An Organizational Network Analysis of the Sprawling U.S. Department of Defense Innovation Ecosystem

by

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Abstract

The 2022 United States National Defense Strategy (NDS) highlights that the greatest strategic challenges for today's security environment are linked to rapidly changing military capabilities and emerging technologies. It is through innovation that the military's technological edge is maintained. Defense innovation refers to the broad set of experimental activities aimed at developing and implementing transformational technologies, strategies, and organizational practices to provide enhanced capabilities for the military or to reduce the cost of military operations.

The Department of Defense (DoD) relies on a massive connected network of government agencies, private industry, academia, and research institutions to accomplish these activities. This Defense Innovation Ecosystem grew rapidly over the last decade, but many organizations that comprise the ecosystem today were established independently of one another to address specific needs. This growth led to a massive ecosystem that is not optimally organized to support innovation at the speed required to maintain the military's technological advantage, especially in light of the rapid commercialization of new technology.

This research develops an organizational network model of the Defense Innovation Ecosystem through a comprehensive review of publicly available data sources. Then, using this model, it conducts an organizational network analysis based on five centrality measures, including degree, weighted degree, eigenvector, betweenness, and closeness. This analysis is then used to update the model visualization. Lastly, a modularity assessment of the network model examines a potential hierarchical realignment that cuts across existing organizational boundaries.

This research aims to better understand the Defense Innovation Ecosystem as it currently exists and then provide one viewpoint on how the DoD might evolve the ecosystem to meet future demands.

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Acronyms, Terms, and Definitions

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Accelerator – An organization that offers competitive and structured programs focused on scaling the growth of an existing company. Accelerators typically provide some amount of seed money and a network of mentors. Resulting programs are typically only a few months in duration culminating in an opportunity to pitch to investors at the conclusion of the program (MITRE AiDA, 2023).

Acquisition – The conceptualization, initiation, design, development, test, contracting, production, deployment, integrated product support, modification, and disposal of weapons and other systems, supplies, or services (including construction) to satisfy DoD needs, intended for use in, or in support of, military missions (DAU Glossary, 2023).

Basic versus Applied Research – Basic research includes scientific studies and experimentation directed toward increasing fundamental knowledge and understanding in the physical, engineering, environmental, and life sciences fields related to long-term national security needs. Applied research translates promising basic research into solutions for broadly defined military needs and includes studies, investigations, and non-system specific technology efforts. It may also include design, development, and improvement of prototypes and new processes to meet general mission area requirements (DAU Glossary, 2023).

Connector or facilitator – An organization that builds networks and creates relationships between government, industry, private equity firms, and academia; facilitate partnerships to solve challenging problems by generating new solutions (MITRE AiDA, 2023).

Defense Innovation Board (DIB) – The DIB is a Federal Advisory Committee comprised of current and former senior leaders from the national security innovation base. The board was established in 2016 to provide independent reviews of Department of Defense documents and policies on behalf the Secretary of Defense and other senior leaders across the Department (*Defense Innovation Board*, 2023).

Defense Innovation Organization (DIO) – Broad term pertaining to any government offices, laboratories, commercial industry, academia, and research institutions that conduct innovation activities for the DoD. These activities include, but are not limited to, research and development, non-traditional contracting, and accelerated capability acquisition, with the overall goal of implementing transformational technologies, strategies, and organizational practices within the DoD (Flagg & Corrigan, 2021; Kotila et al., 2023).

Dual-Use Technology – Technologies that have applications in both military and civilian sectors (DAU Glossary, 2023).

Federal Acquisition Regulation (FAR) – The regulation for use by federal executive agencies for acquisition of supplies and services with appropriated funds. The FAR is supplemented by DoD, the military departments, the Defense Contract Audit Agency (DCAA), the Defense Information Systems Agency (DISA), and the Defense Logistics Agency (DLA). The DoD supplement is called the DFARS (Defense FAR Supplement) (DAU Glossary, 2023).

Federally Funded Research and Development Center (FFRDC) – FFRDCs are Department of Defense-sponsored organizations that operate independently from the U.S. Government. These organizations aim to complement government activities through research and development laboratories, study and analysis centers, and systems engineering and integration centers. FFRDC program details and oversight is codified in Department of Defense Instruction (DoDI) 5000.77 (Office of the Undersecretary of Defense for Research and Engineering [OUSD(R&E)], 2019).

Government Contracting Authority – Organizations that can execute contract awards or agreements for government projects; the promise of government funding for work completed. These organizations have warranted Contracting Officers who are authorized to execute awards and agreements on behalf of the government (MITRE AiDA, 2023).

Government Laboratory – Any laboratory, any federally funded research and development center, or any center established under Title 15 United States Code (U.S.C.) that is owned, leased, or otherwise used by a Federal agency and funded by the Federal Government, whether operated by the Government or by a contractor (*15 U.S. Code § 3703 - Definitions*, n.d.).

Innovation – A wide variety of activities that create value for an individual or organization (i.e., reduced time, reduced resources, increased profit); finding novel solutions to meaningful problems (Dwyer, n.d.).

> **Defense Innovation –** The broad set of experimental activities aimed at developing and implementing transformational technologies, strategies, and organizational practices for enhanced military capability or reduced cost of military operations (Austin, 2022; Hunter & Crotty, 2015; Lewis, 2021; Picucci et al., 2021).

Innovation Steering Group (ISG) – A forum reporting to the Deputy Secretary of Defense and the Vice Chairman of the Joint Chiefs of Staff to drive systemic strategy, policy, programmatic, cultural and budgetary changes for the Department to more effectively identify, invest in, and transition capability to the warfighter (OUSD(R&E), n.d.).

Manufacturing Innovation Institute (MII) – Domestic public-private partnerships that seek to advance research and development for advanced manufacturing technologies (DoD ManTech, 2023).

