/inertial-systems-and-communications/tactical-navigation/tacnav>>.

24 Dialogue on Artificial Intelligence and Strategic Trade Controls, organized by the Strategic Trade Research Institute and the Center for International and Security Studies at Maryland on March 9, 2020, in Washington DC.

4.3 Technology Overview

Because PNT is an expansive category, this analysis delineates between emerging PNT and existing technologies. When specifying the distinction between emerging and existing technology, it is necessary to take into account development trends, technical characteristics, and the state of the existing market. Two trends have outsized influence on emerging PNT platforms: GPS reliability and harsh environments. First, there is an increasing uneasiness about the reliability of GPS that is spurring interest in new PNT development. The concern, in part, is that GPS jamming capabilities could harm civilian and military transportation platforms.²⁵ Although fear of all-out GPS collapse has been tempered by some analysts, cheaper, better PNT systems that can accurately function without GPS for long periods are of interest to numerous countries.²⁶ Second, the environment and platforms demanding PNT capabilities are changing. These environmental demands, including the ability to function underwater or in space, are becoming increasingly high. PNT systems will essentially have to match the strength and advances of the platforms they assist.

To be clear, navigation systems that do not rely on GPS are by no means a new concept, with systems like passenger aircraft having built-in inertial navigation systems for decades.²⁷ However, amid increased fears of GPS denial and higher environmental requirements driving up the number of use cases for advanced PNT, market forces are steering research towards developing more accurate, affordable, and scalable systems. Thus, the difference today is the underlying design and durability of the technologies, not necessarily a lack of reliance on GPS or ability to navigate.

Emerging technologies in the PNT area often have one or more of the following traits:

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- 25 Elisabeth Braw, "The GPS Wars Are Here," *Foreign Policy*, December 17, 2018, <<https://foreignpolicy.com/2018/12/17/the-gps-wars-are-here/>>.
 - 26 For a more skeptical view of GPS tampering risks, see Brandon Davenport and Rich Ganske, "Recalculating Route": A Realistic Risk Assessment for GPS," *War on the Rocks*, March 11, 2019, <<https://warontherocks.com/2019/03/recalculating-route-a-realistic-risk-assessment-for-gps/>>.
 - 27 Sam Miller, "Contribution of Flight Systems to Performance-Based Navigation," Boeing's magazine *Aero*, 2009, <https://www.boeing.com/commercial/aeromagazine/articles/qtr_02_09/pdfs/AERO_Q209_article05.pdf>.

- *Accuracy without Signals*: A cutting-edge area that intersects both timing and navigation capabilities is the development of platforms that remain highly accurate without external signals. For example, this may include timing devices that do not rely on GPS signals or quantum sensors that allow navigation in difficult environments.²⁸
- *Less Power Consumption, Smaller Scale*: There is also an emphasis on developing smaller devices that consume less power. For example, one objective is to develop sensors that could be carried on battlefields by soldiers looking to ensure stable connections with other communications devices.²⁹
- *Withstanding Tough Environments*: Technologies able to withstand high environmental stress, such as in space or underwater are also of interest.
- *Lower Cost*: The expansion of these technologies also means they could be cheaper and more scalable than current available systems. While the most cutting-edge of the platforms considered here are not at this commercialization stage, the progression to this stage could have major security implications.

Using these emerging characteristics and stages of development, this research focuses on two major PNT areas: advanced timing platforms, including chip-scale atomic clocks (CSAC), and advanced navigation and guidance systems that incorporate quantum sensing or other emerging techniques. A report by the Center for New American Security described this relevant category as “radar, timing, imaging, sensing, metrology, and navigation” – these terms overlap well with PNT, although the field of quantum sensing may be even broader.³⁰

Chip-Scale and Advanced Atomic Clocks

Atomic clocks are a fixture of the PNT timing category. Atomic clocks use atomic

28 Andrew Fearnside, “Mapping the Commercial Landscape for Quantum Technologies,” *Physics World*, December 3, 2018, <<https://physicsworld.com/a/mapping-the-commercial-landscape-for-quantum-technologies/>>.

29 Elizabeth Fetter. “How Chip Scale Atomic Clocks Will Change the Future of Time.” September 2013, <<https://www.wired.com/insights/2013/09/how-chip-scale-atomic-clocks-will-change-the-future-of-time/>>, partner content from Wired -- Fetter worked at Symmetricom.

30 Elsa Kania and John Costello, “Quantum Hegemony? China’s Ambitions and the Challenge of U.S. Innovation Leadership,” Center for a New American Security, September 12, 2018, <<https://www.cnas.org/publications/reports/quantum-hegemony>>.

frequencies to provide extremely accurate timing information; they are used in many civilian applications like telecommunications, high-frequency financial interactions, and GPS systems.³¹ The emerging PNT aspect of atomic clocks pertains to miniature atomic clocks that can be used for precise timing in difficult environments. Chip-scale atomic clocks have promise for this application, and the Defense Advanced Research Projects Agency (DARPA) seems to have put considerable emphasis on these devices in recent years.³² These clocks are now commercialized, with the primary leader in the field, Microsemi, being linked to one of the original entities involved in the DARPA project. Microsemi produces a commercially available CSAC advertised for low-earth orbit applications where radiation is present.³³ The National Institute of Standards and Technology (NIST) estimates the market for CSAC-type devices is USD \$260 million.³⁴ The private sector presence of CSAC technology comprises a very small number of firms, almost all of which were related to the original DARPA project. The CEO of one of the related companies argues that these small, low-powered CSACs can be used in mobile environments where GPS may be jammed or otherwise unavailable.³⁵

In addition to CSACs, another area of research includes advanced atomic clock approaches. For the most part, this area of research is occupied by optical lattice clocks, which are extremely accurate (although apparently not yet miniaturized) instruments. Optical lattice clocks use a frequency standard approach that includes two frequencies and a laser.³⁶

Navigation Systems

In addition to advanced atomic clocks, the emerging PNT area also includes enhancements to inertial navigation technologies. It is even possible that CSACs

31 National Institute of Standards and Technology, “A New Era for Atomic Clocks,” February 4, 2014, <<https://www.nist.gov/news-events/news/2014/02/new-era-atomic-clocks>>.

32 Nathan Strout, “Could Chip-Sized Atomic Clocks Replace GPS?,” C4ISR Net, August 28, 2019, <<https://www.c4isrnet.com/battlefield-tech/space/2019/08/28/could-chip-sized-atomic-clocks-replace-gps/>>.

33 Microsemi, “Space Chip Scale Atomic Clock (CSAC),” <<https://www.microsemi.com/product-directory/embedded-clocks-frequency-references/5207-space-csac>>.

34 “Navigation through Timekeeping,” National Institute of Standards and Technology, <<https://www.nist.gov/industry-impacts/navigation-through-timekeeping>>.

35 Ibid.

36 “About,” iqClock, <<https://www.iqclock.eu/about.html>>.

will work in conjunction with inertial navigation systems.³⁷ The fundamental goal of inertial navigation is to accurately keep track of the position of a platform without external signals, which is a type of “dead reckoning.”³⁸ Inertial navigation systems (INS) is an umbrella term for a system that uses a variety of components to determine the location, speed, and direction of an object.³⁹ These systems provide built-in navigation information without an uplink to another communications station.⁴⁰ INS technologies have differing levels of performance without GPS signal support. An Attitude and Heading Reference System (AHRS) is underneath the term INS, and these systems provide attitude and heading information.⁴¹ Underneath AHRS is an Inertial Measurement Unit (IMU) that includes accelerometers and gyrometers. A key legacy advancement in this technology area was achieving the ability to manufacture the components using Micro Electro-Mechanical Systems (MEMS). By the early 2010s, many firms had access to these miniature components.⁴²

Inertial navigation systems are by no means new, but there are contemporary efforts to apply quantum sensing and other quantum approaches to the field. According to a study by the Institute for Defense Analyses (IDA), a major emerging technology area under inertial navigation is the incorporation of quantum sensors in lieu of traditional accelerometers. IDA finds that the systems are still relatively bulky and can be quite expensive, meaning there may not be widespread demand for them beyond military applications.⁴³ A study from the United Kingdom is slightly

37 Steve Fossi (Symmetricom), “Chip-Scale Atomic Clocks can Help with UAV SWaP Design Challenges,” Small Form Factors, <<http://smallformfactors.mil-embedded.com/articles/chip-scale-swap-design-challenges/>>.

38 William E. May, et al, “Navigation,” Encyclopædia Britannica, February 7, 2019, <<https://www.britannica.com/technology/navigation-technology/Dead-reckoning>>.

39 Jean-Phillipe Condomines, “Nonlinear Kalman Filter for Multi-Sensor Navigation of Unmanned Aerial Vehicles: Application to Guidance and Navigation of Unmanned Aerial Vehicles Flying in a Complex Environment,” 2018. Accessed via Google Books, pp. 19-20, <<https://doi.org/10.1016/C2017-0-01436-2>>.

40 For additional information on inertial guidance and navigation, see “Inertial Guidance System,” Encyclopædia Britannica, June 16, 2017, <<https://www.britannica.com/technology/inertial-guidance-system>>.

41 Bethany Whitfield, “How It Works: Attitude and Heading Reference System,” September 16, 2016, Flying Mag, <<https://www.flyingmag.com/how-it-works-attitude-and-heading-reference-system/>>.

42 M. Perlmutter and L. Robin, “Abstract,” High-Performance, Low Cost Inertial MEMS: A Market in Motion!,” April 2012, <<https://www.ion.org/publications/abstract.cfm?articleID=10083>>.

43 Keith W. Crane et al, “Assessment of the Future Economic Impact of Quantum Information Science,” Institute for Defense Analyses, August 2017, <<https://www.ida.org/-/media/feature/publications/a/as/assessment-of-the-future-economic-impact-of-quantum-information-science/p-8567.ashx>>.

more positive, finding that aerospace and defense applications in the next decade, combined with long-term consumer applications, may form a market for these quantum inertial sensors.⁴⁴

Another key technical component for advanced inertial navigation is the quantum accelerometer, which often uses a “cold atom” approach. When incorporated into an accelerometer and used as an atomic measurement tool, this approach could make the system quite accurate without GPS or external signals.⁴⁵ A key part of a quantum accelerometer is an atom interferometer, which includes an atom-cooling laser and a laser that serves as a measurement tool for the atoms.⁴⁶ For example, the United Kingdom has developed a prototype quantum accelerometer for use on a submarine that could make submarines and other systems less reliant on traditional navigation.⁴⁷ The mapping includes a number of entities working on this type of approach to quantum navigation, which requires lasers to cool atoms.

Although the cold atom approach is among the most prominent, there are other techniques that may yield advanced navigation applications. Nuclear Magnetic Resonance (NMR) technologies might have applicability to cutting-edge PNT developments.⁴⁸ Northrop Grumman engineers published a paper in 2014 detailing their efforts to apply NMR to navigation, noting that the technology could be quite accurate but that the “small form factor” for an NMR system was still a work in progress.⁴⁹ There are also studies involving the use of high-energy atoms.⁵⁰ Finally, in addition to the quantum inertial technology discussed above,

44 “A Roadmap for Quantum Technologies in the UK,” UK National Quantum Technologies Programme, <<https://epsrc.ukri.org/newsevents/pubs/quantumtechroadmap/>>, Executive Summary and p. 14.

45 Hayley Dunning, “Quantum ‘compass’ could allow navigation without relying on satellites,” Phys.org, November 8, 2018, <<https://phys.org/news/2018-11-quantum-compass-satellites.html>>.

46 “Quantum ‘compass’ could allow navigation without relying on satellites,” Imperial College London video, November 8, 2018, <<https://www.youtube.com/watch?v=xcqkXkWZhbM>>.

47 Paul Marks, “Quantum positioning system steps in when GPS fails,” New Scientist, May 14, 2014, <<https://www.newscientist.com/article/mg22229694-000-quantum-positioning-system-steps-in-when-gps-fails/>>.

48 “Nuclear magnetic resonance,” Encyclopædia Britannica, July 20, 2018, <<https://www.britannica.com/science/nuclear-magnetic-resonance>>.

49 Doug Meyer and M. Larsen, “Nuclear Magnetic Resonance Gyro for Inertial Navigation,” Gyroscopy and Navigation, 2014, Vol. 5, No. 2, pp. 75–82.

50 “Army Researchers Make Giant Leap in Quantum Sensing,” U.S. Army Research Lab, October 25, 2018, <https://www.army.mil/article/212935/army_researchers_make_giant_leap_in_quantum_sensing>.

the broader area of quantum sensing may overlap with PNT. However, not all of the “quantum sensing” field is PNT, and these terms are not interchangeable.

4.4 Policy Background

There are a few policies and regulations relevant to emerging PNT stemming from direct PNT government guidance and quantum technology initiatives. However, beyond the ANPRM, there are no existing policies and regulations strictly concerning PNT and export controls. A number of government efforts have been aimed at PNT resilience in the United States. The U.S. Department of Transportation has a “National PNT Architecture” that focuses on critical infrastructure risks stemming from loss of GPS, and the U.S. military has been looking at GPS alternatives.^{51,52} There is a PNT-related advisory board featuring people from inside and outside of the government producing recommendations related to these subjects.⁵³ Finally, there is a recent U.S. Executive Order focused on critical infrastructure and preventing PNT disruptions that includes a mandate for the federal government to engage with industry members on PNT topics.⁵⁴ In addition to government-led efforts specific to PNT, there is also an emphasis on quantum technology development in academia and government. Multiple countries have launched quantum technology research programs led by academic and government institutions, which are described further in the findings portion of this section.

4.5 Mapping Analysis

The mapping analysis of emerging PNT organizations highlights the geographical and focus area breadth of organizations involved in emerging PNT research,

51 U.S. Department of Transportation, “National Positioning, Navigation, and Timing (PNT) Architecture,” Accessed June 2020, <<https://www.transportation.gov/pnt/national-positioning-navigation-and-timing-pnt-architecture>>.

52 Connie Lee, “Special Operators Pursuing New Position, Navigation and Timing Capabilities,” National Defense Magazine, May 17, 2018, <<https://www.nationaldefensemagazine.org/articles/2018/5/17/pentagon-pursuing-new-position-navigation-and-timing-capabilities>>.

53 Space-Based Positioning Navigation and Timing, National Advisory Board, “Protect, Toughen, and Augment Global Positioning System for Users,” September 2018, <<https://www.gps.gov/governance/advisory/recommendations/2018-09-topic-papers.pdf>>.

54 “Executive Order on Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services,” The White House, February 12, 2020, <<https://www.whitehouse.gov/presidential-actions/executive-order-strengthening-national-resilience-responsible-use-positioning-navigation-timing-services/>>.

indicating key trends and applications. Advanced navigation and timing equipment has been used by militaries and the private sector for decades, so organizations have been labeled in this research as “emerging PNT” if they focus on major enhancements to existing systems or entirely new research approaches. Many emerging PNT organizations are located in the United States; China, the United Kingdom, and the European Union also have relatively large numbers of organizations. A “quantum” approach to PNT, through quantum sensing and/or quantum-enhanced navigation platforms, is being pursued by numerous academic and corporate organizations. With the exception of some of the advanced timing equipment, many of the identified entities are working on PNT approaches that have not been fully commercialized. Finally, the PNT category diverges significantly from the development trends of quantum computing and computer vision, the other technology categories analyzed in this report.

Selection of PNT Organizations

PNT organizations were selected based on the composition of their current work portfolio and their connections to academic and government interest in the field. While the mapping focuses mostly on emerging PNT work, the PNT organizations in this analysis were initially divided into two categories: emerging and legacy PNT. The emerging group are clearly working on novel PNT applications, including both basic research and commercialized products. For the purpose of this mapping, the legacy organizations are focused in the area of inertial guidance systems. While these are not the only legacy firms in PNT generally (in fact, many GPS firms could be considered PNT), these firms were identified as having supply chains and capabilities that could apply to the future of navigation approaches.⁵⁵ Although they do not appear to be producing PNT platforms that would be considered “emerging,” they are theoretically well-positioned to market and distribute future commercial navigation systems. If there is a significant advancement in the quality of navigation systems that do not rely on GPS and these systems are commercialized, the legacy firms included could be at the forefront of distributing them. These organizations often are recognized names, have well-established sales networks, and have customer relationships with major

55 This mapping analysis for legacy PNT does not claim to be comprehensive, particularly because there are potentially hundreds of legacy firms working on GPS and traditional navigation. Legacy PNT firms in the dataset are meant to be a point of comparison for existing data and a possible network for dispersion of emerging navigation systems once these platforms are commercialized.

