

Position, Navigation, and Timing: A Sectoral Composition Approach

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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.¹ 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.

2. Security Implications

Many eye-catching, modern platforms with possible dual-use applications—autonomous

¹ “What is Positioning, Navigation and Timing (PNT)?,” U.S. Department of Transportation, <<https://www.transportation.gov/pnt/what-positioning-navigation-and-timing-pnt>>.

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.²

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.³ 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.

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,

2 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>>.

3 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.

in part, is that GPS jamming capabilities could harm civilian and military transportation platforms.⁴

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.⁵ 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.⁶ 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:

- *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.⁷
- *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.⁸

4 Elisabeth Braw, "The GPS Wars Are Here," *Foreign Policy*, December 17, 2018, <<https://foreignpolicy.com/2018/12/17/the-gps-wars-are-here/>>.

5 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/>>.

6 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>.

7 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/>>.

8 Elizabeth Fetter. "How Chip Scale Atomic Clocks Will Change the Future of Time." September 2013, <<https://www.wired.com/>>

- *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.⁹

Chip-Scale and Advanced Atomic Clocks

Atomic clocks are a fixture of the PNT timing category. Atomic clocks use atomic frequencies to provide extremely accurate timing information; they are used in many civilian applications like telecommunications, high-frequency financial interactions, and GPS systems.¹⁰ 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.¹¹ 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.¹² The National Institute of Standards and Technology (NIST) estimates the market for CSAC-type

insights/2013/09/how-chip-scale-atomic-clocks-will-change-the-future-of-time/>, partner content from Wired -- Fetter worked at Symmetricom.

- 9 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>>.
- 10 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>>.
- 11 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/>>.
- 12 Microsemi, “Space Chip Scale Atomic Clock (CSAC),” <<https://www.microsemi.com/product-directory/embedded-clocks-frequency-references/5207-space-csac>>.

devices is USD \$260 million.¹³ 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.¹⁴

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.¹⁵

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 will work in conjunction with inertial navigation systems.¹⁶ 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.”¹⁷ 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.¹⁸ These systems provide built-in navigation information without an uplink to another communications station.¹⁹ 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.²⁰ 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

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

14 Ibid.

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

16 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/>>.

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

18 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>>.

19 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>>.

20 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/>>.

firms had access to these miniature components.²¹

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.²² A study from the United Kingdom is slightly 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.²³

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.²⁴ 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.²⁵ 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.²⁶ 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.²⁷ Northrop

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- 21 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>>.
- 22 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>>.
- 23 “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.
- 24 Hayley Dunning, “Quantum ‘compass’ could allow navigation without relying on satellites,” Physorg, November 8, 2018, <<https://phys.org/news/2018-11-quantum-compass-satellites.html>>.
- 25 “Quantum ‘compass’ could allow navigation without relying on satellites,” Imperial College London video, November 8, 2018, <<https://www.youtube.com/watch?v=xcqkXkWZhbM>>.
- 26 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/>>.
- 27 “Nuclear magnetic resonance,” Encyclopædia Britannica, July 20, 2018, <<https://www.britannica.com/science/nuclear-magnetic-resonance>>.

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.²⁸ There are also studies involving the use of high-energy atoms.²⁹ Finally, in addition to the quantum inertial technology discussed above, 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. 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.^{30,31} There is a PNT-related advisory board featuring people from inside and outside of the government producing recommendations related to these subjects.³² 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.³³ 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.

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- 28 Doug Meyer and M. Larsen, “Nuclear Magnetic Resonance Gyro for Inertial Navigation,” *Gyroscopy and Navigation*, 2014, Vol. 5, No. 2, pp. 75–82.
- 29 “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>.
- 30 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>>.
- 31 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>>.
- 32 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>>.
- 33 “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/>>.

5. Mapping Analysis

The mapping analysis of emerging PNT organizations highlights the geographical and focus area breadth of organizations involved in emerging PNT research, 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.³⁴ 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

34 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.