Organizational Network Analysis – Organizational network analysis is an adaptation to social network analysis as a method to explore the relationships and interactions between nodes in an organizational network by examining various aspects of the network's connectivity structure. The analytical measures could include seeking information about highly connected nodes (centrality) and node communities (modularity). There are many types of centrality measures that can be used, each assessing the network in different ways. Centrality measures can be based on the nodes (degree, weighted degree, and eigenvector centrality) or the paths through the network (betweenness, and closeness centrality) (Latora et al., 2017; Newman, 2018). While there are additional measures of centrality, this research includes these five.

Other Transaction (OT) – Statutory authorities that permit a federal agency to enter into transactions other than contracts, grants, or cooperative agreements that are not governed by the Federal Acquisition Regulation; OT agreements are classified as either for research, prototyping, or production (OUSD(A&S), 2023).

Software Factory – A software assembly plant that contains multiple pipelines, which are equipped with a set of tools, process workflows, scripts, and environments, to produce a set of software deployable artifacts with minimal human intervention. It automates the activities in the develop, build, test, release, and deliver phases (DoD CIO, 2019).

University Affiliated Research Center (UARC) – Non-profit research organizations affiliated with a university that operate as independent, trusted advisors and have specific domain expertise or specializations tailored to the long-term needs of the DoD. While any university can receive funds from the DoD to perform work, that does not make them a UARC; all DoD UARCs are approved by the OUSD(R&E) after a rigorous review and competitive selection process conducted by the proposed primary sponsor. Only OUSD(R&E) can establish, transfer, or terminate a UARC (OUSD(R&E), n.d.).

Chapter 1

Introduction

This chapter introduces the research project, including an overview of the historical context behind this research, innovation in the United States (U.S.) Department of Defense (DoD), and the evolution of the associated ecosystem of organizations that conduct and support this innovation. Then, this chapter provides an overview of the research objectives, research questions, and thesis structure. Finally, it provides the author's personal motivation for completing this project.

1.1 Historical Context

Nearly 80 years have elapsed since Japan signed surrender documents aboard the USS Missouri on September 2, 1945, thus marking the end of the last world war. In this post-world-war era of relative peace at the global level, militaries engaged in numerous regional conflicts, but none of which resulted in war between two or more superpowers. However, the militaries of the world's superpowers remained anything but static throughout this period. In the U.S., the DoD and military services continue to evolve, invest in new weapons development, and seek new methods to exploit technological advancements for advanced warfighting capability. Although paradoxical, this constant evolution is necessary to prevent another global conflict by ensuring competitors are not developing unmatched technological advancements that could be exploited. Said differently, militaries that fail to innovate at an ever-increasing pace cannot effectively deter aggression and could fail to preserve national and global security.

The world is starkly different today than it was in 1945. Should any future conflict rise to the level of an all-out global war, this conflict would be unlike anything the world has ever witnessed. This premise underpins the 2022 U.S. National Defense Strategy (NDS), which highlights that the most pressing strategic challenges for today's security environment are linked to rapidly changing military capabilities and emerging technologies. The NDS goes on to state:

> *"Competitor strategies seek to exploit perceived vulnerabilities in the American way of war, including by creating anti-access/area-denial environments; developing conventional capabilities to undertake rapid interventions; posing all-domain threats to the U.S. homeland in an effort to jeopardize the U.S. military's ability to project power and counter regional aggression; and using the cyber and space domains to gain operational, logistical, and information advantages" (Austin, 2022, p. 4).*

This strategic focus underscores the need and urgency for continuous innovation within the DoD as an indispensable tool for adeptly navigating these multifaceted challenges. Failure to do so removes the credible deterrent required to prevent conflict with any potential near-peer adversary. But what does defense innovation actually look like in practice?

1.2 Defense Innovation Overview

In the context of national defense, the term innovation refers to a broad set of experimental activities aimed at developing and implementing transformational technologies, strategies, and organizational practices to provide enhanced capabilities for the military or to reduce the cost of military operations (Austin, 2022; Hunter & Crotty, 2015; Lewis, 2021; Picucci et al., 2021). Defense innovation, therefore, encompasses an expansive spectrum of endeavors, from incremental to radical advancements in products or processes to secure the requisite military capability to maintain peace and deter aggression. This effort includes the full spectrum of offensive and defensive military capabilities to ensure that no potential adversary obtains a technological edge sufficient to attempt exploitation through armed conflict. The imperative for innovation within the DoD extends across multiple dimensions, including:

- Technological Advancement: Maintaining technological superiority is imperative to national defense and is a critical factor discussed throughout the NDS and echoed through the 2023 National Defense Science and Technology Strategy (NDSTS). This effort requires investing in new research from sources internal to the DoD, academia, and defense contractors and harnessing the potential for dual-use technologies developed by and for the private sector. The NDSTS designates three categories of research and development focus areas for fourteen critical technology areas:

(1) Emerging opportunities: biotechnology, quantum science, future-generation wireless, and advanced materials

(2) Vibrant commercial activity: trusted artificial intelligence and autonomy, integrated networked systems-of-systems, microelectronics, renewable energy generation and storage, advanced computing and software, space technology, and human-machine interfaces

(3) Defense-specific areas: directed energy, hypersonic weapons, and integrated sensing and cyber (Department of Defense, 2023)

- Flexible Operational Concepts & Doctrine: Innovation in operational concepts involves reimagining how military forces conduct operations. These innovations could include new practices enabled by technological advances, such as multi-domain operations enabled by advances in technologies that enable remote and mobile communication. Alternatively, operational concept innovation could include rapidly developing new procedures or altering existing practices due to changes in opponent strategies, such as varying convoy routes and procedures to reduce the threat of sabotage or improvised explosive devices until sufficient countermeasures are developed and deployed (Harrison et al., 2017). Innovation in this area often requires the development of new tactics, techniques, and procedures in response to evolving threats or changing operational environments and can be accelerated out of necessity during conflict. The DoD needs to maintain an innovative mindset toward any potential future conflict, and military doctrine needs to remain flexible to ensure military forces can adapt swiftly to changing operational environments and remain resilient in the face of complex operations against an advanced opponent.