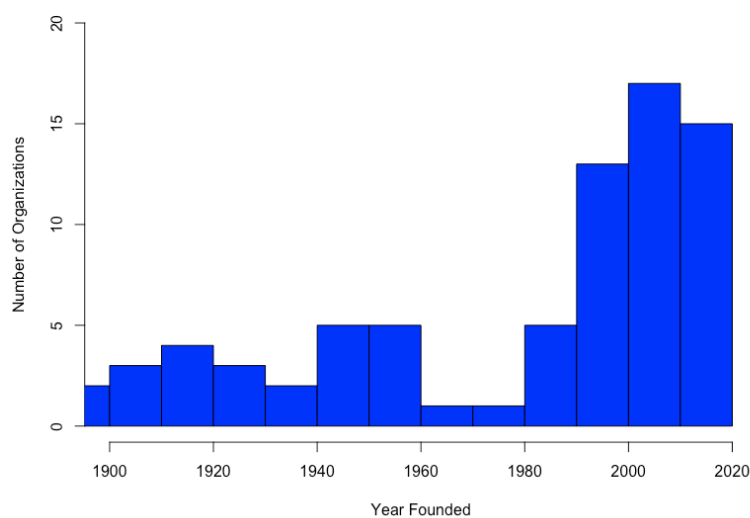
commercial players. In total, 86 emerging PNT organizations were included in the mapping analysis. Each of these organizations was coded according to a consistent set of criteria, with trends presented below.

Organization Types

An important metric for assessing the makeup of the field is the establishment date of the entities involved in this work. This can yield information about the types of organizations working in the area, the prevalence of new firms, and the possibility of future mergers and acquisitions. Emerging PNT firms identified through this mapping analysis have generally new establishment dates. However, there are some exceptions, particularly in the case of well-established government contracting firms who are working in the area.

Figure 1 illustrates that although there are a number of organizations working on emerging PNT that are well-established organizations, there has been a substantial uptick in the number of firms in this space since 1990. Some of the identified entities are start-ups or research laboratories that have been founded in the past five to ten years, which signals additional interest in the field.

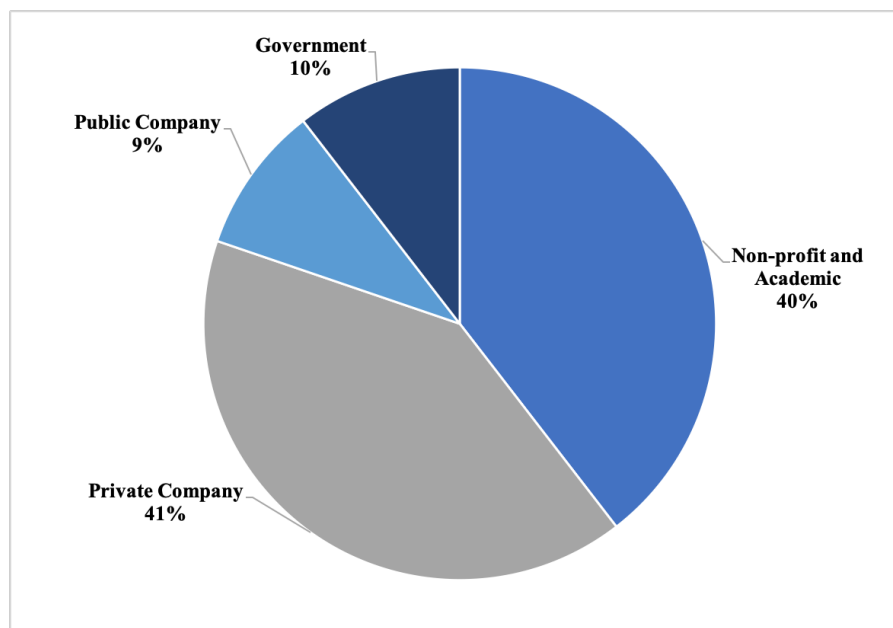
Figure 1. Founding Year of Emerging PNT Firms⁵⁶



56 Figure 1 includes emerging PNT firms with a founding data of 1900 or later. A small number of identified organizations were established before 1900, particularly universities, so the histogram does not add up to 86 entities. Graphic made using R, R Core Team, “R: A Language and Environment for Statistical Computing,” R Foundation for Statistical Computing, 2020, <<https://www.R-project.org/>>.

Beyond the establishment year of the organizations, the type of organization also provides insight into who is interested in each emerging technology field and for what reasons. Many of the PNT firms are privately held companies, which may be a product of the relatively recent emergence of PNT firms focused on novel applications. While the private company category encompasses the majority of the emerging PNT entities, there are also academic organizations, government agencies, and publicly traded corporations included. Because there are numerous universities worldwide that are studying quantum technology, this analysis focused on identifying universities working on specific PNT applications stemming from quantum research. There is vibrant collaboration between different types of emerging PNT organizations, discussed in further detail in the Findings section. Ultimately, many of the organization types also are collaborating on emerging PNT, particularly with government-funded research ventures that support academic and private sector work.

Figure 2. Types of Organizations Involved in Emerging PNT Work⁵⁷



Firm Characteristics

In addition to organization type, each of the emerging PNT entities was coded for various kinds of geographical connections, starting with the headquarters of the

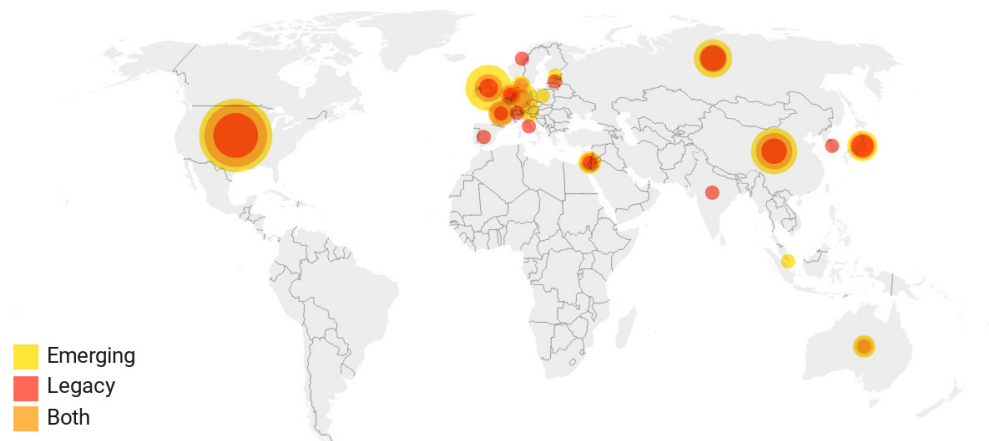
⁵⁷ Note that state-owned enterprises, unless direct government research institutions, are included under the “company” category.

organization. The initial mapping provides a graphical representation of PNT work around the world. Additional international variables further detail the geographic dispersion information and illustrate how many international connections and partnerships exist in the field. Map 1, displaying the geographical dispersion of PNT firms, illustrates the concentration of organizations in the United States, China, and the European Union. Many of the identified emerging firms are from similar regions.

Beyond geographic dispersion of PNT firms, additional information on the multinational nature and foreign involvement of entities in the emerging PNT sector is summarized in Table 1. Our multinational variable's broad definition finds that about half of emerging PNT firms have some type of international connection. The amount of emerging PNT entities with international manufacturing facilities was relatively low at 17%, and about a third have international distribution networks. These relatively low amounts of international distribution and manufacturing are most likely a product of the nascent nature of the development of these systems. Once technologies are more broadly commercialized, it is likely that these numbers will increase.

Map 1. Locations of PNT Organizations

Where are PNT organizations located?



Source: Center for International and Security Studies at Maryland/Strategic Trade Research Institute · Created with Datawrapper

Table 1. Key Traits of Emerging PNT Organizations

Category	Percent of PNT Sector
Government Involvement	87%
Academia Ties	69%
Multinational – Umbrella Category	51%
International Partnership	51%
International Manufacturing	17%
International Distribution	27%
International Headquarters	5%
International Investment	14%
Explicitly Dual-Use	45%

Interestingly, as shown in Table 1, the results also indicate that there is little international investment in emerging PNT firms. There are a couple possible explanations for this: first, the concentration of U.S.-based firms and the dual-use nature of many of the organizations included in the dataset mean that the firms are contained to a single country. Second, there appears to be relatively little interest in private sector PNT ventures, and venture capital firms that fund start-ups seemed to show little interest in PNT as a category. This lack of investment and private sector interest could suggest PNT technologies are not seen as lucrative private sector opportunities, but are rather seen as a necessity for specialized, dual-use scenarios. At the same time, the lack of investment data for smaller, private companies may distort the levels of investment in the area.

Role of Academia and Government

Academic and government actors play an important role in emerging PNT development, and potentially a major role compared to the other technologies analyzed in this research. The U.S. government has been a pioneer in the quantum field generally, with most active research being pursued by the military, national laboratories, and other organizations.⁵⁸ Many of these quantum initiatives touch

58 For background on government roles in quantum and a concise primer on quantum development in general, see Michael J. Biercuk and Richard Fontaine, “The Leap Into Quantum Technology: A Primer for National Security Professionals,” *War on the Rocks*, November 17, 2017, <<https://warontherocks.com/2017/11/leap-quantum-technology-primer-national-security-professionals/>>.

on PNT applications. The government has become involved through partnerships with specific organizations, as well as wholesale calls for grants and projects. For example, the U.S. Air Force opened a call for funding proposals in 2019 that was focused especially on “early-stage,” academic teams that among other items included language about quantum sensors and clocks.⁵⁹ Additionally, there is also the possibility of academic and government partnerships, including with defense groups. Last year, the *Washington Post* reported that a Chinese research lab pursuing quantum-related technology at the University of Science and Technology of China had partnered with a major Chinese shipbuilding company to research applications for submarine navigation.⁶⁰ Finally, there are additional government efforts involving navigation, including an attempt to produce an “all-source positioning and navigation system” that could harness all types of GPS and non-GPS signals for active navigation.⁶¹ While DARPA has indicated that they are pursuing such a technology, there is relatively little publicly available information about the project.

In addition to government-based work, academic settings are an important component of emerging PNT basic research. The cold atom and other advanced navigation approaches in particular demand high-quality laboratory settings. There is clear interest in this and CSAC work among academic research communities in the United States, European Union, and China. There is a consortium of European universities and companies collaborating on a new atomic clock approach with funding from a government initiative.⁶² This project illustrates a unique model of development for the technologies, where publicly funded institutions invest in a group of universities and/or companies to work on these emerging approaches.

Over forty percent of identified PNT organizations explicitly advertise their

59 Small Business Innovation Research, “Open Call for Science and Technology Created by Early-Stage (e.g. University) Teams,” 2019, AF19C-T010, <<https://www.sbir.gov/sbirsearch/detail/1621015>>.

60 Jeanne Whalen, “China’s Top Quantum Scientist has Ties to the Country’s Defense Companies,” *The Washington Post*, December 26, 2019, <<https://www.washingtonpost.com/technology/2019/12/26/chinas-top-quantum-scientist-has-ties-countrys-defense-companies/>>.

61 David Kramer, “DARPA Looks beyond GPS for Positioning, Navigating, and Timing,” *Physics Today*, 67, 10, 23, 2014, <<https://physicstoday.scitation.org/doi/full/10.1063/PT.3.2543>>; “Micro-Technology for Positioning, Navigation and Timing (Micro-PNT) (Archived),” DARPA, <https://www.darpa.mil/program/micro-technology-for-positioning-navigation-and-timing>>.

62 “European Consortium to Develop New Quantum Clocks,” University of Amsterdam, October 29, 2018, <<https://iop.uva.nl/content/news/2018/10/european-consortium-to-develop-new-quantum-clocks.html?cb>>.

research or products as dual-use. This is, in part, due to the high levels of government contracts involved in the field. This high fraction of dual-use designation is an additional reason to consider the strategic trade implications of emerging PNT. Even for organizations that do not explicitly identify their work as dual-use, eventual applications may have dual-use significance. For example, many of the academic institutions do not explicitly claim their work as dual-use, but the eventual commercialization of systems like quantum navigation platforms could have real dual-use relevance. Conversely, there are also a number of emerging PNT firms in the United States that seem to be working exclusively, at least for now, on direct military applications due to funding from major U.S. Department of Defense research centers like DARPA.

Major Applications

Emerging PNT technologies tend to have a range of both civilian and military applications, and often the delineation between civilian and military technology is unclear or non-existent. If commercialized, a future “quantum inertial navigation system” may be used on multiple civilian or military platforms, since the purpose of the navigation system is somewhat unrelated to the rest of the platform.⁶³ A research lab in the United Kingdom is working on quantum sensors using cold atom technology. The sensors could be used in a variety of underground applications, since the technology could detect and navigate through the ground.⁶⁴

There are other quantum PNT approaches with direct military applications, including radar. In China, there is reported research into a “quantum radar” system, which harnesses photons to potentially detect otherwise stealth aircraft. A Chinese state-owned enterprise claimed in 2016 that they have a working prototype of this application, although others are skeptical of the platform’s effectiveness beyond a laboratory environment as of the date of publication.⁶⁵ The radar capabilities have been characterized as over-hyped as there is insufficient technical information

63 For one example of a quantum inertial navigation system see Leibniz Universitat Hannover, “Quantum Inertial Navigation Systems,” <<https://www.iqo.uni-hannover.de/en/research-groups/guided-matter-wave-interferometry/quantum-inertial-navigation-systems/>>.

64 University of Birmingham, “Gravity Pioneer: Industry Leaders Enter Partnership to Develop New Industry of Gravity Sensors,” November 9, 2018, <<https://www.birmingham.ac.uk/schools/physics/news/2018/quantum-gravity-pioneer-project.aspx>>.

65 Martin Giles, “The US and China are in a Quantum Arms Race that will Transform Warfare,” *MIT Technology Review*, January 3, 2019, <<https://www.technologyreview.com/2019/01/03/137969/us-china-quantum-arms-race/>>.

to support claims that the radar can detect aircraft that are currently difficult to locate.⁶⁶ While quantum sensing is a broad category aside from PNT, quantum radar is a quantum sensing application that has direct implications for PNT. Although the firms analyzed in this report signal significant government interest in PNT, the private sector use cases for emerging PNT are, at least right now, relatively limited.

With respect to CSAC applications, the commercialized technology is currently marketed globally through a small number of firms. In the early 2010s, a partnership involving government entities DARPA and Sandia National Laboratories alongside private organizations Draper Labs and Symmetricom Inc. announced that their CSAC had been advanced to commercialization.⁶⁷ Symmetricom was acquired by another firm, Microsemi, in 2013.⁶⁸ The firm has additional locations throughout Asia, Europe, and the Middle East.⁶⁹ The Microsemi CSAC is marketed as the “first commercially available” CSAC with low power consumption and high performance in difficult environments.⁷⁰

Key Industries

Once commercialized, emerging PNT technologies could aid a number of industries in navigation and surveying work. The research and development occurring today is advertised for a number of these civilian and military uses, summarized in Figure 3. Additional illustrative examples of dual-use applications are summarized in Table 2.

66 Michael J. Biercuk, “Read Before Pontificating on Quantum Technology,” *War on the Rocks*, July 13, 2020, <<https://warontherocks.com/2020/07/read-before-pontificating-on-quantum-technology/>>.

67 “World’s Smallest Atomic Clock on Sale,” Sandia National Laboratories, May 2, 2011, <https://share-ng.sandia.gov/news/resources/news_releases/atomic-clock/>.

68 “Microsemi Corporation to Acquire Symmetricom, Inc.,” PR Newswire, October 21, 2013, <<https://www.prnewswire.com/news-releases/microsemi-corporation-to-acquire-symmetricom-inc-228666761.html>>.

69 “Locations,” Microsemi, <<https://www.microsemi.com/locations>>.

70 “Chip Scale Atomic Clock,” Microsemi Product Portfolio, <<https://www.microsemi.com/product-directory/clocks-frequency-references/3824-chip-scale-atomic-clock-csac>>.

Figure 3. Major Industries, Emerging PNT Organizations

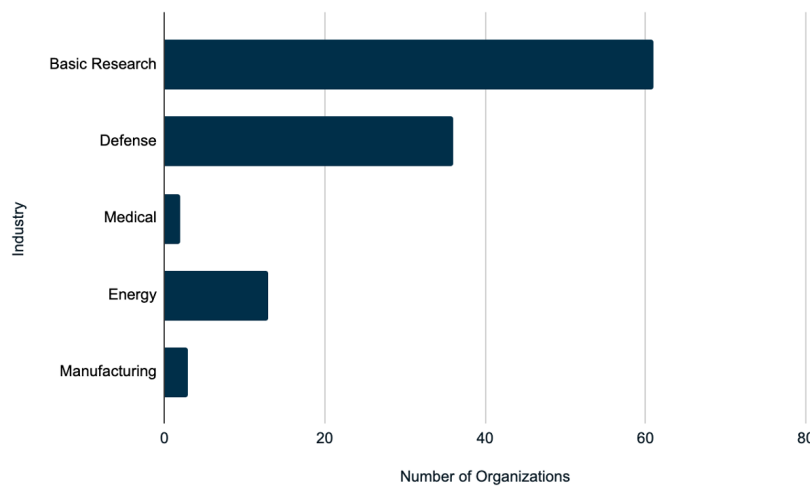


Table 2. Applications for Emerging PNT Technologies⁷¹

Technology	Civilian	Military
Chip-scale and other advanced atomic clocks	<ul style="list-style-type: none"> • Uncrewed aerial vehicles used for non-military purposes (communication and navigation) • Telecommunications and transportation sensors • Geological monitoring • Astronomy (wave detection) 	<ul style="list-style-type: none"> • Military uncrewed aerial vehicle communication and navigation • Anti-improvised explosive device (IED) systems • Battlefield sensors for soldiers • Direct weapons system applications • Missile defense radar timing

71 References for the industry table include: Ibid.; Steve Fossi; Ibid, iqClock; NIST, “Navigation through Timekeeping,” <<https://www.nist.gov/industry-impacts/navigation-through-timekeeping>>; Edric Thompson, “Miniaturized Atomic Clock to Support Soldiers in Absence of GPS,” U.S. Army, October 4, 2012, <https://www.army.mil/article/88361/miniaturized_atomic_clock_to_support_soldiers_in_absence_of_gps#:~:text=%22The%20CSAC%20is%20a%20critical,and%20commanders%2C%22%20Olson%20said%20>; Adam Stone, “Tactical Timekeeper: Army to Roll Out Tiny Atomic Clocks,” C4ISR Net, October 12, 2016, <<https://www.c4isrnet.com/intel-geoint/sensors/2016/10/12/tactical-timekeeper-army-to-roll-out-tiny-atomic-clocks/>>; Nathan Strout, “Orolia to Contribute Timing System to Missile Defense Radar,” C4ISR Net, July 14, 2020, <<https://www.c4isrnet.com/battlefield-tech/2020/07/14/orolia-to-contribute-timing-system-to-missile-defense-radar/>>; Ibid, Max I Turner, “Real-World Applications for Atom Interferometric Quantum Sensors,” Phys Org, August 10, 2020, <<https://phys.org/news/2020-08-real-world-applications-atom-interferometric-quantum.html>>; M Squared Lasers, “Quantum Navigation,” <https://www.m2lasers.com/images/MSquared_QuantumAccelerometer_Handout.pdf>; Ibid, Paul Marks; and Heidi Vella, “Could Quantum Radars Expose Stealth Planes?,” Engineering & Technology, April 18, 2019, <<https://eandt.theiet.org/content/articles/2019/04/could-quantum-radars-expose-stealth-planes/>>.