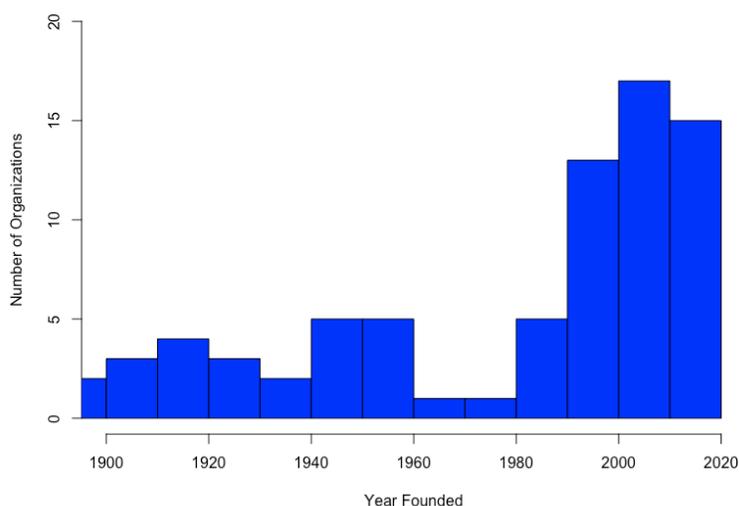
distributing them. These organizations often are recognized names, have well-established sales networks, and have customer relationships with major commercial players. In total, 86 emerging PNT organizations were included in the mapping analysis. Each of these organizations was coded according to a consistent 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.

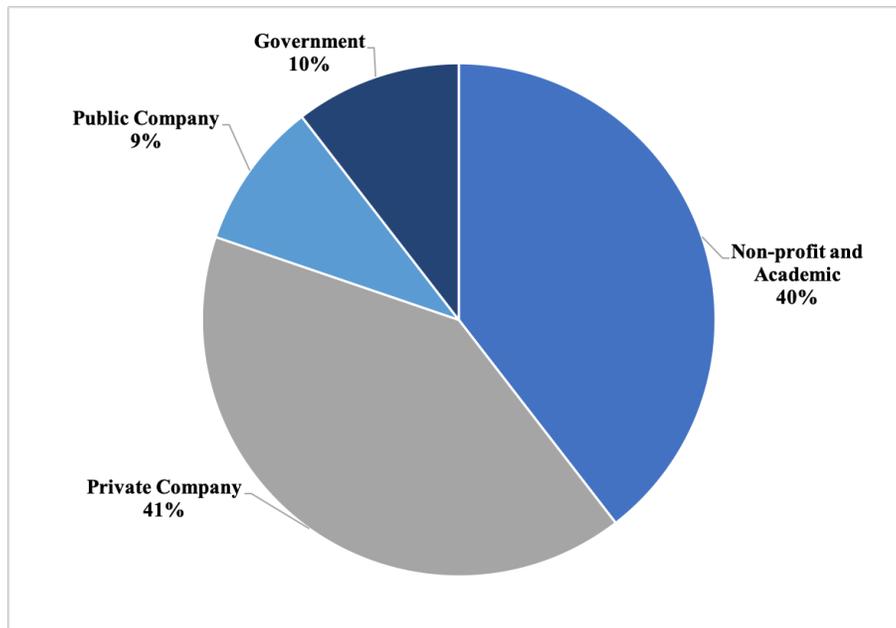
Figure 1. Founding Year of Emerging PNT Firms³⁵



35 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 Work³⁶



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 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