- Improved Resource Allocation: The DoD needs to optimize resource allocation to sustain current operations and maintain a preparatory posture to protect against any near-term conflict while simultaneously investing in research and development aimed at any potential future conflict. This complex challenge necessitates innovative cost-saving measures, unconventional resource management methods, and strategies for streamlining the cumbersome procurement processes necessary for large-scale military acquisition programs and Federal Acquisition Regulation (FAR)-based contracts. The NDS states that "Our current [DoD acquisition] system is too slow and too focused on acquiring systems not designed to address the most critical challenges we now face" (Austin, 2022, p. 19). Further, Congress established the Commission on Planning, Programming, Budgeting, and Execution (PPBE) Reform via the Fiscal Year 2022 National Defense Authorization Act (NDAA) Section 1004 to review current budgeting practices and identify improvements to deliver military operational capabilities at the speed necessary to outpace any near-peer competitors (National Defense Authorization Act for Fiscal Year 2022, 2021). The DoD must find ways to maintain military technological advantages despite fiscal constraints.
- Partnerships and Alliances: The complex, rigid, and burdensome traditional acquisition process drove the DoD to establish new public-private partnerships to attract early-stage ventures and non-traditional DoD contractors (Kotila et al., 2023). These partnerships must extend beyond traditional Defense Industrial Base companies to academia, startup companies, and research institutions. Some examples of the DoD's recent renewed focus in this area include:

- Establishment of the Defense Innovation Unit in 2015 to connect the DoD with the nation's tech hubs (Pellerin, 2015).
- Establishment of Manufacturing Innovation Institutes in 2012 as public-private partnerships for connecting the DoD with emerging manufacturing technology and market sectors in the U.S. (Vergun, 2022).
- Establishment of four new University Affiliated Research Centers (UARC), including the National Strategic Research Institute at the University of Nebraska in 2012, the Applied Research Laboratory for Intelligence & Security at the University of Maryland, College Park in 2017, the Geophysical Detection of Nuclear Proliferation at the University of Alaska in 2018, and the Research Institute for Tactical Autonomy established at Howard University in 2023 (Lopez, 2023; Office of the Undersecretary of Defense for Research & Engineering (OUSD(R&E), n.d.).
- Establishment of the Accelerate the Procurement and Fielding of Innovative Technologies (APFIT) program in 2022 to aid in the partnerships between the DoD and non-traditional defense contractors and accelerate the rate of technology transition (*DoD Announces First Set of Projects to Receive Funding From the Pilot Program to Accelerate the Procurement and Fielding of Innovative Technologies (APFIT) [Press Release]*, 2022).

These examples do not represent the total effort but offer insight into how the DoD is looking for diverse perspectives, access to cutting-edge technologies, and rapid innovation cycles that can significantly enhance the ability to stay at the forefront of defense capabilities. This network of partnerships is rapidly expanding, highlighting the DoD's recognition of the success to date and the continued importance of leveraging this external expertise. This effort requires the DoD to maintain a broad Defense Innovation Ecosystem where novel ideas can thrive to aid in advancing military capabilities.

1.3 The Defense Innovation Ecosystem

Innovation activity in the DoD is accomplished through a massive, multifaceted network of government agencies, private industry, academia, and research institutions, collectively known as Defense Innovation Organizations (DIO). The proliferation of this Defense Innovation Ecosystem over the last decade can be traced back to actions taken following a November 2014 memorandum from then-Defense Secretary Chuck Hagel titled *The Defense Innovation Initiative.* In this memorandum, Secretary Hagel highlights how technological advances changed the security landscape in the past, and technological advances will continue to be the driving force behind a rapidly changing security landscape in the future (Hagel, 2014). However, a 2023 report from the RAND National Defense Research Institute highlights that many of the organizations that comprise the Defense Innovation Ecosystem were established independently of one another to address specific needs. This independent growth led to a massive ecosystem that is not optimally organized to support innovation in the DoD at the speed required to maintain peace and deter aggression (Kotila et al., 2023).

To begin addressing this challenge, Deputy Secretary of Defense Kathleen Hicks established the Innovation Steering Group (ISG) in 2021 to foster improved innovation across the DoD by driving any changes necessary to strategy, policy, culture, and funding. The Deputy Secretary of Defense and the Vice Chairman of the Joint Chiefs of Staff now chair the ISG, which includes representation from across the DoD, including the military services, combatant commands, and the Joint Staff. One of the early tasks of the ISG included the establishment of a database and network model of the total ecosystem (Eversden, 2021; OUSD(R&E), n.d.). The DoD Chief Technology Office's interactive network model includes ten organizational grouping categories: Innovation Organizations, University Affiliated Research Centers (UARC), Federally Funded Research and Development Centers (FFRDC), Manufacturing Innovation Institutes (MII), Consortiums, Science and Technology Reinvention Laboratories, Partnership

Intermediary Agreements (PIA), Software Factories, Centers of Excellence, and Governance Organizations. Figure 1 below depicts a high-level, total system overview of this Defense Innovation Ecosystem model to highlight the ecosystem's scale and complexity, with each node representing a separate organization and the linkages representing an organizational hierarchy.