Quantum-aided navigation and advanced quantum sensing applications	<ul style="list-style-type: none"> • Undersea surveying for mineral and gas deposits • Civilian transportation (cargo ships, trains) 	<ul style="list-style-type: none"> • Submarine navigation • Advanced and stealth-detecting radar
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4.6 Comments on Data

The most notable limitation of this PNT mapping analysis is the challenge of accurate distinction between emerging and legacy organizations. There is no shortage of organizations, particularly academic institutions, doing work on PNT-related technology. There are also PNT technologies that do enhance systems like drones but may not have a novel technological approach. Because of this, the research takes a relatively narrow definition of emerging PNT. While this narrow definition provides a list of organizations useful to study because of their cutting-edge activities, there may be other companies working on interesting PNT approaches that are not included in this analysis. In addition, information on the technical operations of companies (particularly start-ups) is not always readily available. This is especially true with regards to information on primary investors for companies, strategic plans for companies, and partnerships between firms. To ameliorate some of these uncertainties, additional research in this area could interview industry stakeholders to get a better sense of the sector's target applications and international activities.

4.7 Conclusions and Trade Control Implications

Technology Conclusion

Emerging PNT work is characterized by novel approaches to long-standing navigation and timing challenges. Many institutions with well-documented academic and government involvement are working on new approaches for civilian and military PNT technologies. This mapping analysis finds that emerging PNT technologies are often described in dual-use terms, with about half of the organizations touting military uses. While China, the European Union, and the United States comprise the largest shares of emerging PNT organizations, there are some differences between the three regional approaches. The United States has many private sector, start-up style companies relying on government

contracts. Both the European Union and the United States have high levels of academic interest and collaborations between academia and the private sector. China also has academic institutions working on the technologies, but many of these institutions are directly connected to the government through a system of “key” laboratories. All three regions are working on PNT technologies with dual-use implications.

Export Controls and Emerging PNT

Because emerging PNT research is in a relatively early stage and there is a limited academic and industry research community, export controls may be a feasible option for controlling the spread of cutting-edge technology in the area. If policymakers decide controlling emerging PNT would be beneficial, they could use a combination of existing list-based controls, new controls, and outreach to non-government communities.

There are already existing list-based export controls on certain PNT systems in the United States and other jurisdictions, as indicated in Table 3. These current guidelines, primarily on the CCL, may apply to emerging PNT platforms. However, the extent of this connection may be nebulous. For example, there is uncertainty over whether 3A002/2g includes CSACs given the emphasis on where/how the technology is applied. According to one of their major manufacturers, they are not all covered by these existing list-based export controls. A Microsemi CSAC brochure says one of the clock models falls under category 99 (EAR99) of export control classification, so the company says the export of the CSAC generally does not require a license.⁷² Additionally, current export control language in the area is often based on how well a sensor performs, regardless of its underlying design.⁷³ This further increases the uncertainty over which specific technologies fall under the scope of controls. Thus, controls that are more clear in their targets should be a future priority.

72 The EAR99 classification means the model is apparently not subject to list-based export controls. However, this does not mean an export of a chip-scale atomic clock would never need a license (for example, because of end-use/end-user considerations). Quantum™ SA.45s CSAC Frequently Asked Questions,” Microsemi.

73 Mike Perlmutter, interview with one of the authors, phone, June 17, 2020.

Table 3. Examples of Current U.S. PNT-Related Controls⁷⁴

Control Number	Description of Control
U.S. Commerce Control List, 3A002	Electronics control, specifically Section 2G which controls “atomic frequency standards” that may include clocks; control based on being “space qualified” and/or performance-based.
U.S. Commerce Control List, 7A001	Accelerometers; section A3 applies to inertial navigation based on the acceleration levels it functions at.
U.S. Commerce Control List, 7A003	Inertial measurement equipment, defined to include inertial navigation systems, with certain characteristics. Applies to aircraft, land vehicles, and vessels.
U.S. Commerce Control List, 7A103	“Instrumentation, navigation equipment and systems;” includes some controls on “integrated flight instrument systems” including for rockets, missiles, and uncrewed aerial vehicles.

Likewise, the relevance of current export controls to emerging quantum applications is less clear because of lack of precedent and uncertainty over the end-use. It remains to be seen, for example, if a commercialized “quantum accelerometer” would be treated in the same way as existing accelerometers. There may be a need for new export controls on combinations of quantum technology and PNT applications to ensure that emerging PNT systems could be controlled once commercialized.

Finally, all of these export control mechanisms could be complemented with targeted academic and industry outreach. Research mapping emerging technology work can provide a road map for targeted non-government outreach by identifying types of organizations that are working in a given area. PNT outreach would be particularly useful to organizations working on cold atom and quantum inertial navigation approaches because those types of emerging PNT are at a relatively early stage of development, unlike CSACs which have now been commercialized. Although many of these organizations explicitly identify their work as dual-use,

74 U.S. Department of Commerce, “The Commerce Control List,” June 29, 2020, Category 3, pp. 16-19, Category 7, pg. 1, Category 7, pgs. 2-3, and Category 7, <<https://www.bis.doc.gov/index.php/documents/regulations-docs/2330-cc10-to-9-10-24-18/file>>, pp. 8-9.

about half do not, despite the potential for dual-use applications in some of their work. Academic and industry outreach focused on major research institutions and start-ups working on the technology may go a long way in educating technical communities about the dual-use nature and possible export regulations associated with commercialized technology. Even at a pre-commercial stage, deemed exports and intangible technology transfers may be a concern as start-ups build international partnerships. This outreach can focus on legal obligations for organizations as they collaborate and export these technologies, including the importance of due diligence and internal compliance programs.

5. Quantum Computing Technology

5.1 Introduction: The Rise of Quantum Computers

Quantum computing efforts have made significant strides in recent years, earning quantum technologies a position among many “disruptive” or “emerging” technologies lists.⁷⁵ In late 2019, Google self-designated its accomplishment of operating a 53-qubit processor as the achievement of a long-time benchmark of “quantum supremacy,” (where quantum supremacy refers to a quantum computer’s ability to outperform a traditional computer).⁷⁶ Meanwhile, competitors in the quantum industry have also improved their quantum computing capabilities. For example, IBM celebrated 2019 as the fourth year in a row that it was able to exceed doubling the qubit, or the smallest computational unit of a quantum computer, capacity of its quantum systems.⁷⁷ Computing-adjacent quantum technologies, such as quantum communication, which rely on similar techniques and scientific knowledge, have also seen dramatic improvements. In early 2020, China announced the successful transmission of a message through a quantum satellite

75 See, for example: “Emerging Technology and National Security,” Department of Homeland Security, 2018 Analytic Exchange Program, 2018, https://www.dhs.gov/sites/default/files/publications/2018_AEP_Emerging_Technology_and_National_Security.pdf; “Long-Range Emerging Threats Facing the United States as Identified by Federal Agencies,” United States Government Accountability Office - Report to Congressional Committees, December 2018, <<https://www.gao.gov/assets/700/695981.pdf>>; “Emerging Military Technologies: Background and Issues for Congress,” Congressional Research Service, August 4, 2020, <<https://crsreports.congress.gov/product/pdf/R/R46458>>.

76 Frank Arute, et. al, “Quantum Supremacy Using a Programmable Superconducting Processor,” *Nature*, October 23, 2019, <<https://www.nature.com/articles/s41586-019-1666-5>>.

77 Smith-Goodson, Paul, “IBM Doubles It’s Quantum Computing Power Again,” *Forbes*, January 8, 2020 <<https://www.forbes.com/sites/moorinsights/2020/01/08/ibm-doubles-its-quantum-computing-power-again/#70e2aba961ab>>.

at a record-breaking 1,120 kilometers land distance.⁷⁸ This introduces the ability to ensure hyper-encrypt communication between reasonably distanced cities. Each of these benchmarks individually marks concrete steps towards operable quantum technologies that offer dramatically increased computing power and security benefits. Together, they signal a resounding interest and commitment to achieving usable quantum-based systems.

5.2 Security Implications

Given the immense promise of quantum technologies and the surge of interest and investment, scholars and practitioners have been quick to identify potential security implications. Primarily, implications have been categorized based on the major branches of foreseeable quantum technologies: communication and information processing. Although the two technology branches are based on different physical phenomena, they are often conflated due to the crossover of certain techniques and basic research. While technical knowledge in one area may make one country or organization more prepared to pursue another technology area, when considering specific security threats, the two technology categories should be considered separately.

Quantum communication promises improved security of communication between two separate actors through entanglement of photons or atoms. Primarily, this could benefit actors attempting to secure their communications through advanced encryption and interference detection capabilities. However, a secondary effect is the impact that the application of quantum communication may have on actors who rely heavily on intelligence infiltration of other actors' systems.⁷⁹ With respect to these potential security implications, important metrics for the continued development of quantum communication capabilities worth monitoring include achievable distance of communication, method of security improvement, method of entanglement, and scalability.

Quantum information processing encompasses a much broader category of technologies, and thus is associated with a wider set of security concerns; this

78 Juan Yin, et. al, "Entanglement-Based Secure Quantum Cryptography Over 1,120," *Nature*, June 15, 2020, <<https://www-nature-com.proxy-um.researchport.umd.edu/articles/s41586-020-2401-y>>.

79 Martin Giles, "Explainer: Quantum Communication," MIT Technology Review, February 14, 2019, <<https://www.technologyreview.com/2019/02/14/103409/what-is-quantum-communications/>>.

is typically the implied category when discussed by scholars and practitioners. These concerns are generally less concrete but revolve around the increased computing capability of quantum systems. Identified concerns include increased decryption power, improved AI performance, and more robust data processing/detection capabilities.⁸⁰

Additional concerns that extend beyond strictly dual-use applications have been raised about the importance of American technological advantage, and the potential security impact should America lose technological advantage. These arguments claim that technological advantages could impact military or economic drivers of a state's national power.⁸¹ Thus, under this reasoning, a loss of American technological superiority could result in loss of economic standing (and the associated national power), and/or military technology competency.

Additionally, technology leadership allows a country to maintain robust security and safety measures in non-military areas such as public utilities and critical infrastructure.⁸² Furthermore, technology leadership in a field like quantum computing, that may yield advances in other industries such as medicine, manufacturing, and AI, creates precedent for national leadership in other critical areas.⁸³ Although this motive for controls has received criticism, as a potential “weaponization” of trade,⁸⁴ it is worth noting that this may be a secondary driver of controls. Depending on the specific motive, different types of controls will be applied.

Potential Use of Trade Controls as a Remediation

Given the security concerns regarding quantum computer applications, as well as

80 Biercuk, Michael, and Richard Fontaine, “The Leap into Quantum Technology: A Primer for National Security Professionals,” *War on the Rocks*, November 17, 2017, <<https://warontherocks.com/2017/11/leap-quantum-technology-primer-national-security-professionals/>>.

81 Elsa Kania and John Costello, “Quantum Hegemony? China’s Ambitions and the Challenge to U.S. Innovation Leadership,” Center for New American Security, 2018.

82 “American Leadership in Quantum Technology,” Joint Hearing before the Subcommittee on Research and Technology and Subcommittee on Energy Committee on Science, Space, and Technology House of Representatives, October 24, 2017, p. 9, <<https://docs.house.gov/meetings/SY/SY15/20171024/106555/HHRG-115-SY15-20171024-SD003.pdf>>.

83 Ibid, p. 28.

84 Mark Linscott, “Should Trade be More Strategic?” *Atlantic Council Blog*, September 10, 2020, <<https://www.atlanticcouncil.org/blogs/new-atlanticist/should-trade-be-more-strategic/>>.

the highly esoteric and technical nature of quantum computing research, export controls may play a role in guiding early development of quantum computer research and innovation. Compared to some of the other technologies listed in the ANPRM, quantum computer research is at a relatively nascent stage of development. This means that export controls may be effective in limiting final users of the technology through directing the types of research that receive investment in the private sector. Combined, these two factors (the security relevance and the early stage of development/high susceptibility to export controls), make quantum computing an ideal chokepoint technology for trade control policy. However, given the immense promise of quantum computing, early trade controls attempting to mitigate security-relevant activities would likely have to be extremely targeted. Otherwise, overly broad controls risk meriting criticism from the private sector that may ultimately lead to non-compliance, or loss of American technological competence through excessive burden on economic benefits.⁸⁵

5.3 Technology Overview

Although quantum technologies are in a relatively nascent stage of production, this mapping analysis shows that a number of technical and social trends have shaped the industry thus far. As noted above, main technology areas that have emerged are quantum communication and quantum information processing. However, quantum metrology, or the use of quantum technologies to improve measurement and timing capabilities, has also been prioritized among basic research and academia groups. Quantum sensing, which was introduced in the PNT technology section, is an example of a quantum metrology application.

While quantum communication and quantum metrology comprise smaller segments of businesses and research circles, innovation in these areas has the potential to translate to improvement in quantum information processing technologies. This is largely due to the fact that there is still significant uncertainty regarding the fastest path to operable quantum computers and the best system control technologies to

85 For example: “Comment for the Department of Commerce ANPRM on ‘Review of Controls on Certain Emerging Technologies’,” Jeffery Rittener, Vice President of Global Trade at Intel Corporation, <<https://www.regulations.gov/document?D=BIS-2018-0024-0199>>; “Comment for the Department of Commerce ANPRM on ‘Review of Controls on Certain Emerging Technologies’,” Vern Brownell, CEO at D-Wave, <<https://www.regulations.gov/document?D=BIS-2018-0024-0150>>; “Comment for the Department of Commerce ANPRM on ‘Review of Controls on Certain Emerging Technologies’,” Edward Bond, Director of Export Regulation Office at IBM Corporation, <<https://www.regulations.gov/document?D=BIS-2018-0024-0122>>.

apply. Experimental findings related to quantum communication and quantum metrology may illuminate new approaches to quantum computing. Additionally, advances in quantum communication and quantum metrology practical application could provide adjacent technologies needed to meet the extremely difficult criteria for operational quantum computers, including technologies such as quantum repeaters or cryogenics.⁸⁶ Thus, given that interactions between the three sectors is likely, the quantum information sector should not be analyzed in isolation from quantum communication and quantum metrology in the context of the mapping exercise.

As will be discussed below, many different quantum computer frameworks are currently being researched. Due to the influx of quantum computer hardware ideas and the lack of a consensus over which development path will yield the best computer, there is a general push to make framework-agnostic quantum computing software. In many cases, the specific hardware or software decisions are made with respect to the applications or types of industries that companies are targeting.

This section will provide a brief overview of the different quantum technologies, the various applications and industries being targeted by quantum innovators, and the relevant policies/national strategies that are currently in place.