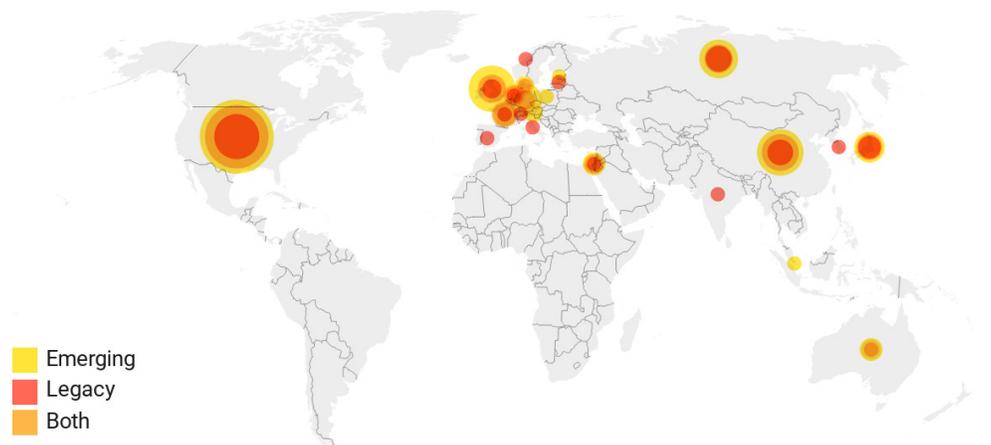
³⁶ Note that state-owned enterprises, unless direct government research institutions, are included under the “company” category.

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.³⁷ Many of these quantum initiatives touch 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.³⁸ 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

37 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/>>.

38 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>>.

shipbuilding company to research applications for submarine navigation.³⁹ 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.⁴⁰ 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.⁴¹ 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 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.

39 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/>>.

40 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>>.

41 “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>>.

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.⁴² 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.⁴³

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.⁴⁴ The radar capabilities have been characterized as over-hyped as there is insufficient technical information to support claims that the radar can detect aircraft that are currently difficult to locate.⁴⁵ 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.⁴⁶ Symmetricom was acquired by another firm, Microsemi, in 2013.⁴⁷ The firm has additional locations throughout Asia, Europe, and the Middle East.⁴⁸ The Microsemi CSAC is marketed as the “first commercially available” CSAC with low power consumption

42 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/>>.

43 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>>.

44 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/>>.

45 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/>>.

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

47 “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>>.

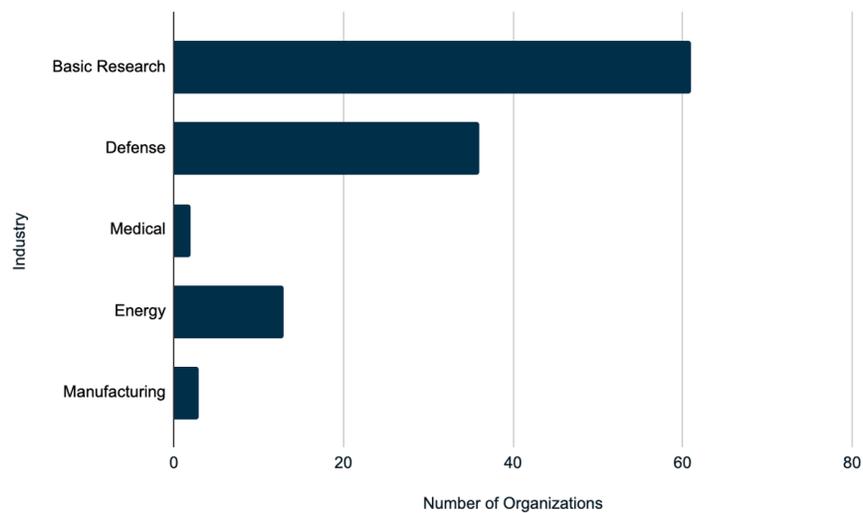
48 “Locations,” Microsemi, <<https://www.microsemi.com/locations>>.

and high performance in difficult environments.⁴⁹

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.

Figure 3. Major Industries, Emerging PNT Organizations



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

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.

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.⁵¹

Additionally, current export control language in the area is often based on how well a sensor performs, regardless of its underlying design.⁵² 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.

Table 3. Examples of Current U.S. PNT-Related Controls⁵³

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

51 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.

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

53 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-ccl0-to-9-10-24-18/file>>, pp. 8-9.

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, 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.