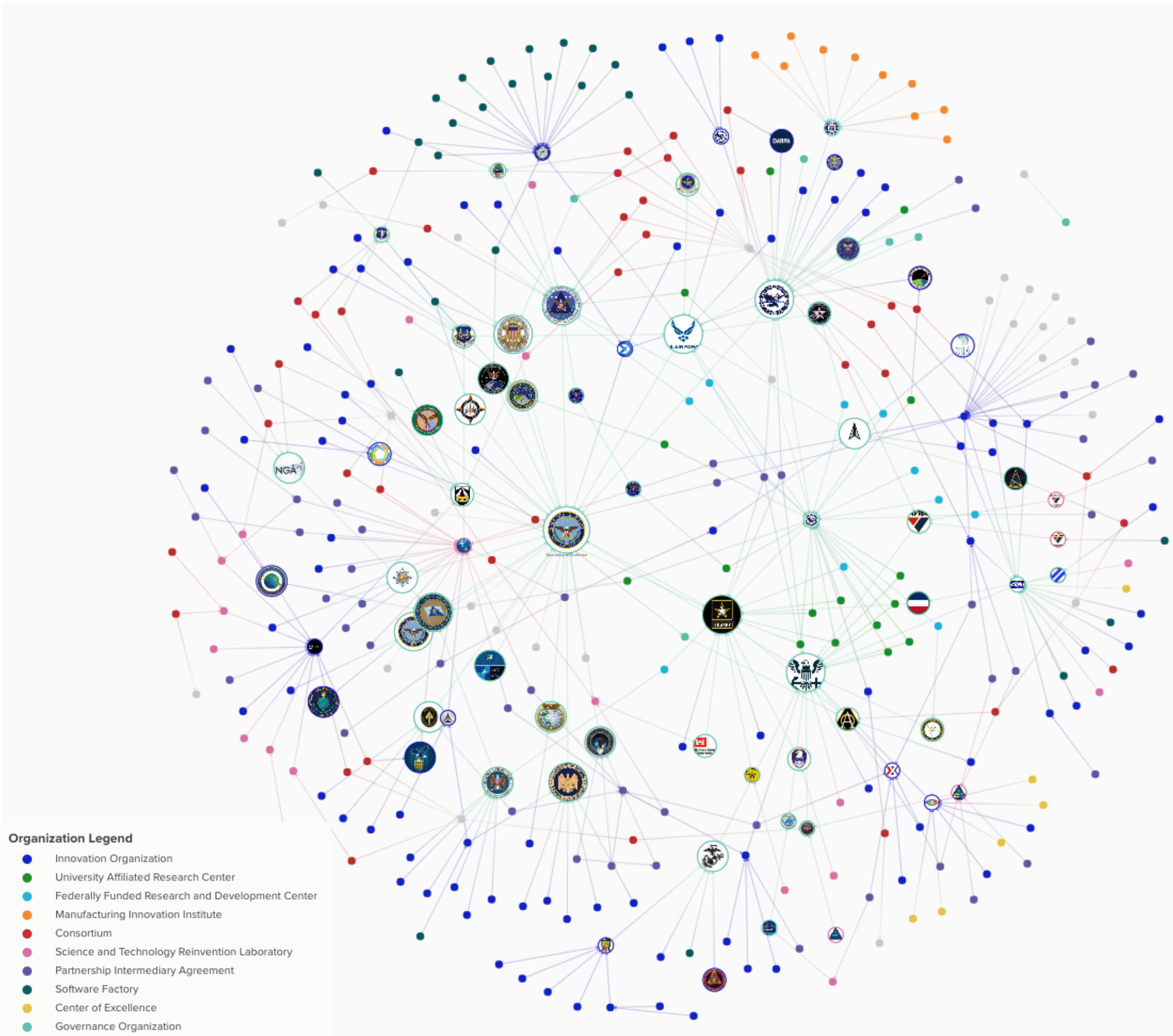

Figure 1 - DoD CTO Innovation Ecosystem Model
(source: https://www.ctoinnovation.mil/innovation-ecosystem)

1.4 Research Objectives

The rapid expansion of the DoD Innovation Ecosystem over the last decade, coupled with the massive potential positive impact on technology advancement and technology transfer across multiple sectors, makes it essential for the DoD to fully understand and actively manage this ecosystem. A July 2023 Defense Innovation Board task force review of the National Defense Science and Technology Strategy highlighted that "…no one should be under the illusion that a handful of scattered offices, programs, and initiatives will enable us to meet our most challenging national security problems" (Thornberry et al., 2023, p. 4). Therefore, this research aims to accomplish the following objectives:

- Establish a baseline of what is considered the current DoD Innovation Ecosystem
- Model the ecosystem as it currently exists and conduct systems-level analysis
- Identify organizational leaders, gaps, and redundancies within the ecosystem
- Investigate how organizational changes could improve the ecosystem

1.5 Research Questions

The thesis addresses the following research questions:

1. What is the current state of the DoD Innovation Ecosystem?
2. What insights can be gained by exploring the ecosystem connectivity?

   2a. Where are the organizational nodes of high connectivity and influence in the system?

   2b. How well does modularity by connectedness align with the DoD organizational structure?
3. What system improvements can be made to streamline innovation?

1.6 Thesis Structure

Chapter 1: This chapter introduces the thesis topic, including background information, a description of the scope, research methodology, and the research questions explored herein. This chapter explains the importance, timeliness, and relevance of the research.

Chapter 2: This chapter includes a review of the relevant literature, including a historical analysis of innovation in defense strategy, an exploration of the evolution of innovation activities found in the DoD, and an exploration of the various DIOs that comprise the Defense Innovation Ecosystem.

Chapter 3: This chapter overviews the DoD innovation organizational hierarchy, including government-owned and government-funded research and development centers, innovation organizations, software factories, the other transaction (OT) consortia model, and the supporting governance and oversight organizations. Further, this chapter includes a description of the data sources, the organizational model development process, scope decisions, and an overview of the data organization. This chapter gives the reader a thorough understanding of the data supporting the model development and begins the initial data visualization exploration.

Chapter 4: This chapter provides an overview and results of the organizational network analysis methods. This analysis serves as the basis for addressing the research questions and includes the following centrality measures: degree, weighted degree, eigenvector, betweenness, and closeness. This chapter provides an overview of each centrality measure and then discusses the results of each analysis and the aggregated results to determine the nodes of importance within the model. Finally, this chapter details the findings from the modularity assessment.