Technical Background

Although there is still no clear technical direction driving quantum computer hardware development, a few pathways are gaining significant momentum and capturing large portions of funding and interest. Each of the different system types vary with respect to the type of qubit, where a qubit is analogous to a bit in a traditional computer, that it relies on. Systems may also vary with respect to the specific material used for the qubit, as well as the way in which they harness the quantum phenomenon of the qubit. Most of the pathways currently being pursued are gate-based quantum computing technologies, as they are touted as being building blocks for eventual universal quantum computers; this is in comparison to quantum annealing technologies, which are easier to develop but limited in application. Although quantum annealing technologies have been

86 Geza Toth and Iagoba Apellaniz, "Quantum Metrology from a Quantum Information Science Perspective," *Journal of Physics*, 2014, <<https://iopscience.iop.org/article/10.1088/1751-8113/47/42/424006/pdf>>.

successfully produced with higher qubit numbers, they tend to not reflect the true quantum benefits of quantum computing and are only able to perform a limited range of tasks. Quantum annealing technologies are able to perform a narrow set of operations based on finding local minima or maxima, but are limited in the extent to which they can be applied to other varieties of computing problems, and the extent to which they can harness the benefits of quantum superposition and entanglement.⁸⁷ The main gate-based quantum computer approaches being explored include: trapped ion qubits, superconducting qubits, spin qubits, photonic qubits, and topological qubits.⁸⁸

- *Trapped ion qubits*, which served as the computing unit basis for the earliest quantum computer demonstration in 1995, rely on extensive ancillary hardware, including lasers to cool the ions inside vacuums in order to trap and manipulate them.⁸⁹ Trapped ion qubit systems have achieved success at smaller scales, but have faced obstacles in scaling up to larger systems, due to difficulties in maintaining appropriate, consistent ambient environments across qubits.⁹⁰
- *Superconducting qubits*, otherwise known as “artificial atoms,” are macroscopic electronic circuits that exhibit quantized energy levels when cooled to extreme temperatures. Superconducting qubits may be applicable to gate-based quantum computation as well as quantum annealing. Similar to trapped ion qubits, superconducting qubits also become more difficult to operate in higher quantities, as qubit quality may decrease due to inter-qubit interactions. Thus, higher order systems will require unique arrays that spatially separate qubits.⁹¹
- *Spin qubits*, which can be achieved through a number of different methods, have also received significant investment, including support from Intel. Silicon is a leading contender for spin qubits; although silicon qubits require

87 Arnab Das and Bikas Chakrabarti, “Quantum Annealing and Analog Quantum Computation,” *Review of Modern Physics* vol 80, pg 1061, 2008, <<https://arxiv.org/pdf/0801.2193.pdf>>.

88 *Quantum Computing: Progress and Prospects* (National Academies of Science, Engineering, and Medicine, 2019).

89 Iulia Georgescu, “Trapped Ion Quantum Computing Turns 25,” *Nature Review Physics*, May 18, 2020.

90 *Quantum Computing: Progress and Prospects* (National Academies of Science, Engineering, and Medicine, 2019). p. 122.

91 *Ibid*, pp. 124-125.

extreme temperatures in order to remain operable, they are known for their stability.⁹²

- *Photonic qubits*, based on single units of light, called photons, are in a more experimental stage of research than those listed above. Photonic qubits offer unique strengths in that photons do not notably interact with the environment or with one another. However, they are also uniquely challenging in that they are difficult to localize and manipulate.⁹³
- *Topological qubits*, comprising an area that has received less funding and media focus to-date, rely on topological symmetry to increase the fidelity of qubits and to improve the error correction process. However, topological qubits are at such an early stage of research that their existence has yet to be experimentally observed.⁹⁴

Beyond quantum computing hardware, there is also a rapidly growing industry for quantum computing software, encompassing control systems, operating platforms, and programming languages. As enumerated above, quantum computing systems require highly specified environmental conditions, with control systems serving as an important fulcrum for many quantum computer milestones. Thus, significant research and funding has been devoted to control system software (in addition to hardware). Most control system software is necessarily developed specific to the type of quantum computer that it is intended for. Additionally, operating platforms, which are able to harness the benefits of quantum computers in order to more easily address identified problems, are also receiving significant interest. Operating platforms that are intelligently designed under the specific processor parameters, including the computing limits and error bounds of the system, may also play a significant part in fully actualizing the utility of a given quantum computing system. Finally, programming languages serve as a more universal method for coding quantum computer operations. Many programming languages aim to be hardware agnostic, in that they are able to be applied to any of the various quantum computers under development.

92 Thaddeus Ladd and Malcolm Carroll, "Silicon Qubits," Sandia National Lab Report – DOI: 10.1016/B978-0-12-803581-8.09736-8, 2018, <<https://www.osti.gov/biblio/1429799-silicon-qubits>>.

93 Ibid, p. 127.

94 Ibid, p. 128.

In addition to quantum computing, other areas are emerging in the realm of quantum technologies, including quantum metrology and quantum communication. Compared to quantum computing, which encompasses technologies that are programmable and able to accomplish a number of different types of computation, quantum metrology and quantum communication are areas that apply specific quantum mechanics principles in order to accomplish explicit tasks. Quantum communication typically applies the quantum entanglement phenomenon to increase the security of communication and to increase the ease of detection if an attempt to hack a communication link occurs.⁹⁵ Quantum metrology applies quantized energy levels, quantum coherence, and quantum entanglement to measure extremely sensitive physical quantities.⁹⁶

Applications/Target Industries

Given the wide variety of technologies and strategies currently applied to quantum information technology research, many applications and target industries have been identified. In some cases, the target application or industry is specific to a certain type of quantum computer/technology, in other cases the target application or industry is relevant to an advancement in any type of quantum computer/technology approach. For example, early analyses have been conducted to determine ways in which quantum computers could be applied to solve complex problems in the financial industry.⁹⁷ Such surveys attempt to identify what specific problems quantum computers would be ideal for, and furthermore which types of quantum computers and quantum computing software would be most suitable.

5.4 Policy Background

American policymakers are eagerly pursuing strategies for governance in the quantum computing field for a variety of reasons. Specifically, policymakers

95 Martin Giles, “Explainer: Quantum Communication,” MIT Technology Review, February 14, 2019, <<https://www.technologyreview.com/2019/02/14/103409/what-is-quantum-communications/>>.

96 Stuart Wolf, et. al., “Overview of the Status of Quantum Science and Technology and Recommendations from the DoD,” *Institute for Defense Analysis*, June 2019, <<https://www.ida.org/-/media/feature/publications/o/ov/overview-of-the-status-of-quantum-science-and-technology-and-recommendations-for-the-dod/d-10709.ashx>>.

97 Roman Orus, Samuel Muga, Enrique Lizaso, “Quantum Computing for finance: Overview and prospects,” *Review in Physics*, 2019.

are seeking actionable strategies that enable domestic firms to reap economic gains from developing quantum computers, that ensure national competence and technological advantage on quantum computing, and that mitigate potential security risks from global quantum computing development.⁹⁸ In an effort to encompass all of these objectives, the largest overarching policy agenda was introduced as a congressional bill in 2018 under the name of the National Quantum Initiative Act.⁹⁹ This bill was quickly followed by an Executive Office publication titled the “National Strategic Overview for Quantum Information Science,” which outlines more specific steps in advancing U.S. quantum competency.¹⁰⁰ In addition to providing financial assistance for basic research projects and companies pursuing novel quantum computing efforts, the national strategy includes plans to capitalize on the economic benefits of quantum computing leadership. To further this effort, the National Institute of Standards and Technology convened the Quantum Economic Development Consortium (QED-C), in order to support a robust American manufacturing base and supply chain for quantum technologies.¹⁰¹

The private sector is also pursuing the development of its own standards for quantum technologies. In 2018, the Institute of Electrical and Electronics Engineers (IEEE) published two standards, P7130 and P7131, which establish specific terminologies for quantum technologies and performance metrics for quantum computers, respectively.¹⁰² Other members in the industry have also been calling for the development of quantum computing ethics research.¹⁰³

98 Domestic Manufacturing Capabilities for Critical DOD Applications: Emerging Needs in Quantum-Enabled Systems: Proceedings of a Workshop. National Academies of Science, Engineering, and Medicine. 2019.

99 S.31433 - National Quantum Initiative Act, 115th Congress, 2017-2018, <<https://www.congress.gov/bill/115th-congress/senate-bill/3143>>.

100 National Strategic Overview for Quantum Information Science, The White House, 2018, <<https://www.whitehouse.gov/wp-content/uploads/2018/09/National-Strategic-Overview-for-Quantum-Information-Science.pdf>>.

101 The Quantum Consortium, <<https://quantumconsortium.org/>>.

102 P7130- Standard for Quantum Technologies Definitions, IEEE Standards Associations, 2019, <https://standards.ieee.org/project/7130.html>. P7131 - Standard for Quantum Computing Performance Metrics & Performance Benchmarking, IEEE Standards Association, 2018, <<https://standards.ieee.org/project/7131.html>>.

103 “The Time to Talk About The Ethics of Quantum Computing is Now,” QC Ethics, <<https://qcethics.org/>>.

5.5 Mapping Analysis

Overview

Although there is a significant amount of R&D that must be completed in order to produce more usable quantum computers, there is a rapidly burgeoning manufacturing base, including entities with diverse characteristics. In fact, the diversity of entities may be the result of the nascency of the R&D, allowing for organizations that tackle the problem of quantum computing through different types of funding methods, specific foci, and unique partnerships.

This research surveys the different types of components that firms are pursuing, the geographical dispersion of the industry, and firm characteristics, such as organization type, government involvement, and academic partnerships. Although many of the quantum computing firms are researching and investing in specific hardware approaches to quantum computing (largely based on the type of qubit used), this research found that the number of firms developing hardware-agnostic software for quantum computers has been increasing substantially within the last ten years. With respect to geographical dispersion of the manufacturing base, a large number (43.5%) of quantum companies are based in North America, but there is also a global presence, with other regions such as Europe and Asia capturing sizable fractions of the market as well. Most of these entities are private, although there are a handful of government-specific entities (such as national labs) and larger, public companies pursuing quantum computing technologies as well.

Selection of Organizations

Organizations were selected for this quantum computing analysis based on whether they currently operate, actively develop, or pursue quantum computing (or, in a few cases, quantum computing-adjacent) technologies. This overarching categorization includes large companies that have added quantum computing branches to their current portfolios, as well as small companies that have sought out investment in hopes of developing quantum computer technology. This also includes certain government labs and non-governmental organizations that are pursuing quantum computing technology on the basis that they are in partnerships with companies and corporations that could eventually disperse the technologies. Notably, the decision was made to include quantum computing software companies for the purposes of gaining a better understanding of how quantum computers

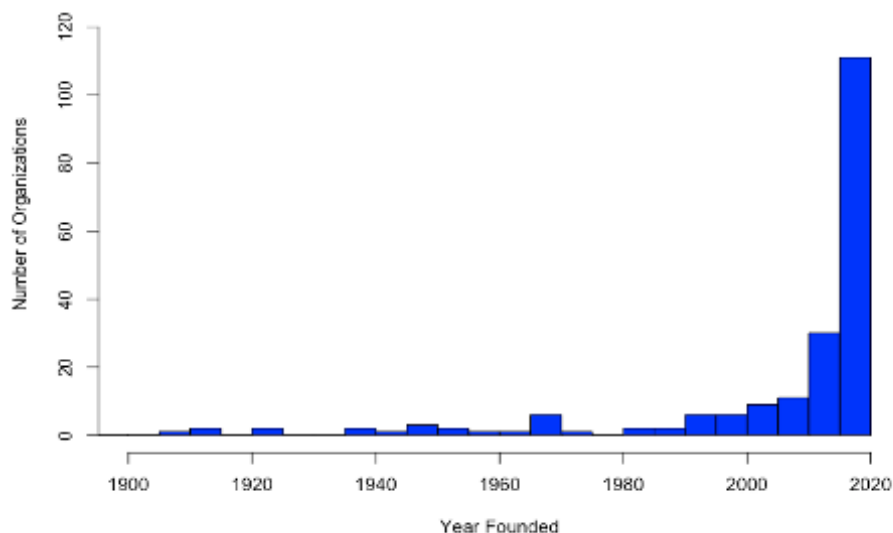
will ultimately reach various industries. Additionally, certain software companies are involved in partnerships to share quantum computer processing time once computers are developed. In total, this report includes the analysis of exactly 200 quantum computing companies; at the time that the data acquisition was completed, this was deemed to be a fairly comprehensive scope of the quantum computing manufacturing base. However, it is worth noting that, given the young age of many of the organizations, the growth of the sector is rapid and there is a need to keep the mapping research up to date, as well as continuously account for organizations that collapse, merge, or become acquired by other entities.

Findings

1. Organization Age and Type

A significant number of new firms have emerged over the past ten years seeking to benefit from growing interest among global investment groups. This large recent surge of organizations since 2010 is shown in Figure 4. Given the growing investment channels available to the younger small, private companies, it may be worth specifically analyzing the characteristics of the new firms in order to understand in what specific areas investors are interested. Throughout the research presented, we will attempt to compare differences between the newer wave of companies and the older, pre-existing companies.

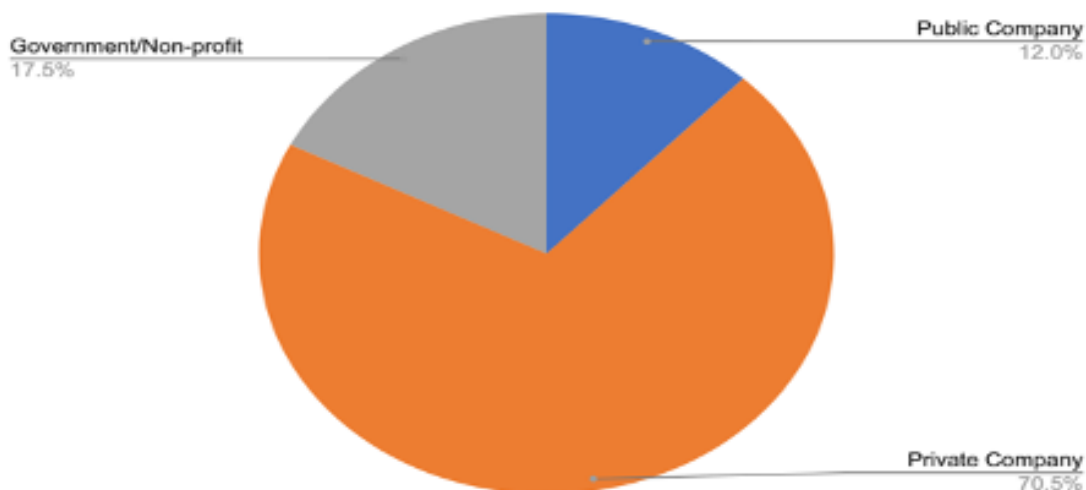
Figure 4. Founding Years of Quantum Computing Organizations (1900-2000)



As mentioned, most of the quantum computing firms are private and for-profit, although there are some public for-profit, government, and non-profit organizations as well. This breakdown is provided in Figure 5. Private companies make up the lion's share, likely because they are able to be more agile in changing R&D foci and scope of technology development. They are also able to better maintain a certain amount of privacy and information control over how their development of the new technology is progressing. This is important in a nascent field, like quantum computing, where any given breakthrough may yield significant profit or acclaim for a company. Private companies are also able to engage in international, academic, and government partnerships more easily, as there is less oversight. Finally, it is worth noting that a large number of the private quantum computing firms are start-ups that have been backed by various global investors.

The fact that there are so many private companies, supported by a large cohort of interested investors, substantiates the notion that quantum computers are predicted to be a potentially big windfall once they can be successfully built. This is because there are many different applications of quantum computers, extending well beyond military and defense applications. Furthermore, because there is still so much uncertainty over what the best technical approach is to quantum computer development, there may be a significant amount of profit for the first few companies to exemplify the benefits and usability of their own quantum computer type. However, because it is a nascent field and many of the younger, smaller firms are performing cutting-edge research, it is possible that many of them will be acquired after a few years if they show promising results and are open to the idea of being acquired by a larger company or organization.

Figure 5. Quantum Computing Organization Type



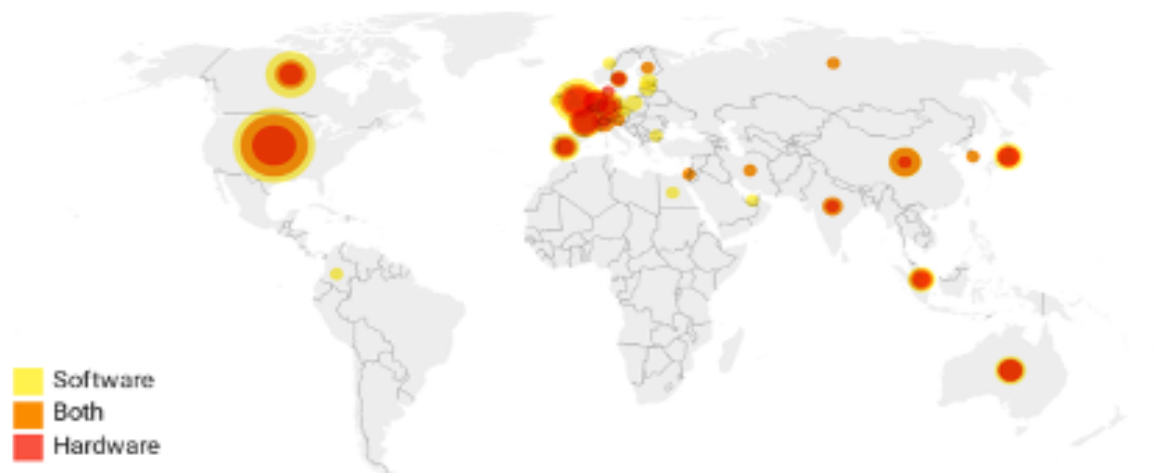
2. Global Dispersion

The global dispersion of the quantum computing manufacturing base was analyzed using two methods: sheer visualization of the company headquarters locations (Maps 2 and 3) and analysis of multinational operations. As Map 2 shows, quantum computing organizations are located predominantly throughout North America, Europe, and Asia, with smaller bases in the Middle East and Australia. However, as Map 2 and 3 demonstrate, information can be drawn out from sorting the companies by age (older companies compared to those formed in the past ten years), and by the type of technology the company is developing (hardware, software, or both). As Map 2 shows, the newer organizations have a more global presence than the older organizations. As Map 3 shows, companies building hardware, which may be more directly impacted by trade controls, are located in a narrower set of countries, but are still fairly global.