Chapter 5: This chapter applies the organizational network analysis results to refine the model visualization. These visualizations include altering the model displays to adjust the node sizing based on the selected centrality measures. Further, this chapter visualizes the modularity assessment to illustrate the overlap of the underlying node connectivity structure with the existing organizational hierarchy.

Chapter 6: This chapter summarizes the research conducted to address the research questions, discuss the research limitations, and make recommendations for future research.

1.7 Personal Motivation

This research aims to provide a deeper understanding of the Defense Innovation Ecosystem as it currently exists. By understanding the limitations and strengths of the hierarchical connectivity underpinning the ecosystem, the DoD can better strategize how it might evolve to meet future demands. Although the DoD drove technological innovation for many years, that expertise continues to shift to the commercial industry. The DoD needs to keep pace to maintain competitive advantages gained from technological superiority. This research applies to any individuals or organizations that operate within the DoD Innovation Ecosystem or organizations that seek to partner with the DoD that could gain from understanding the system's complexity.

Chapter 2
Literature Review

This chapter reviews the relevant literature on innovation within the DoD. This review is conducted through three lenses: published defense strategy documents, historical perspective on DoD innovation, and the various organizations that comprise the Defense Innovation Ecosystem as it currently exists.

2.1 Defense Strategy Documents

2.1.1 National Defense Strategy

The DoD publishes periodic NDS documents to align Department priorities and resources behind the National Security Strategy (NSS) signed by the President and Commander in Chief of the U.S. Armed Forces. The DoD started using the current NDS format in 2005 and has published five iterations of the strategy to date, including 2005, 2008, 2012, 2018, and 2022. The timeline for revisions can vary but is generally in response to major revisions of global military priorities or significant shifts in the NSS from changing presidential administrations. The 2005 NDS, which the DoD wrote amid the Global War on Terrorism in the years following the September 11, 2001 terrorist attacks in New York City and Washington, D.C., is therefore heavily focused on the global eradication of violent extremist organizations. The 2005 NDS makes only one reference to fostering a culture of innovation within the DoD. However, this reference is within the context and urgency established by the Global War on Terrorism (Rumsfeld, 2005).

By the next NDS in 2008, the DoD remained focused on combating violent extremism but recognized a renewed focus on the rise of great power competition from China and Russia. This iteration of defense strategy makes several references to innovation, but only one of which is in the context of technological innovation. The 2008 NDS discusses the need to accelerate the procurement of new technology to maintain global defense through a changing strategic environment (Gates, 2008). While only briefly discussed in the 2008 NDS, the idea of accelerating technological development through innovative capabilities and organizations is discussed in greater detail by the 2012 iteration of the NDS, referred to as the 2012 Defense Strategic Guidance (DSG). Additionally, the 2012 DSG promised to maintain an adequate industrial base for defense and continued investment in science and technology (Panetta, 2012).

Although defense innovation did not garner much attention in prior defense strategy documents, the concept of innovation within the DoD and a clearly stated DoD priority of reforming practices and organizational structures to drive innovation became a prominent theme by the 2018 iteration of the NDS. Although not published in an NDS, then-Defense Secretary Hagel published a memorandum to the DoD between the 2012 DSG under Defense Secretary Panetta and the 2018 NDS under Defense Secretary Mattis, which likely explains the increased focus. In this memorandum, Secretary Hagel established a DoD-wide effort called the Defense Innovation Initiative under the purview of then-Deputy Secretary of Defense Robert Work, calling it a catalyzing effort that will spread throughout the DoD. Secretary Hagel identified five areas of focus to accelerate innovation within the DoD, including:

(1) Leadership development

(2) Long-range research and development (R&D) planning

(3) Reinvigorated wargaming

(4) Develop new operational concepts

(5) Whole-of-government approach and cooperation

(6) Self-reflection and analysis for effectiveness (Hagel, 2014).

While the full version of the 2018 NDS is maintained in a classified document, it is evident through the eleven-page unclassified summary that the DoD remained energized behind the Defense Innovation Initiative in a way it had not been previously. The 2018 NDS summary highlights a shift from eliminating violent extremists that dominated the previous strategies toward inter-state strategic competition as the primary concern for U.S. national security. It calls for the military to adopt practices toward rapid innovation and highlights U.S. technological innovation as a core strength of the DoD (Mattis, 2018). General James McConville, U.S. Army Chief of Staff, summarized the 2018 NDS in two words: strength and innovation (Vergun, 2020).

Continuing with this trend toward innovation as a top DoD priority in an era of great power competition, the 2022 iteration of the NDS established the building of a resilient Joint Force and defense ecosystem as one of four top-level defense priorities. The 2022 NDS states that the DoD encourages innovative approaches to fielding new technologies and that "The Department will support the innovation ecosystem, both at home and in expanded partnerships with our Allies and partners" (Austin, 2022, p. 19). The 2022 NDS further describes the extensive innovation ecosystem, including academia, small businesses and technology firms, and university-affiliated and federally funded research and development centers (UARCs and FFRDCs) (Austin, 2022). Through this exploration of national defense strategies over the last two decades, it is clear that fostering a defense ecosystem focused on innovation is now a top priority within the DoD. This strategic focus is consistent with the rapid growth in the type and quantity of innovation-focused organizations supporting the DoD.

2.2.2 National Defense Science & Technology Strategy

The DoD publishes the NDSTS annually to establish the priorities and goals of the defense research and engineering (R&E) enterprise and, therefore, synchronize the various science and technology (S&T) efforts across the Department. The DoD published the most recent instantiation of the NDSTS in May 2023 to reestablish S&T priorities and synchronize efforts with the 2022 NSS and NDS. The 2023 NDSTS highlights "Accelerated technology advancement and innovation are key elements to…ensure our national security over the long term" (Department of Defense, 2023, p. 1). Through this strategy document, the DoD established three lines of effort, including: (1) Focus on the Joint Mission, (2) Create and field capabilities at speed and scale, and (3) Ensure the foundations for research and development (Department of Defense, 2023)

The first line of effort focuses on the investments and processes to conduct analysis to improve the DoD's decisions for future S&T investment priorities. This focus area shows that the DoD needs to carefully focus its investments on attainable technologies that increase competitive advantage rather than expend resources chasing wasteful technologies. To do this, the DoD established three investment categories for the fourteen specific critical technology areas that warrant investment, including:

(1) Emerging opportunities: biotechnology, quantum science, future-generation wireless, and advanced materials
(2) Vibrant commercial activity: trusted artificial intelligence and autonomy, integrated networked systems-of-systems, microelectronics, renewable energy generation and storage, advanced computing and software, space technology, and human-machine interfaces
(3) Defense-specific areas: directed energy, hypersonic weapons, and integrated sensing and cyber (Department of Defense, 2023)

The second line of effort focuses on developing a thriving Defense Innovation Ecosystem that ensures the DoD can efficiently and effectively implement new and emerging technologies across the Department. This effort includes establishing alternative pathways to onboard new and non-traditional defense contractors and developing new methods to fund and field prototype capabilities that can later transition to full-scale production. The NDSTS identifies three separate failure points where technologies often fail, known as valleys of death. These include a valley between basic research found in a lab and a fielded prototype, a valley between a working prototype and a real product, and a valley from a product to production at scale. The NDSTS establishes that bridging these valleys can be accomplished by expanding and energizing the total defense innovation ecosystem, including academia, government and national labs, FFRDCs and UARCs, individual military service innovation centers, non-profit entities, commercial industry, other U.S. government departments and agencies, and international allies and partners (Department of Defense, 2023). To aid in this effort, the DoD CTO office developed an initial database and mapping of the total innovation ecosystem. Figure 2 below provides a geographical depiction of the ecosystem map shown previously in Figure 1 to highlight the expansive network captured within this total ecosystem.

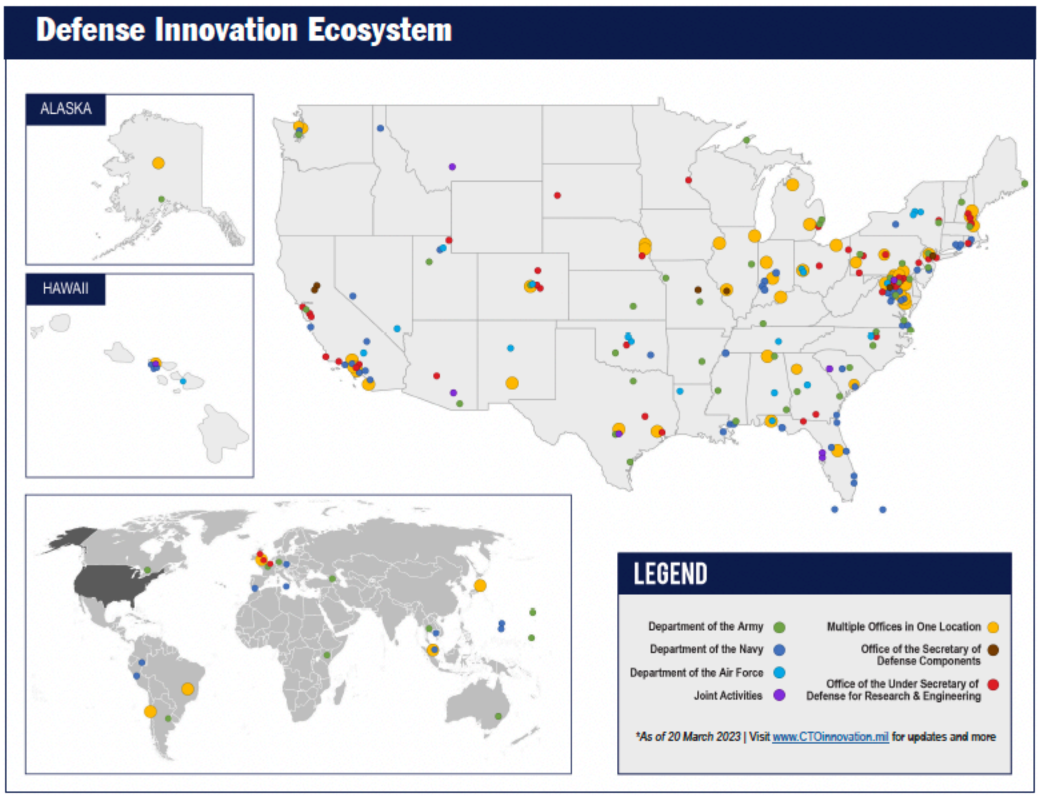

Figure 2 - Geographical Depiction of the Defense Innovation Ecosystem
(source: https://media.defense.gov/2023/May/09/2003218877/-1/-1/0/NDSTS-final-web-version.pdf)

The third line of effort focuses on upgrading the laboratory and test infrastructure and recruiting and retaining the requisite workforce to develop and validate any new technologies for assured operations in the 21st Century. This level of effort requires information sharing between the DoD and industry and with trusted U.S. allies and partners. Further, it requires targeting and developing the workforce and expertise necessary to support the research and development of complex new technologies (Department of Defense, 2023).

The 2023 NDSTS provides a comprehensive strategy for the DoD, with a clear need to foster a diverse and vibrant Defense Innovation Ecosystem. Further, it establishes a sense of urgency to this endeavor, which affirms the importance of this research project to garner a deeper understanding of the current state and influential organizations within the Defense Innovation Ecosystem.

2.2 Defense Innovation: The Technological Edge

While a professor at Harvard University's John F. Kennedy School of Government, and drawing from his prior experience in multiple senior-level defense positions and defense consulting work, Dr. Ashton Carter co-authored a book titled *Keeping the Edge: Managing Defense for the Future.* Published in 2001, 14 years before Dr. Carter assumed the role of Defense Secretary, many of the arguments posed in this forward-thinking book on defense policy foreshadowed the rising importance of innovation within the DoD and remain relevant today. In this book, Dr. Carter and his co-authors highlight several challenges facing the DoD, including recruiting and retention concerns for top-tier talent, overly complex organizational bureaucracy that is not properly organized, and a military capability acquisition system that is burdened with the cumbersome FAR, which impedes the DoD from delivering capability at the speed necessary to maintain technological superiority (Carter & White, 2001).