Map 2. Quantum Computing Global Dispersion by Age



Source: Center for International and Security Studies at Maryland/Strategic Trade Research Institute •
Created with Datawrapper

Map 3. Quantum Computing Global Dispersion by Technology Focus

Source: Center for International and Security Studies at Maryland/Strategic Trade Research Institute
Created with Datawrapper

Although visualizing the location of the headquarters can be useful to gain cursory insight into the potential effectiveness of trade controls, a deeper analysis into the types of global transactions that companies are involved in is also necessary given the interconnectedness of the current globalized marketplace. Table 4 provides a summary of the data analyzing the extent to which companies engage in multinational interactions. The overarching multinational category is dictated by whether or not companies engage in international research partnerships, have international manufacturing or distribution bases, have international headquarters, or receive international investment. These individual characteristics are also provided in Table 4. The data concludes that 62.5% of companies are engaged in multinational relations, with the largest driver being international investment (at 48%) and international research partnerships (at 51%). This can be explained through the large number of small, private companies. The large amount of international investment is due to the rise of quantum computing start-up companies which require investment in order to get initial funding. Additionally, start-ups are frequently engaged in international research partnerships in order to help share the burden of researching the entire quantum computing process.

Table 4. Quantum Computing Summary Table

Category	Percent of Quantum Computing Sector
Government Involvement	56%
Academia Ties	55%
Multinational – Umbrella Category	63%
International Partnership	51%
International Manufacturing	16%
International Distribution	20%
International Headquarters	13%
International Investment	48%
Explicitly Dual-Use	26%

3. Partnerships with Academia and Government

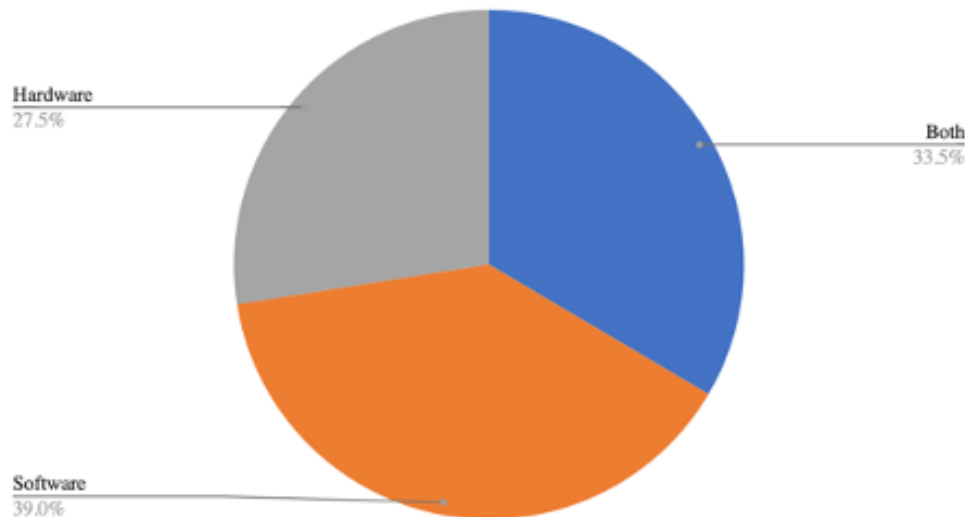
Relations to academia and government can also be a good indicator for the stage of the research in a given field and whether or not the government deems a technology to be security-relevant. As Table 4 above shows, about 55% of companies in the quantum computing manufacturing base have government involvement, which entails research partnerships or direct funding. This is fairly high considering the fact that many of these companies are private. This means governments are considerably engaged in developments or may even be trying to shape the direction of the research. Roughly 55% of companies are also engaged in partnerships with academia. This may include the sharing of facilities or scholars, or it may be a more overt research partnership. Again, this is a fairly high percent of companies with academic partnerships, indicating that the field is nascent and that research is being shared not only within the private industry (as was noted in the previous section), but also across different sectors.

4. Technology Trends

Under the broader scope of quantum computing, this research also attempted to tease out the specific focus areas for the industry, in order to determine which areas of research have been prioritized. Interestingly, this research found a fairly even three-way split between companies working explicitly on hardware, software, and both.

Perhaps the least-expected conclusion from this analysis is that there is already a significant base of companies working specifically on software for quantum computers, despite the fact that wide-scale use of quantum computers still lies in the future. A couple of factors could account for the number of companies working on quantum computing software. Likely some of the companies are seeking to profit from software that utilizes quantum computers for a specific industry or purpose that may return large profits. In this case, stating that a software is being designed for use by a quantum computer, even without a specific quantum computer in mind, may increase investment interest. However, another group of those companies is seeking to maximize the use of limited or rudimentary quantum computers through specific software approaches. For example, the sheer limit in the number of quantum computers is being tackled through quantum clouds, where companies can provide software that allows users to access quantum computer time remotely. Another example is software that is able to compensate for high error rates in early generation quantum computers through highly specified and elaborate algorithms.

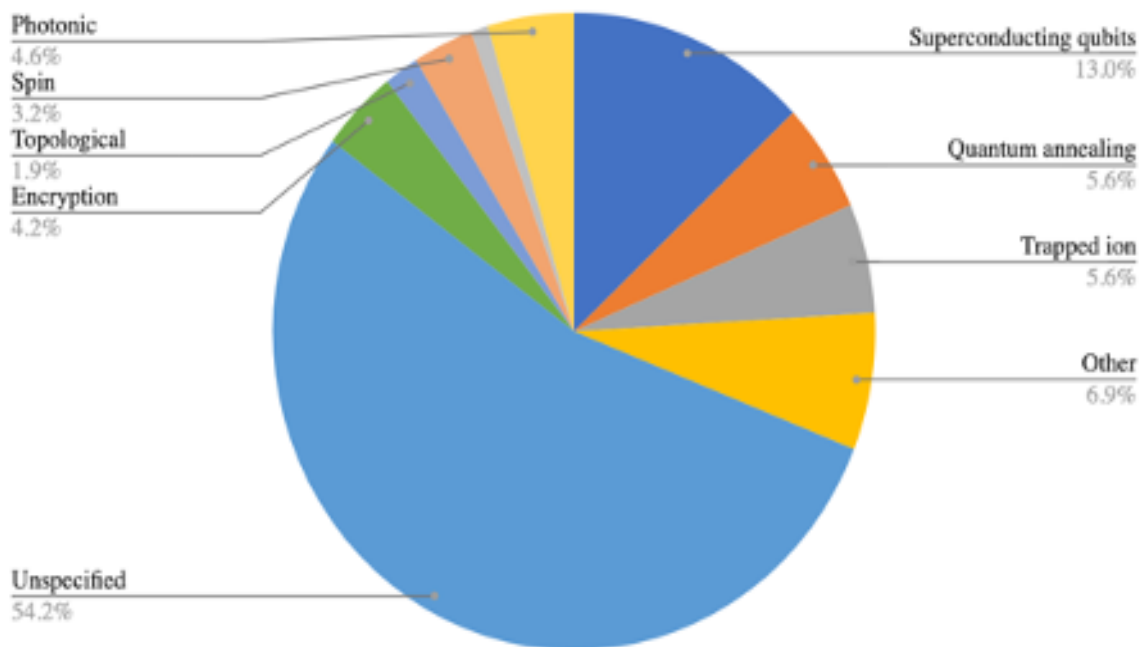
Figure 6. Quantum Computing by Technology Focus



In terms of hardware, it is also interesting to analyze the different approaches taken by the quantum computer hardware (or hardware and software) companies. Figure 7 shows that there is still a wide variety in qubit approaches being pursued. Superconducting qubits, trapped ions, and photonic qubits are certainly gaining a lot of interest. However, there are also a few other avenues being pursued by the manufacturing base, including spin-based qubits and topological qubits. Interestingly, most companies that are pursuing a specific type of qubit are

also identifying specific industries where their qubit focus may be best applied. Notably, this type of analysis is limited in its ability to account for the variation in the size of companies. Although certain qubit approaches, such as the spin qubit, may appear to have a smaller share of the manufacturing base, it is supported by Intel, which is one of the largest companies in the manufacturing base. Finally, as indicated by the Technology Overview section, there may be overlap between some of the qubit types and certain companies may be pursuing multiple different approaches.

Figure 7. Quantum Computing by System Type Focus

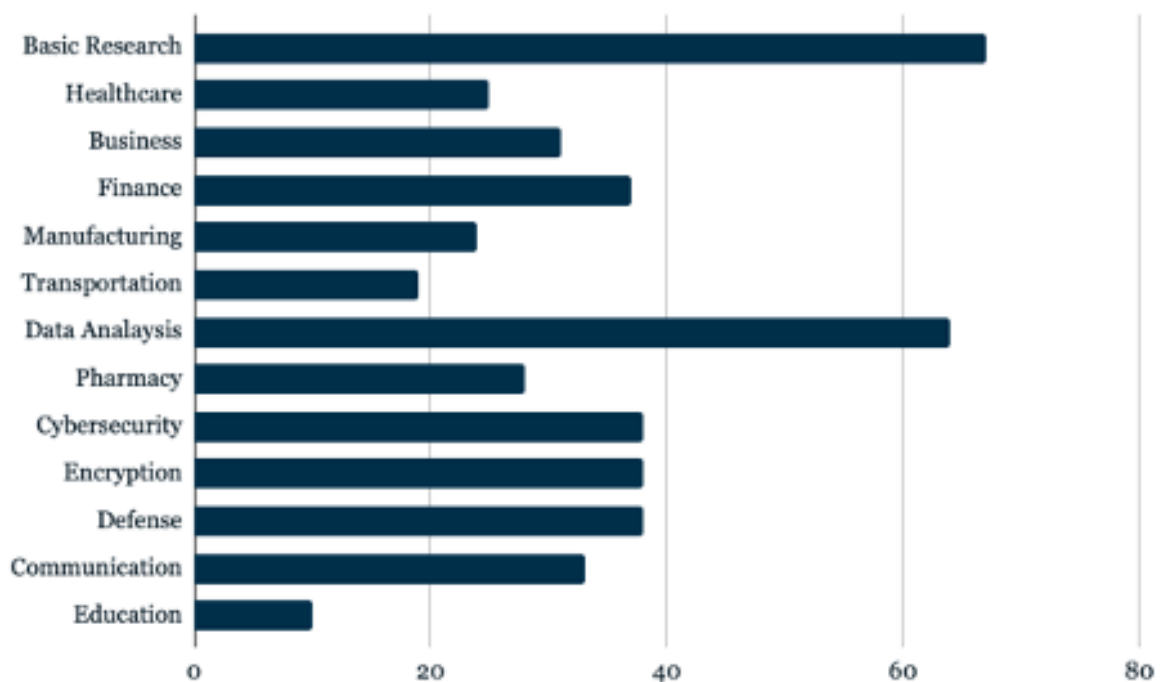


5. Targeted Industries

In this analysis, the “target industries” for each firm were also recorded. This involved identifying the types of industries to which each firm was advertising the utility of their product. The purpose of this analysis was to determine if there was a specific priority industry that was driving investment interest. Although there was a large spread in the target industries for quantum computing firms, the leading industries targeted were “Basic Research” and “Data Analysis.” The high prevalence of “Basic Research” suggests either that a large number of firms are targeting scientific endeavors for their quantum computing development, or that they are applying basic research in developing new quantum computing methods.

The two were often conflated across the different types of firms. “Data Analysis” was likely used as a catch-all term to signify that quantum computers could also generally be used to compute and analyze data. Beyond these two industries, there was also considerable emphasis on the impact that quantum computers could have on finance, cybersecurity, encryption, defense, and communication industries, as well as healthcare, business, manufacturing, pharmacy, and education.

Figure 8. Quantum Computing Target Industries



With respect to the defense industry specifically, 40 organizations (translating to roughly 20 percent of the manufacturing base) have potential dual-use applications. Of those organizations that indicated the defense industry as a target industry, many identified operation analysis and automation (for vehicles and drones) as potential industry applications. Additionally, cybersecurity, and the potential for quantum computers to break standard encryption models, may be another key source of dual-use tension.¹⁰⁴

104 Jake Tibbetts, “Quantum Computing and Cryptography: Analysis, Risks, and Recommendations for Decisionmakers,” Lawrence Livermore National Laboratory, Center for Global Security Research, September 2019, <<https://cgsr.llnl.gov/content/assets/docs/QuantumComputingandCryptography-20190920.pdf>>.

5.6 Comments Data

Despite efforts to maintain timely and comprehensive management of the data used for this report, a few limitations exist that could be skewing the data collected and the analysis produced. A primary limitation is the potential for data omission due to covert companies and organizations. Because all of the data was collected using open source means, entities that are less forthcoming about their ties to quantum computing might have been omitted. This may be occurring at the national level for countries in which such data might only be shared in a less public setting. There is also a potential limitation with respect to the timeliness of data updates. Because the industry includes a large number of younger, smaller companies, there is a higher than normal turnover and transition rate, where companies may either halt operations or be acquired by a larger company. Finally, the challenge of designating the dual-use potential should be noted. Companies were only coded as having dual-use potential if they specifically claimed the defense industry or defense applications as targets. However, in many cases it may be beneficial or required for companies to omit this type of information from their public profiles. Thus, it is possible that the dual-use category could be undercoded. Despite these limitations, the data produced in this report is still useful in capturing as many trends in the industry as possible, even if specific numeric values prove fallible.

5.7 Conclusions and Trade Control Implications

Technology Conclusion

This analysis has found that the quantum computing manufacturing base is made up largely of private companies that have extensive global, academic, and government partnerships. A large number of the firms are young, shifting towards hardware-agnostic software relevant to specific applications, and actively involved in partnerships to help fill gaps in the services and components they provide. Given the fact that the hardware manufacturing base is not expanding as rapidly as the software manufacturing base, it is likely that much of the industry will be supported by a smaller number of large companies that produce the hardware, and ultimately computers, needed to drive the industry. However, among those companies developing quantum computing hardware, there is significant uncertainty over which quantum computing pathway will be most fruitful.

Trade Control Implications

Given the potential security concerns that have been identified here and that have been voiced by policymakers, the findings that this data analysis has produced will prove useful in determining policy strategies for implementing trade controls on the quantum computing manufacturing base. By determining major evolving trends in the industry, more targeted and practicable trade implications are able to be identified, such as hardware and end-use specific trade controls. Additionally, security concerns associated with quantum computing, such as decryption, automation, and optimization augmentation, must be ranked based on strategic priority.

Based on the general trends identified, there is a potential for hardware-relevant controls to be impactful, especially if strengthened by trade controls on end-use-specific software with security implications. Due to the fact that the industry will likely have a smaller group of companies that develop the quantum computing hardware that is then shared by the larger number of smaller firms, there is a potential hardware chokepoint. However, in identifying which node of the chokepoint should be trade controlled, consideration must be given as to more narrowly defining what the security concern is over quantum computers. If the concern is generally large computing power that could enable decryption (or other security-relevant activities), then the chokepoint might be technologies that enable firms to scale up their qubit capacities. For example, this could be environment-controlling hardware such as cryogenic technologies, or specific types of processors that spatially separate qubits. However, then a specific, allowable size of quantum computing power will need to be determined. Additionally, for certain high-risk activities, such as quantum decryption, end-use controls could be applied to firms developing relevant software technologies. Importantly, as argued by many of the ANPRM comments, trade controls on the quantum computing manufacturing base must be highly targeted so as to avoid overarching controls that will result in the U.S. losing research prominence or economic gains to be secured by nations with leading quantum computing companies.

6. Computer Vision

6.1 Introduction: Projected Computer Vision Industry Growth

Computer vision, an offshoot of AI and machine learning, has found secure industry support due to the variety of applications it yields for civilian use. As a field, computer vision includes science and technologies that incorporate advanced analytic capabilities, including AI, machine learning, and neural networks, in order to enable computers to see videos and images. In this case, “seeing” the videos and images means that the computers are able to scan the media with the purpose of distilling certain pieces of information -- a complicated task despite the fact that it is innate to humans and most living species. The fields for which the computer vision industry is finding market interest are diverse and varied, including transportation, education, research, government, defense, security, business, finance, and agriculture.

Recently published market research projects that the computer vision market may grow by nearly 10% in the next five years (increasing from USD \$12 Billion to USD \$19 Billion).¹⁰⁵ Many of the activities which are now receiving heightened attention and support due to COVID-19 involve computer vision capabilities, including remote education, virtual healthcare provision, and public health governance. Furthermore, computer vision technologies are benefiting from the continued improvement in foundational analytic technologies, such as AI and machine learning.¹⁰⁶

6.2 Security Implications

Given the projected growth of the computer vision market, and thus the likely expansion of the computer vision production base, the security implications of computer vision development (and wider public dispersion) must also be considered. The two primary security implications for a growing computer vision

105 “Computer Vision Market Research Report by Component, by Application - Global Forecast to 2025 - Cumulative Impact of Covid-19,” Markets Insider, July 30, 2020, <<https://markets.businessinsider.com/news/stocks/computer-vision-market-research-report-by-component-by-application-global-forecast-to-2025-cumulative-impact-of-covid-19-1029453298#>>.