Recent history of the DoD relying on technological superiority as a strategy to offset adversarial overmatch points back to the Cold War and President Dwight D. Eisenhower's New Look strategy. Although historians now retroactively refer to this as the "First Offset" strategy, the U.S. military observed a massive arms build-up within the Soviet Union and its Warsaw Pact allies that the U.S. could not match in quantity one-for-one. Therefore, the U.S. sought superior firepower through the pursuit of technologically superior nuclear weapons, coupled with stringent security protocols and export controls, which aimed to complement tactical forces and preserve the ability to maintain a much smaller military fighting force that was still capable of deterring a land invasion in western Europe (Gentile et al., 2021).

By the mid-1970s, the technological edge gained by nuclear weapons eroded due to nuclear arms treaties and the Soviet Union's nuclear weapon development program. Therefore, a "Second Offset" strategy focused on quality over quantity was required. Therefore, the U.S. focused on fielding superior technology for the battlefield to provide the outnumbered forces with superior weapons that significantly enhanced their combat effectiveness. The advanced weaponry included precision-guided munitions, stealth technologies, revised military doctrine, and technologies to enable new cross-domain (air-land-sea) cooperation, surveillance, targeting, and command and control. Further, the DoD focused on developing next-generation hardware, such as new mechanized vehicles and fighter aircraft (Gentile et al., 2021; Grant, 2016).

As with the First Offset strategy, the technologies that supported the Second Offset strategy eventually proliferated throughout the world's militaries and negated the technological edge, leading to a Third Offset strategy. As the then-chief executive officer (CEO) of the Center for a New American Security (CNAS) and just prior to his term as Deputy Secretary of Defense and eventual selection to lead the Defense Innovation Initiative as the Third Offset in 2014, Robert Work and his co-author Shawn Brimley outlined this strategy in a paper titled *"20YY: Preparing for War in the Robotic Age."* In this paper, the authors urge the DoD to begin preparations for securing technological advantage for the coming era of conflict utilizing unmanned and autonomous systems. They provide evidence of four trends related to maintaining the technological edge to support their claim, including the proliferation of guided munitions among state and non-state actors, the rising cost of manpower and crewed combat systems, rapid advances in data computing, artificial intelligence, robotics, and miniaturization, and lastly a return toward mass (quantity of systems) due to advanced weaponry. Contrary to the Cold War, when DoD-sponsored R&D drove military innovation, the authors argue that commercial industry will drive the next military technology revolution (Work & Brimley, 2014).

Returning to the Carter and White (2001) analysis, the authors correctly predicted the DoD's shift from exquisite DoD-specific technology development toward relying on private sector technological innovation adapted for military applications. As highlighted by the authors and echoed by Work & Brimley (2014), a reliance on commercial technology can also lead to technological surprise as potential opponents can access the same technologies on the global market. Therefore, for the Third Offset strategy to succeed, the DoD must become the world's fastest adopter of commercial technology. The DoD must depend on more than just the commercial industry for R&D investment to achieve this fastest adopter goal. It must maintain a strong base of internal, DoD-focused R&D while funding investments in commercial R&D with the potential for dual-use capabilities (Carter & White, 2001).

Although research identified this methodology of investing in commercial technology to ensure success twenty years prior, a 2021 report from the Center for Strategic and International Studies (CSIS) highlights that DoD acquisition spending has yet to shift away from the large defense contractors to non-traditional partners and innovation programs. The report highlights that non-traditional innovation programs for defense account for less than one percent of the total DoD acquisition funding. In contrast, defense and aerospace companies spend, on average, less than three percent of their total revenue on R&D (Lewis, 2021). However, Lewis (2021) also points out that as the DoD transitions from a producer of technological innovation toward a primarily consumer role, the Department requires broad changes in two additional areas. First, the DoD needs a culture change focused on fostering a culture of innovation and entrepreneurship (risk-taking). This culture change is challenging for a defense community generally regarded as very risk-averse, especially under the over-bearing acquisition regulation geared toward eliminating risk during large-scale procurement programs, such as fighter jets and aircraft carriers. Therefore, the second recommendation highlighted in the report is the need for process reform to gain more flexibility in DoD acquisition, including acquisition authorities and accelerated budgeting practices not currently allowed under the existing Planning, Programming, Budgeting, and Execution (PPB&E) system (Lewis, 2021).

The review of relevant literature thus far viewed defense innovation as solely those activities and technological advancements aimed at increasing military performance. However, Kuo (2022), an assistant professor at the U.S. Naval War College Strategic and Operational Research Department, offers an alternative view. The author claims that innovation is actually more likely to reduce military effectiveness when a gap exists between commitments and resources. When this harmful innovation cycle is completed during peacetime and thereby not driven by operational necessity during a conflict with real-time feedback on its effectiveness, there is an increased likelihood that expertise and resources for traditional, proven capabilities become cannibalized in favor of new innovative technologies that have not been battle-tested. In the resource-constrained environment in which the DoD currently operates, it must seek a balance of investing in new innovative capabilities with the selective erosion of proven traditional capabilities, ensuring that it creates more capability than it destroys in the process. The author describes how this is an exercise in risk management and that the commitment-resource gap could result in a costly gamble toward exquisite solutions at the expense of proven combat capability (Kuo, 2022). How, then, does the DoD determine the optimal investment criteria in new versus old technology to protect against this harmful innovation risk? One way is by maintaining a diverse and effective innovation ecosystem that cuts across the full spectrum of potential military technologies while ensuring the effective exchange of information and ideas into, out of, and within this ecosystem.