106 Kim Martineau, “Toward a Machine Learning Model that can Reason about Everyday Actions,” *MIT News*, August 31, 2020, <<https://news.mit.edu/2020/toward-machine-learning-that-can-reason-about-everyday-actions-0831>>.

market include 1) data availability and privacy concerns and 2) augmentation of strategic military technologies.

With regard to data accumulation, personally identifiable information (PII) and military-sensitive information may be more easily acquired through computer vision, both through enhancing quality of current vision systems and enhancing the ability to continuously collect data with limited human assistance.^{107,108} This data may then be used for nefarious purposes through better identifying targets and methods to achieve objectives. Accumulated data may also be used to manipulate military or civilian groups through disinformation.

Computer vision also promises to increase the threat of other strategic technologies. Missiles, drones, and other types of military playforms, when augmented with powerful computer vision systems, will likely experience improved performance and capabilities with respect to targeting as well as maintaining a continuous state of readiness.¹⁰⁹

Additionally, and with a more tangential relation to national security, there are economic impacts of unrestrained computer vision transfer. The ability to capture a significant portion of the computer vision market may lead to large economic returns, as well as monopolization of data storage and collection, resulting in an economic/technological leadership. As noted in the quantum computing section, although this consideration deviates from standard dual-use delineation into a more politically motivated realm, it still may be a driver of future trade controls. Distinguishing between the true motives for a given control will be necessary in order to argue the direct benefits of the control.

107 Chris Ciabarra, "AI Vs. Privacy: Does Computer Vision Violate Your Right to Privacy?" *Forbes Technology Council*, December 18, 2019, <<https://www.forbes.com/sites/forbestechcouncil/2019/12/18/ai-vs-privacy-does-computer-vision-violate-your-right-to-privacy/#1535d7571327>>.

108 Christopher Chyba, "New Technologies and Strategic Stability," *Daedulus*, 2020. [Note, Chyba discusses 'persistent overhead surveillance' which is enabled through computer vision technologies].

109 Rand Waltzman and Thomas Szayna, "First, Manage Security Threats to Machine Learning," *War on the Rocks*, November 4, 2019, <<https://warontherocks.com/2019/11/first-manage-security-threats-to-machine-learning/>>.

Potential Use of Trade Controls

Due to concerns over the dual-use nature of computer vision technologies and the data accumulated using computer vision technologies, trade controls may offer a viable method to constrain widespread dispersion of either the technologies or the associated data, depending on the security concerns identified and the ability to limit impact on civilian-purposed technology markets. Computer vision was specified by the United States Department of Commerce as a subset of AI technologies that may be deemed subject to export controls for national security purposes.¹¹⁰ Because computer vision is an application of AI, it is worth noting that export controls on AI may ultimately act as computer vision software restrictions. However, computer vision hardware, including sensors, lenses and processors, may also be deemed the subject of export controls if a specific chokepoint piece of hardware is found that offers a strategic military advantage with national security implications. Finally, specific types of data collection, transfer, or use may also be designated as controllable due to security implications, which could impact the broader computer vision field. Data regulations were noted in ANPRM comments as an area that could benefit from more robust export controls.¹¹¹

Given the fact that certain computer vision technologies are already widely dispersed (as will be surveyed by this report), the most viable options for trade controls are emerging hardware components with large augmentation power, data accumulation and transfer, and controls on specific applications/uses. However, in determining appropriate controls, it will also be necessary to consider potential technology limitations that could arise from barring access to different countries and types of technology transfers.¹¹²

110 Justin Doubleday, "Commerce Considering Emerging Technologies, Including AI, for Export Controls," *Inside Defense*, November 21, 2018, <<https://insidedefense.com/insider/commerce-considering-emerging-technologies-including-ai-export-control>>.

111 "Comment for the Department of Commerce ANPRM on 'Review of Controls on Certain Emerging Technologies'," Amir Husain, Founder and CEO of SparkCognition, Inc., <<https://www.regulations.gov/document?D=BIS-2018-0024-0096>>.

112 Will Knight, "Export Controls Threaten the Future of AI Outposts in China" *Wired*, January 1, 2020, <<https://www.wired.com/story/export-controls-threaten-ai-outposts-china/>>.

6.3 Technology Overview

Computer vision is a subset of AI technologies and most often is associated with deep learning and machine learning. The overarching goal of computer vision is to enable computers to analyze images and videos in order to ascertain certain kinds of information from various types of media. While this may be a simple task for humans, it has historically been challenging for computers, as it requires complex algorithms and software platforms capable of analyzing the numeric basis of images and videos (pigment counts, color coding, etc.) in order to “see” the image. Improvements in AI techniques, including deep learning, machine learning, and convolutional neural networks, have catalyzed dramatic improvements in computer vision capabilities.¹¹³ Currently, computer vision systems are able to perform a large number of tasks (3D imaging, 2D image analysis, facial recognition, augmented reality, etc.) using a handful of hardware technologies (optical vision, laser scanning, infrared and ultraviolet vision, etc.) and software techniques (object/pattern recognition/detection, image classification, object tracking, semantic segmentation, instance segmentation, etc.). This section will outline the different hardware bases, the software techniques, and the general applications. Finally, this section will discuss current policies and regulations over computer vision applications.

Technical Background

Computer vision is typically understood as a subcategory or application of AI that deals with image analysis.¹¹⁴ A widely accepted definition for computer vision is: “the science and technology of machines that see, where seeing in this case means that the machine is able to extract information from an image that is necessary to solve some task.”¹¹⁵ Computer vision research began as early as the 1970s with basic image processing and has continued to improve to the point of achieving machine learning through computer vision. This has been enabled largely through advances in tangential software fields such as AI, neural networks, and deep

113 Ben Dickson, “What is Computer Vision?” *PC Magazine*, February 9, 2020, <<https://www.pcmag.com/news/what-is-computer-vision>>.

114 Mark Sturdevant, “Introduction to Computer Vision,” *IBM Developer Series*, July 12, 2019, <<https://developer.ibm.com/technologies/artificial-intelligence/articles/introduction-computer-vision/>>.

115 Sota Yoshida., ed., *Computer Vision, Computer Science, Technology and Applications* (N.Y.: Nova Science Publishers, 2011), p. Vii.

learning.¹¹⁶ The technology's growing applicability and popularity has even earned it a spot among the top AI technology trends for 2020.¹¹⁷

Given that computer vision has grown to be such an expansive field, different variations of the technology can be distinguished along a number of key axes, including: software versus hardware; 2D versus 3D vision, optical vision versus non-optical sensing, and the main techniques programmed for a given application. These different axes will be briefly reviewed below, although should not be considered exhaustive in enumerating the distinguishing characteristics of unique computer vision systems.

1. **Software and Hardware:** In computer vision, the required hardware includes a type of sensor and a processor to run software analyses. Typically a camera serves as the sensor, but some computer vision systems use other types of sensors, such as a laser, radar or thermal scanner. Recent hardware processor advances include newer graphical processing units (GPUs) and field-programmable gate arrays (FPGAs).¹¹⁸ Software includes the program language, algorithms, and mathematical techniques used to convert the image produced by the sensor into meaningful information.
2. **2D and 3D Analysis:** Within the field of computer vision, there is another key distinction between whether a specific technology performs two dimensional (2D) analysis or three dimensional (3D) analysis. Traditional computer vision, or 2D analysis, involves the analysis of a single image in order to identify specific characteristics and gain relevant information. However, more recently, the field of 3D computer vision has emerged.¹¹⁹ Requiring multiple photos or a video, 3D computer vision allows for the determination of factors that vary spatially and/or temporally. It may also allow for the reconstruction of a 3D process or object through the use of

116 Richard Szeliski, *Computer Vision: Algorithms and Applications* (London: Springer, 2011), pp. 10-16.

117 Bernard Marr, "The Seven Biggest Technology Trends in 2020 Everyone Must Get Ready for Now," *Forbes*, September 30, 2019, <<https://www.forbes.com/sites/bernardmarr/2019/09/30/the-7-biggest-technology-trends-in-2020-everyone-must-get-ready-for-now/#309411362261>>.

118 Computer Vision Algorithms and Hardware Implementations: A Survey," *Integration*, the VLSI Journal, 2019, pp. 309-320.

119 Mariya Yao, "What are Important AI & Machine Learning Trends for 2020?" *Forbes*, January 22, 2020, <<https://www.forbes.com/sites/mariyayao/2020/01/22/what-are--important-ai--machine-learning-trends-for-2020/#79f53c232391>>.

a point cloud which measures different aspects of an object or process.¹²⁰

3. **Optical and Non-Optical Vision:** Another distinction is whether traditional optical vision cameras are serving as the sensors/initial data producers or if other methods of imaging are used such as thermal vision, infrared or ultraviolet light, or laser scanners. (Here, optical is referring to visible imaging; while lasers may fall under the scientific field of optics, when applied in computer vision they are used to track motion and non-visible phenomenon).
4. **Main Techniques:** Finally, more narrow distinctions among computer vision software depend on the type of technique applied by a given system to accomplish a specific task. The main technique types applied include:¹²¹
 - Object/pattern recognition/detection identifies the objects or patterns that appear in an image;¹²²
 - Object/image classification identifies broader categories that the objects or patterns appearing in an image belong to, or potentially classifies the image as a whole;¹²³
 - Motion sensing/object tracking follows the motion of a single object as it changes form or position between frames;¹²⁴
 - Semantic segmentation classifies or predicts labels for all pixels in a given image based on the object they belong to, and thus is similar to image classification but more comprehensive and granular;¹²⁵

120 Boguslaw Cyganek and J. Paul Siebert, *An Introduction to 3D Computer Vision Techniques and Algorithms* (Wiley, 2009).

121 Jason Brownlee, "A Gentle Introduction to Computer Vision," *Deep Learning For Computer Vision*, March 19, 2019, <<https://machinelearningmastery.com/what-is-computer-vision/>>.

122 Mark Sturdevant, "Introduction to Computer Vision," *IBM Developer Series*, July 12, 2019, <<https://developer.ibm.com/technologies/artificial-intelligence/articles/introduction-computer-vision/>>.

123 Ibid.

124 Ibid.

125 "Semantic Segmentation Using Deep Learning," *MathWorks Documentation*, <<https://www.mathworks.com/help/vision/examples/semantic-segmentation-using-deep-learning.html>>.

- Instance segmentation extends beyond semantic segmentation by labeling instances of objects within the same class;¹²⁶
- Facial recognition specifically identifies a person through recognizing a face based on features and shape.

6.4 Policy Background

Because computer vision is a subcategory of AI, many current policies that are strictly related to AI, by nature of the relationship between the two technologies, include computer vision. U.S. policy regarding AI has been numerous in recent years. In 2019, the Executive Order on Maintaining American Leadership in Artificial Intelligence was issued.¹²⁷ In January 2020, BIS issued a new control on AI, which incidentally impacts the computer vision industry.¹²⁸ The control covers software designed to automate geospatial imagery analysis, which could be included under the category of computer vision technologies, even if not explicitly stated in the ruling.¹²⁹ Interestingly, and potentially worthy of note, the difficulty of finding policies explicitly focused on computer vision highlights the challenges of broad national strategies on AI as a whole, rather than national strategies or policies towards specific AI subcategories.

One area of computer vision that has received a significant amount of attention among policymakers is facial recognition. Many governmental agencies have expressed interest in applying facial recognition to their activities, particularly organizations under the Department of Homeland Security, including Customs

126 Abdul Mueed Hafiz and Ghulam Mohiuddin Bhat, "A Survey on Instance Segmentation: State of the art," *Journal of Multimedia Information Retrieval* (2020):1-19, <<https://arxiv.org/abs/2007.00047>>.

127 "Executive Order on Maintaining American Leadership in Artificial Intelligence," United States White House Archive, February 11, 2019, <<https://www.whitehouse.gov/presidential-actions/executive-order-maintaining-american-leadership-artificial-intelligence/>>.

128 Burke et. al., "Bureau of Industry and Security Issues First "Emerging Technology" Control on Artificial Intelligence-Based Geospatial Imagery Software," White and Case - Publications, February 7, 2020, <https://www.whitecase.com/publications/alert/bureau-industry-and-security-issues-first-emerging-technology-control-artificial#:~:text=On%20January%20%2C%202020%2C%20the,geospatial%20imagery%20and%20point%20clouds>.

129 "Addition of Software Specially Designed To Automate the Analysis of Geospatial Imagery to the Export Control Classification Number 0Y521 Series," U.S. Department of Commerce, Federal Register, Vol. 85, No. 3, January 6, 2020, pgs. 459-462, <<https://www.govinfo.gov/content/pkg/FR-2020-01-06/pdf/2019-27649.pdf>>.

and Border Patrol and the Transportation Security Agency.¹³⁰ However, other members in the government, and even in the private sector, have expressed concern over certain applications, calling for federal protections on facial recognition use and associated data sets.¹³¹

6.5 Mapping Analysis

Overview

This mapping analysis found that the computer vision industry has largely surpassed the research and development stage of technology production. Private industry interest in computer vision has fostered a robust, global manufacturing base. Because the technology is no longer in the early research and development stage, many of the partnerships that exist for younger technology areas, like quantum computing, do not exist. Instead, firms are staking their claim for certain applications of computer vision and producing patented computer vision technologies. There is also significantly less government and academia involvement. Thus, although computer vision was listed as a potential target for export controls, this research shows that computer vision technologies are already widely available. However, export controls on certain byproducts of computer vision technologies, such as data libraries and training data sets, may be desirable. Additionally, specific, high-resolution or high-performance computer vision sensors and cameras may still be controllable, if a security relevance is identified.

Selection of Organizations

Organizations were selected for the computer vision mapping analysis if they are actively developing computer vision hardware or software technologies. This includes companies that use computer vision as a subcomponent of some larger technology (for example, drones), companies that have included computer vision technologies in a larger portfolio, and companies that work exclusively on computer vision. In some cases, a distinction had to be made between machine

130 “Facial Recognition: CBP and TSA are Taking Steps to Implement Programs, but CBP Should Address Privacy and System Performance Issues,” United States Government Accountability Office: Report to Congressional Requesters, September 2020, <https://www.gao.gov/assets/710/709107.pdf>.

131 Tom Simonite, “A Bill in Congress Would Limit Uses of Facial Recognition,” *Wired*, June 12, 2020, <https://www.wired.com/story/bill-congress-limit-uses-facial-recognition/>.

vision and computer vision because the former falls outside of the scope of this mapping analysis. For these cases, an assessment was made based on the description provided by the company about the type of programming used and the actions performed by the computer vision system. Computer vision systems based on non-optical sensors, such as lasers, radars, and heat sensors were also included in the database.

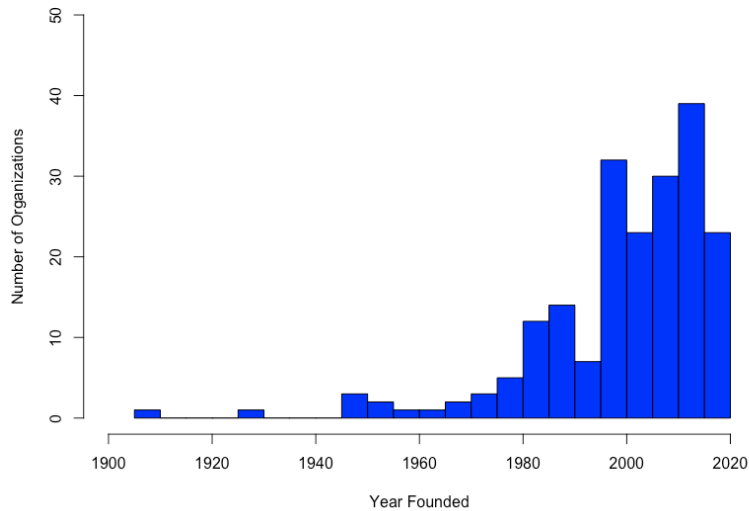
In total, this analysis identified 200 computer vision firms. This likely only represents a fraction of the industry, given the wide dispersal and large manufacturing base. For reference, a survey conducted in August 2020 on start-up companies alone found 529 companies labeled under the category of computer vision on an investment platform.¹³² However, because the firms were chosen through a number of different manners (including business database searches and computer vision libraries), the authors hope to have captured a representative piece of the computer vision industry. It also must be noted that although the computer vision industry is not in a nascent stage of development, there have still been organizations that have ceased operation or have been acquired since the beginning of data collection. In these cases, the mapping data has been updated as much as possible to account for changes.

Findings

1. Organization Age and Type

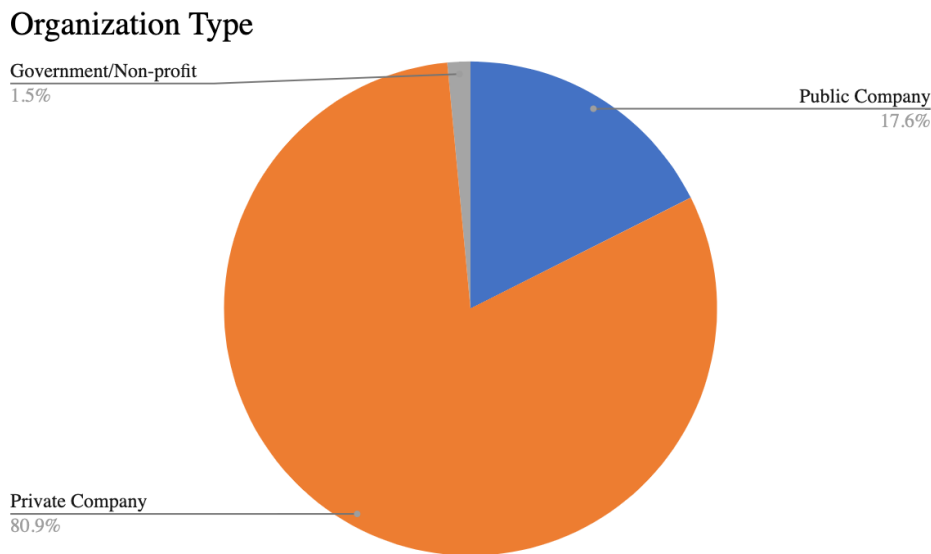
Based on this analysis, the computer vision manufacturing base may have already seen its peak organization establishment period. As shown in Figure 9, the large surge in computer vision entity development began in the 1990s and continued through the early 2000s. However, given that the average ages for the organizations focused on hardware, software, or both are 37, 13, and 25 years, respectively, it is likely that the peak for hardware company development occurred much earlier, and thus the increase in growth in the manufacturing base in the 2000s can be attributed to computer vision software companies.

132 Irina Peregud and Anastasiya Zharovskikh, "Computer Vision Applications Examples Across Different Industries," InData Labs, August 19, 2020, <<https://indatalabs.com/blog/applications-computer-vision-across-industries>>.

Figure 9. Computer Vision Founding Years, 1900-2000

A large majority of the computer vision manufacturing base is composed of private or public companies. As shown in Figure 10, private companies make up 80.9% of the manufacturing base and public companies make up 17.6%, leaving just 1.5% of the organizations analyzed to be government or non-profit firms. This further supports the hypothesis that the field of computer vision technologies is no longer in the research and development stage.

Computer vision has a larger percentage of public-for-profit organizations (17.6%) than PNT (9%) or quantum computing (12%). This is likely due to the fact that computer vision is already marketable and distributable. This means that computer vision products are already able to be profitable and therefore public companies are more willing to acquire private companies that produce computer vision capabilities or are more willing to create their own line of computer vision products so that they can capitalize on computer vision sales.

Figure 10. Computer Vision Industry by Entity Type

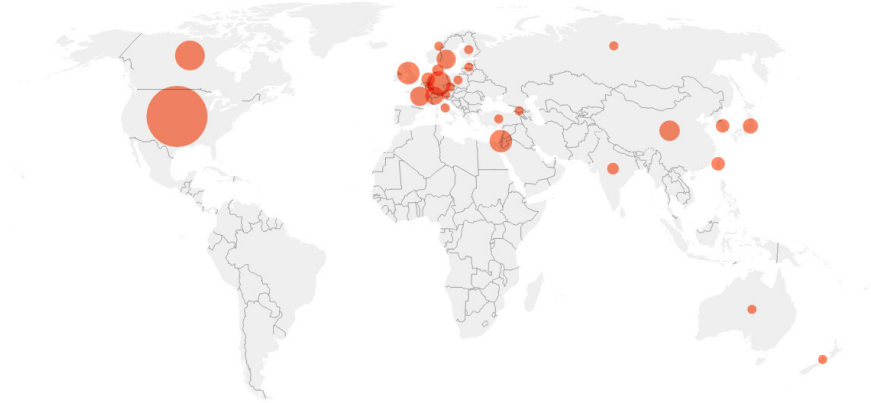
2. Global Dispersion

The global dispersion of the computer vision manufacturing base was analyzed using both a mapping visualization of the headquarters locations of the organizations and through quantitative analysis of multinational operations. As Map 4 shows, computer vision organizations are spread out globally, though maintain large presences in North America, Europe, and Asia. A smaller hub of organizations also exists in the Middle East (largely concentrated in Israel).

Map 5 specifically shows the geographical distribution of organizations based on whether they produce hardware, software, or both. Due to the fact that the hardware manufacturing base is smaller, it might be more directly susceptible to trade controls. However, because the organizations that distribute hardware technologies tend to be large firms with distribution and manufacturing facilities in multiple countries, the utility of the mapping visualization may be limited, especially compared to manufacturing bases where firms do not have multiple locations and are predominantly located at their headquarters' country.

Map 4. Computer Vision Global Dispersion

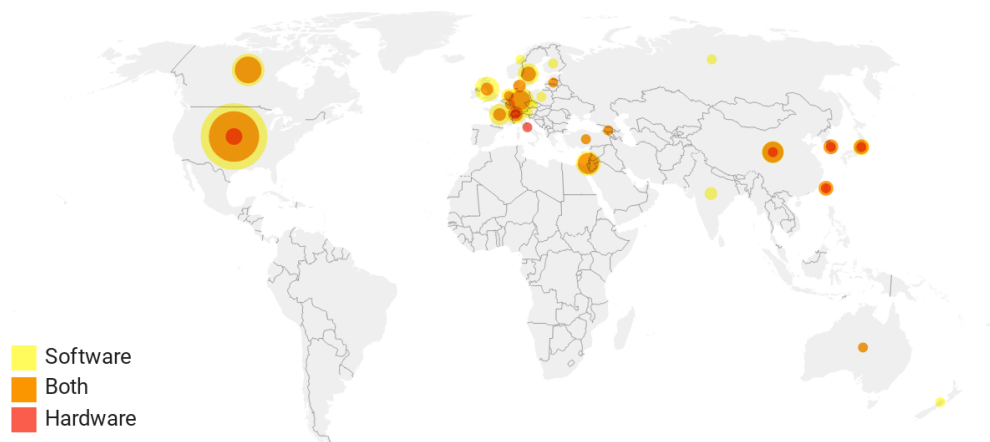
Where are computer vision organizations located?



Source: Center for International and Security Studies at Maryland/Strategic Trade Research Institute · Created with Datawrapper

Map 5. Computer Vision Global Dispersion by Technology Focus

Computer vision software or hardware organization?



Source: Center for International and Security Studies at Maryland/Strategic Trade Research Institute · Created with Datawrapper

In order to determine the extent to which the headquarters mapping visualization utility is limited, and to gain a better understanding of the global presence of the manufacturing base, international transaction mechanisms were also analyzed. The results of this analysis are presented below in Table 5. In this research, the overarching designation of whether or not an organization is “Multinational” was coded on the basis that an organization engages in an international research partnership, has international manufacturing or distribution bases,

has international headquarters, or has received international investment. The analysis found that 70.85% of computer vision organizations have multinational presences, with large drivers being international manufacturing and distribution facilities (36% and 58%, respectively) and international investment (30%). The high percent of organizations with international distribution facilities, relative to quantum computing and PNT technologies, supports the hypothesis that the computer vision industry has progressed much further than the other emerging technologies analyzed in this report and has reached a stage where the technology is marketable to consumers. Finally, the significant international investment found in this analysis can be attributed to the large presence of public companies and smaller start-up firms developing highly specialized computer vision application packages.

Table 5. Key Traits of Computer Vision Organizations

Category	Percent of Computer Vision Sector
Government Involvement	20%
Academia Ties	8%
Multinational – Umbrella Category	71%
International Partnership	16%
International Manufacturing	36%
International Distribution	58%
International Headquarters	8%
International Investment	30%
Explicitly Dual-Use	16%

3. Partnerships with Academia and Government

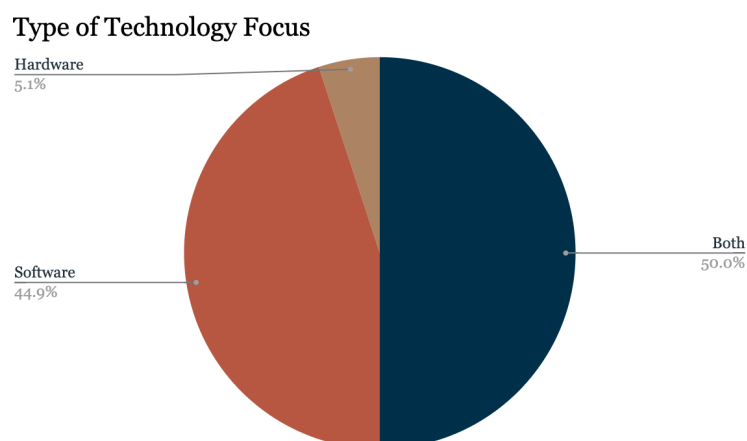
Table 5 also provides the results for the analysis of government and academia interactions with the computer vision industry. Government involvement is at 19.6%, which is relatively low compared to the government involvement with the other technologies analyzed in this research project. This is likely due to the sheer size of private interest in computer vision, compared to that of governmental interest. Largely, the 20% portion of government interest can be attributed to defense projects supporting computer vision companies for drone and surveillance

purposes and city and national governance projects utilizing computer vision capabilities for security, surveillance, and automation purposes. There is a fairly low tie to academia, with only 8% of organizations having academic affiliations or partnerships. Again, this supports the hypothesis that the computer vision field has surpassed the basic research stage. Interestingly though, the lower presence of academia engagement could increase the viability of trade controls, because academia serves as a mechanism for technology and knowledge exchange that is particularly difficult to control.

4. Technology Trends

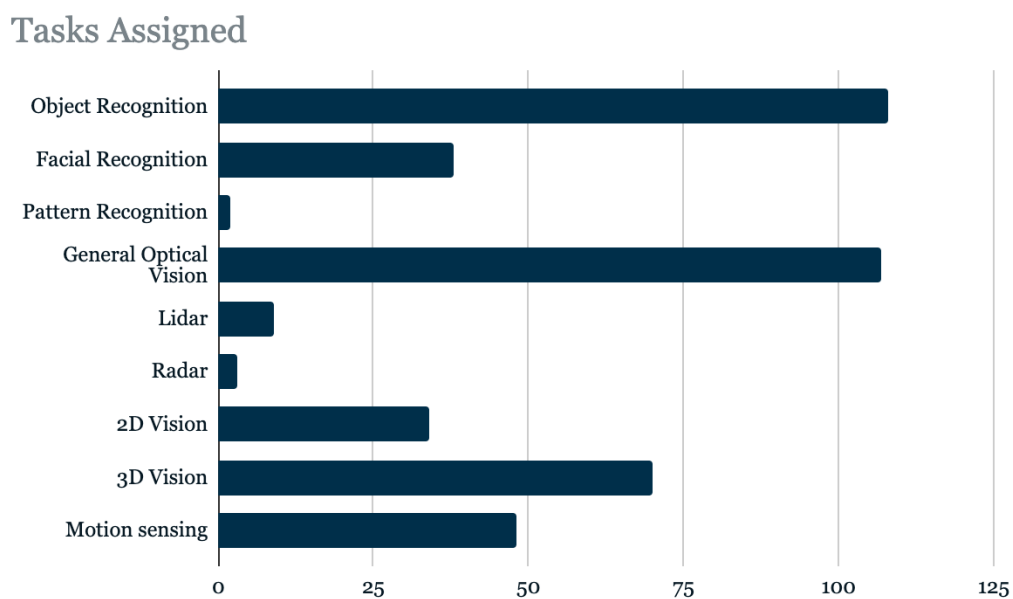
Given the wider dispersion and later stage in development of the computer vision industry, this research attempted to categorize the composition of the manufacturing base in terms of the types of technologies that are being prioritized and the tasks these technologies are performing. As shown below in Figure 11, this research found a significant fraction of organizations working specifically on software, at 44.9%, and a large fraction working on both hardware and software, at 50%, with only a small fraction, 5.1%, working exclusively on hardware. This distribution can be attributed to the fact that computer vision hardware knowledge is fairly dispersed, meaning that having unique computer vision technologies is not a high priority for many companies, who instead focus on how to apply quantum computing hardware through customized software. Additionally, although few in number, the hardware-only firms tend to be large and have widespread manufacturing and distribution bases, meaning that fewer organizations are able to supply a larger portion of the industry with hardware.

Figure 11. Computer Vision Industry by Technology Focus



Given the sizable presence of organizations working on computer vision software, the tasks that software systems were created to perform may provide insight into those organizations' priorities and the extent to which specialization is occurring. As Figure 12 shows, many companies are focused on fairly general tasks, including object recognition, general optical vision, and 3D vision. This means that very few firms are focusing on specialized tasks, such as LIDAR-based or radar-based computer vision, pattern recognition, and even 2D vision. This could also be explained by the fact that the majority of areas which have received less focus among the computer vision industry require highly specialized components, including hardware such as laser and radar sensors, and software such as data libraries in order to train computer vision systems on pattern recognition.

Figure 12. Computer Vision Industry by Task Assigned

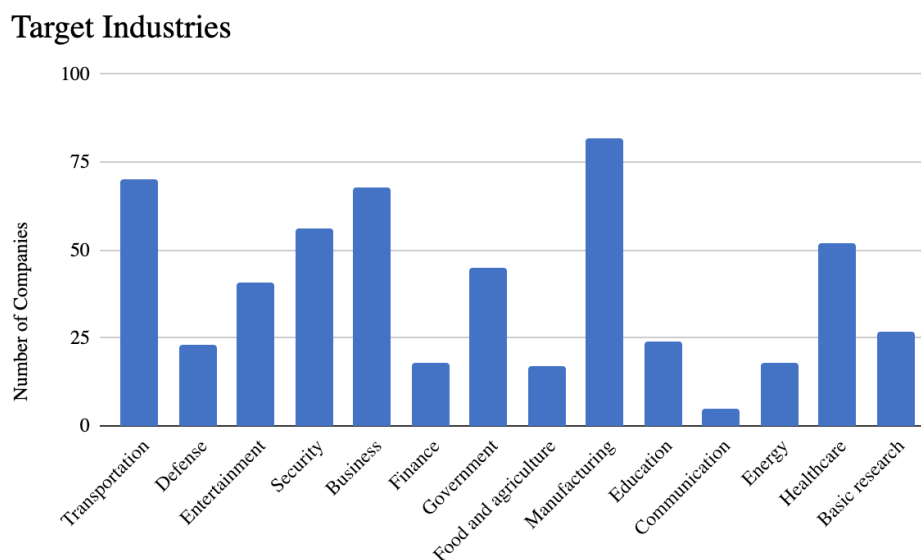


5. Target Industries

The “target industries” for each firm were also recorded in order to understand which industries are most responsible for driving the computer vision manufacturing base. The results of this analysis are shown in Figure 13. Computer vision firms advertise to a large number of industries, but manufacturing, transportation, business, and security are of particular interest, with each being targeted by over 25% of the manufacturing bases (here security is taken to mean civilian security, such as home or office surveillance). Healthcare, government, and entertainment are also popular targets for the computer vision manufacturing base. Defense,

finance, education, communication, energy, government, basic research, and food and agriculture are also often targeted, though not found to be leading industries.

Figure 13. Computer Vision Target Industries



With respect to the defense industry, and thus dual-use interest, over 20 organizations identified the defense community as potential consumers, which is over 10% of the organizations surveyed. Of those organizations that identify the defense industry as consumers, automation and surveillance are major fields indicated as suitable for computer vision implementation. Facial recognition may also be a task that surfaces dual-use concerns, depending on the scope of the definition of security and is rapidly being applied by governmental agencies.¹³³ However, not all facial recognition organizations identified the defense industry as primary consumers.

6.6 Comments on Data

Due to the more advanced stage of the development in the computer vision manufacturing base, one of the key concerns regarding the data analyzed in this report is the extent to which it accurately represents the manufacturing base as a whole. Again, as with other emerging technologies, data omitted due to lack

133 “Facial Recognition: CBP and TSA are Taking Steps to Implement Programs, but CBP Should Address Privacy and System Performance Issues,” United States Government Accountability Office: Report to Congressional Requesters, September 2020, <<https://www.gao.gov/assets/710/709107.pdf>>.

of publicly available information is a limitation. Data omission may occur due to privacy concerns, either arising through threat of IP theft or persuasion by government agendas or policies of opacity. This may lead either to entire companies being omitted from the analysis or specific applications/technologies developed by the company to be omitted. In general though, the data included in this report is not attempting to extend to the entire computer vision manufacturing base, instead it is just representing a subsection of the industry to the extent that the companies were able to be identified through publicly available methods and were able to be identified when the data was collected. However, the data collected does cover a diverse array of companies in the manufacturing base, including global, technical, and organizational variety.

Another central concern with the data and analysis is the designation of “dual-use” applicability. Companies were coded as developing “dual-use” technology only if defense (or defense-related activities) were openly identified by the company as potential applications. This means that the dual-use category may be undercounted, if there are organizations pursuing deals with defense industries but excluding this information from their publications and/or if the technologies may still have dual-use implications despite not being marketed toward the defense industry.

The extent to which computer vision capabilities translate to meaningful security threats is also a source of uncertainty, as the sheer application to the defense industry are sometimes not immediately clear. Furthermore, the extent to which “government application” in comparison to “defense application” translates to dual-use capability is somewhat nebulous. Recent sanctions on surveillance firms related to Uighur populations in Xinjiang, China, are an example of how surveillance technologies attract dual-use attention, despite not necessarily being direct military hardware.¹³⁴ Computer vision algorithms may not appear as dual-use initially, but they may have dual-use applications depending on how they are manipulated later, which differs from some physical dual-use hardware.

134 “U.S. Sanctions 8 China Tech Companies Over Role in Xinjiang Abuses,” *Nikkei Asian Review*, October 8, 2019, <<https://asia.nikkei.com/Economy/Trade-war/US-sanctions-8-China-tech-companies-over-role-in-Xinjiang-abuses>>.

6.7 Conclusions and Trade Control Implications

Technology Conclusions

The results of this analysis demonstrate that the computer vision manufacturing base has evolved beyond a research-oriented industry and has established a relatively global distribution reach. However, this analysis also indicates that hardware development is concentrated in a relatively small number of larger firms. This hardware is used by a larger number of smaller private organizations that incorporate their own software technologies for specific applications. Among these organizations, there are relatively few research partnerships with governments, academia, or other industry members. Despite the lack of research partnerships, there is a relatively high number of organizations identified as engaged in multinational activities, largely driven by a wide distributional reach.

Implications for Trade Controls

The trends identified in this report offer insight into chokepoint technologies and suitable targets for trade controls. Although these findings illustrate an already expansive computer vision manufacturing base, the security concerns regarding certain computer vision byproducts and applications merit consideration of potential trade control options. Indeed, the U.S. private sector, in addition to flagging this issue in ANPRM comments, has begun to lobby policymakers to adopt responsible controls to evade misuse of the technology. In September 2020, IBM submitted specific recommendations to the U.S. Department of Commerce for limiting the export of facial recognition systems in specific cases.¹³⁵ IBM's CEO explained the reasoning behind its assertiveness, stating that,

“IBM firmly opposes and will not condone uses of any technology, including facial recognition technology offered by other vendors, for mass surveillance, racial profiling, violations of basic human rights and freedoms, or any purpose which is not consistent with our values and Principles of Trust and Transparency.”

135 IBM, “A Precision Regulation Approach to Controlling Facial Recognition Technology Exports, September 11, 2020, <<https://www.ibm.com/blogs/policy/facial-recognition-export-controls/>>.”

The mapping data and analysis support the potential use of trade controls to mitigate these risks. In light of the identified trends, hardware-specific trade controls focused on security-relevant sensor technology and software-specific trade controls focused on data accumulation and transfer or end-use application all could be viable trade control options. Because hardware development, and specifically non-optical sensor technology development, is consolidated into a relatively tight circle of organizations, trade and investment controls restricting the transfer of high-power, non-optical sensors may be a feasible option. Furthermore, non-optical sensors, including laser, radar, and thermal sensors, make up a smaller percentage of the private industry interest. This means that, should they be identified as having security implications, their production and trade could be restricted without creating a notable impediment to potential private industry profits.

Software technologies, which have already been identified as potentially problematic in terms of restrictability through trade controls, may require more finesse. Because software technologies are what ultimately connect computer vision hardware to specific industry use cases, software-specific trade controls must be highly targeted, either through restricting their application to certain activities or through restricting specific types of data incorporation, accumulation, or transfer.

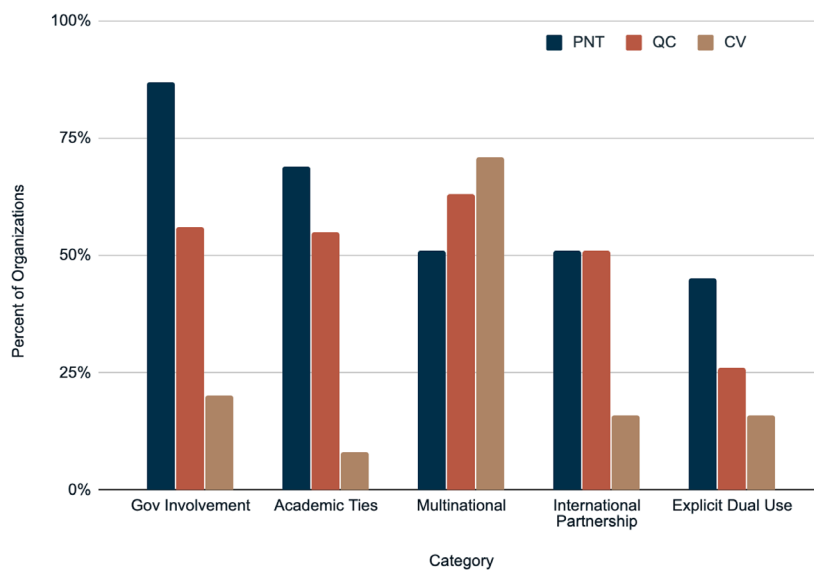
7. Key Findings and Conclusions

7.1 Technology Findings

Taken together, the three different technology analyses provide a comprehensive image of the development stages of each sector. Variations in sector composition characteristics exist with regard to government and academia involvement, global dispersion, and targeted industries, depending on specific characteristics of the technology itself. Although this report only includes an analysis of three technologies, the differences between the technologies analyzed support the hypothesis that, though they may all be listed under the same “emerging” category, each will require different types of trade controls in order to more effectively target chokepoint components to address dual-use concerns.

As Figure 14 illustrates, there are meaningful differences in the data between the three technology categories. There is relatively high academic and government involvement in PNT compared to quantum computing; computer vision has low numbers of both academic and government involvement. All three categories have reasonably high numbers of organizations engaged in multinational activities. Analysis of a subcomponent of multinational involvement, international partnerships, indicates that while PNT and quantum computing firms have relatively high levels of partnerships abroad (over 50%), computer vision organizations have less partnership-based international activity. Finally, nearly half of PNT organizations explicitly identified their work as dual-use, while only a quarter of quantum computing and about 15% of computer vision organizations highlighted these defense-related applications.

Figure 14. Key Metrics in Each Technology Area



Although, as noted, all three sectors have fairly high percentages of organizations with multinational activities, drivers for the multinational categorization vary by technology. Computer vision's high multinational number, summarized in Table 6, stems from an elevated prevalence of international distribution and manufacturing facilities. Quantum computing multinationalism is driven by international partnerships and investment. And the largest multinational driver for PNT is international partnerships and international distribution facilities.

Table 6. Multinational Variables for PNT, Computer Vision, and Quantum Computing¹³⁶

Category	Positioning, Navigation, and Timing	Computer Vision	Quantum Computing
Multinational	51%	71%	63%
International Partnership	51%	16%	51%
International Manufacturing	17%	36%	16%
International Distribution	27%	58%	20%
International Headquarters	5%	8%	13%
International Investment	14%	30%	48%

Certain key variations between the three technologies can help explain the variances of characteristics identified in the data analyses, including intrinsic technology discrepancies and stages of development differences. At a basic level, each technology will find applicability in certain industries that may help drive investment and interest in the technology. Computer vision has been identified as having utility across a wide spread of industries, many of which make it a technology directly marketable towards consumers. Although quantum computing also has suitability in many industries, because of the extremely high technology cost, it may not be marketed directly towards individual consumers in the near future. Emerging PNT technologies are either in a pre-commercialized stage or only available for a narrower set of advanced (and often military) applications, so there is less private sector and investment interest in the field. These distinctions have resulted in vastly different markets for the three technologies and thus have contributed to the evolution of sectoral compositions unique to each technology with respect to government and academia collaboration, multinational relations, and international research partnerships.

It should also be noted that the variations in sectoral composition characteristics are also impacted by the stage of the development for each of the technologies. For example, because computer vision has surpassed the basic research and

136 The table shows the percent of organizations in each technology category that were coded “Yes” for the international variables. Multinational is an umbrella term for having any international connections. Full definitions of each variable are available in Section III.

development stage, most of its multinational relations are driven by international distribution facilities; this is in contrast to PNT and quantum computing, which are driven by international research partnerships. Additionally, because the PNT and quantum computing industries are still at earlier stages of development, they also display higher proportions of government and academia involvement.

7.2 Trade Controls and Emerging Technologies Recommendations

This discussion of the differences between the three technology areas informs how a strategic trade control approach could be applied to each of them, taking into account the variations in global dispersion and market trends.

The stage of development and characteristics in the mapping methodology differ between the three chosen technology areas discussed in this report, suggesting the need for a nuanced approach to thinking about controls for emerging technologies. In addition, some of the technology areas are in a development stage where traditional list-based controls may not be effective.

Trade control approaches should be informed by the data on the state of the markets for each technology. Because the three areas are at differing stages of development and commercialization, a nuanced trade control approach would vary for each of them. When considering the feasibility and desirability of trade controls in this area, policymakers should evaluate the state of the market, the applicability of existing list-based controls, the possibilities for additional controls, and the targets for non-government outreach efforts.

The state of the market and characteristics of each technology area should be the lens through which policymakers view trade control prospects in a given area.

Position, Navigation, and Timing

Many existing PNT technologies are already commercially available, but there are new research approaches in a nascent stage. These new approaches include cold atom, nuclear magnetic resonance, and other atom interferometry approaches to navigation, under the umbrella of quantum navigation approaches. These emerging PNT platforms have many dual-use applications, and their early stage of development makes it more possible to control dispersion.

Quantum Computing

Hardware is consolidated into a narrow group of companies, with many software companies identifying creative approaches towards sharing time and usability of quantum computers. Due to the large upfront cost of quantum computing hardware, this trend is unlikely to change for the foreseeable future. This means that access to the actual quantum computers could be restricted based on user or application by targeting quantum clouds, or platforms that share access to quantum computers.

Computer Vision

The majority of the computer vision technology innovation has already occurred, and systems are cost-effective and commercially available. This means that computer vision is likely not a suitable target for trade controls. However, as indicated by the BIS ruling on geospatial imagery software in January 2020, heightened security concerns over data collection and analysis methods may become new targets for controls.¹³⁷ Furthermore, recent calls for controls on facial recognition make the field ripe for policy motivation.

7.3 Applicability of Current and New Controls

After considering the market characteristics informed by the mapping analysis presented in this report, policymakers can consider the applicability of current controls. Analyzing market trends and characteristics of the categories makes it possible to both understand the trends in the market and identify which current controls may be applicable. Entire emerging technologies or their subcomponents may be subject to existing list-based controls, or new technologies may take such a different approach that current controls are not applicable. For example, emerging PNT research approaches are aimed at greatly improving existing navigation platforms. Many of those navigation platforms, however, are subject to existing controls based on how well they perform. Other technologies may be less applicable depending on how novel they are, though many underlying

137 “Addition of Software Specially Designed To Automate the Analysis of Geospatial Imagery to the Export Control Classification Number 0Y521 Series,” U.S. Department of Commerce, Federal Register, Vol. 85, No. 3, January 6, 2020, pp. 459-462, <<https://www.govinfo.gov/content/pkg/FR-2020-01-06/pdf/2019-27649.pdf>>.

components (certain software, computing hardware, etc.) are controlled.

While existing controls may be applicable in some instances, in others the new approaches or subcomponents may mean current regulations do not cover emerging technology developments. Through a variety of legislation, the United States has means to define new “emerging and foundational” technologies. ECRA includes a process by which the government can label new technologies and control them. The law says an inter-agency process can identify new “emerging and foundational technologies,” taking into account foreign technology development, expected effects of controls, and potential for foreign dispersion.¹³⁸

Based on the findings of the mapping analysis in this report, it appears export controls could be feasibly applied to emerging aspects of PNT. Certain aspects of quantum computing may be suitable to trade controls. For example, controls that target cloud/technology sharing programs that connect organizations globally and across different sectors could be effective given the bottleneck of quantum computing hardware but could also be politically or economically unpalatable. Finally, given that global dispersion of computer vision technologies has already occurred, trade controls are unlikely to be effective. However, in light of the high pressure from policymakers due to security concerns, trade controls may be attempted on data storage, transfer, and analysis in highly specified applications.

There is an important distinction between feasible and desirable trade controls. In some cases, such as the accumulation and analysis of security-relevant data in the computer vision field, trade controls may be desirable, but challenging with respect to implementation feasibility. In other cases, such as access to narrow quantum computing technology areas, trade controls may be feasible, but not patently security-relevant or desirable. Beyond feasibility of trade controls, which has been a large focus of this report, desirability must merit consideration. Certainly, trade controls increase in desirability as their ability to mitigate security risks increases. However, at some point trade controls that increase security on the surface may become undesirable if they place excessive burden on private industry, which results in a depression in domestic technological competency and economic gains from commerce abroad.

138 50 U.S. Code § 4817, “Requirements to identify and control the export of emerging and foundational technologies,” <<https://www.law.cornell.edu/uscode/text/50/4817>>.

7.4 Private Sector Outreach

Regardless of whether policymakers choose to adopt new controls, apply existing controls, or take a different approach entirely, effective outreach to academic and industry communities remains a useful mechanism for raising awareness about the dual-use nature of technologies. Part of effective outreach includes cultivating personnel that have a credible grasp of the specific technology area. Interacting with export control officers or outreach officials with a grasp of the industry, which can be informed by the mapping analysis, can build credibility with private sector communities and ensure government opinions are explained in the nuanced terms of the particular industry. The mapping analysis of individual areas can improve the quality of outreach by suggesting what communities should be engaged with more expediency and fervor. For some technologies, there may be widespread private sector, for-profit interest, which favors an outreach strategy focused on investment groups and for-profit companies. In other areas, academic research and existing government partnerships may be more prevalent. Finally, for emerging technologies in the basic research stage, raising awareness among academic researchers and potential investors about dual-use implications may be particularly useful.

7.5 International Capacity-Building and Multilateral Considerations

The results of this research are important as they inform international trade control capacity-building efforts and work towards multilateral consensus. With investment controls increasingly entering discussions of building effective capacity to counter security threats both within borders as well as from cross-border flows, identifying and targeting countries that have increasing activity in sensitive sectors, as identified from the mapping data, and ensuring that they have adequate legal and enforcement mechanisms to preclude security threats, should be a priority for U.S. policy-makers.

Understanding the international composition, trends, and patterns of the three technologies in this report can help target where trade control outreach efforts, such as the State Department's Export Control and Related Border Security Program (EXBS) should focus its resources. These activities should further be coordinated with other capacity-building programs such as the EU Partner-to-Partner (EUP2P) program. Doing so can help build a common understanding of security approaches with allies, and thus strengthen the likelihood of U.S.-backed

controls in multilateral export control regimes. Aligning U.S. trade control policy with like-minded international partners should be a priority in order to increase the effectiveness of any new control.

7.6 Future Analysis

This report has illustrated the diversity of industries being considered under the umbrella terminology of emerging technologies. In its proposed rulemaking announcement, the U.S. Commerce Department categorized 13 dramatically different technologies under the overarching term of emerging technologies. As this report has demonstrated however, the technologies within this category vary with respect to many characteristics, including the extent to which they actually are emerging. Specifically, the technologies diverge with respect to the age of the manufacturing, research, and development base, the type of organizations involved, the level of global dispersion and multinational commerce, breakdown of sub-technology focus areas, and target industries. Notably, the technologies also deviate with respect to dual-usability and government interest in development. Each of these metrics must be considered in analyzing the historic growth and future potential of the technologies' manufacturing base.

The findings from this report suggest that these technology-specific metrics must be considered in developing trade controls that are both feasible and desirable. This report has demonstrated the importance of technology mapping to ascertain unique qualities of individual emerging technologies and develop actionable, realistic trade policies and outreach efforts to sensitize the private sector to the security risks of their activities, including actions to mitigate these risks.

In the case of dual-use technologies, the strategic purpose of trade controls is to mitigate security risks associated with a given technology's dispersal without imposing unjustifiable negative effects on technology development and economic competitiveness. As the concept of security becomes more multifaceted, including personal privacy and protection against abusive behavior by internal security forces, it may be overly narrow to define dangers posed by dual-usable technologies only in terms of the potential military advantages they could provide hostile states. And, it may be short sighted to try to control the development and diffusion of many, if not all, emerging technologies when the efforts do more to hurt U.S. technological competency (or leadership, depending on policy objectives), and economic power than to truly enhance national security.

The research approach of mapping the sectoral composition of specific technologies can and should be applied to other sensitive technologies under consideration for controls, given its importance in helping to understand potential effects of controls on competitiveness and security. In addition, given the heightened sensitivity to the security risks of FDI in emerging technology sectors, further research could analyze data on Merger and Acquisition (M&A) activity, market trends, and ownership changes in these sectors. This data would shed light on potential security risks in terms of ownership and control of sensitive sectors. While this research would be important to conduct in the U.S. context, it would also be useful for understanding how these trends are impacting the technology and security landscape worldwide.

It is clear that the risks as well as the opportunities posed by emerging technologies are here to stay. Research undertakings such as the sectoral composition mapping and subsequent analysis conducted as part of this report are crucial to policymaking that finds a sound balance between security, technological development, and competitiveness.