2.3 Defense Innovation Ecosystem

In the years following World War II, the U.S. was the clear global leader in R&D investment. The federal government funded most of this R&D, with the DoD being the most prominent government spender, dedicating significant R&D investments through academia, government-owned laboratories, and defense contractors (Flagg & Corrigan, 2021). In this post-war era, today's sprawling ecosystem of defense innovation organizations began to take shape. Flagg & Corrigan (2021) identify the establishment of the Office of Naval Research (ONR) in 1946 as one of the earliest expansions of the innovation ecosystem, followed by the creation of the Advanced Research Projects Agency (later renamed Defense Advanced Research Projects Agency (DARPA)) and National Aeronautics and Space Administration (NASA) in 1958. The build-up of service-oriented laboratories continued with the establishment of the Office of Air Research (OAR) in 1948 and the Army Research Office (ARO) in 1951 (*AFOSR - History*, n.d.; *DEVCOM Army Research Laboratory*, n.d.), but also includes the national laboratories at Los Alamos (LANL) and Lawrence Livermore (LLNL).

Many of the university-based research partnerships created to conduct military-focused research during World War II began transitioning to full-time federally funded research centers. This network of FFRDCs grew to around 70 total research centers at one point (U.S. Congress, Office of Technology Assessment, 1995), and is now comprised of the ten centers detailed in Table 1 below. Several university-affiliated research centers that did not become FFRDCs later became codified as UARCs. Today, the DoD manages and funds R&D efforts through 15 UARCs, as detailed in Table 2 below, which ensures the DoD maintains access to basic and applied research from academia that could affect future military technological capabilities (OUSD(R&E), n.d.).

Table 1 - DoD FFRDCs (source: https://rt.cto.mil/ffrdc-uarc/)

DoD FFRDCs	Primary Sponsor	Founded
Focus: Study & Analysis		
Center for Naval Analyses	Navy	1942
RAND - Project Air Force	Air Force	1948
Institute for Defense Analyses (IDA) -Studies and Analyses	DoD	1956
RAND Corporation - Arroyo Center	Army	1982
RAND Corporation - National Defense Research Institute (NDRI)	DoD	1984
Focus: Systems Engineering & Integration		
MITRE Corporation - National Security Engineering Center (NSEC)	DoD	1958
Aerospace Corporation	Air Force	1961
Focus: R&D Laboratories		
Massachusetts Institute of Technology-Lincoln Laboratory (MIT/LL)	DoD	1951
Institute for Defense Analyses (IDA) – Communications & Computing	NSA	1959
Software Engineering Institute (SEI)	DoD	1984

Table 2 - DoD UARCs (source: https://rt.cto.mil/ffrdc-uarc/)

DoD UARCs	University	Primary Sponsor	Founded
Applied Physics Laboratory	Johns Hopkins University	Navy	1942
Applied Physics Laboratory	University of Washington	Navy	1943
Applied Research Laboratory	University of Texas at Austin	Navy	1945
Applied Research Laboratory	Penn State University	Navy	1945
Georgia Tech Research Institute	Georgia Institute of Technology	Army	1995
Space Dynamics Laboratory	Utah State University	MDA	1996
Institute for Creative Technologies	University of Southern California	Army	1999
Institute for Soldier Nanotechnologies	Massachusetts Institute of Technology	Army	2002
Institute for Collaborative Biotechnologies	University of California, Santa Barbara	Army	2003
Applied Research Laboratory	University of Hawaii	Navy	2008
Systems Engineering Research Center	Stevens Institute of Technology	DoD	2008
National Strategic Research Institute	University of Nebraska	USSTRATCOM	2012
Applied Research Laboratory for Intelligence & Security	University of Maryland, College Park	DoD	2017
Geophysical Detection of Nuclear Proliferation	University of Alaska	DoD	2018
Research Institute for Tactical Autonomy	Howard University	Air Force	2023

While these networks of DoD-funded laboratories and research centers were sufficient to sustain the technologies required for the First and Second Offset strategies, the 2014 announcement of the Defense Innovation Initiative and the Third Offset strategy highlighted the need for a new approach to innovation that could capitalize on the rapid expansion of the commercial technology market (Hunter & Crotty, 2015). Hunter and Crotty (2015) emphasize the need for the DoD to maintain its own R&D program, as there are military-unique products with no commercial application. However, the DoD cannot rely solely on this internal research network and must complement it with technologies sourced from commercial R&D endeavors. Following then-Defense Secretary Hagel's departure, then-Defense Secretary Carter took over the implementation of the Defense Innovation Initiative. Then-Defense Secretary Carter implemented several innovation-focused efforts, including the establishment of the Defense Innovation Unit Experimental (DIUx) in Silicon Valley in 2015, investment in the Intelligence Community's In-Q-Tel startup-focused venture capital organization, and the establishment of the Strategic Capabilities Office (SCO) just a few years prior (Gentile et al., 2021; Hunter & Crotty, 2015). The commercially focused innovation momentum within the DoD began to build through these new organizations, but more was needed as process improvements were still required. Hunter and Crotty (2015) identify four forces acting on the global innovation environment that threatened the DoD's ability to maintain the technological edge, including:

(1) Increased globalization of the world's economies brought on by faster and cheaper international trade, which shrinks the DoD's awareness and influence on global R&D.
(2) Increased privatization of commercial industry R&D brought on by lower costs, reduced barriers to access cutting-edge technology, and expanded global markets for marketization.

(3) Increased commercialization of multiple research sectors with significant military implications, including communications and information technology, where the DoD is no longer the global leader in technological advancement.

(4) An acceleration of the pace of technological change brought on by advancements in communications and information technology, which is incompatible with the DoD's archaic, lengthy acquisition processes (Hunter & Crotty, 2015).

An investigation of U.S. R&D expenditure data from the National Center for Science and Engineering Statistics of the National Science Foundation affirms the privatization trend identified by Hunter and Crotty (2015). The graph in Figure 3 below depicts the shrinking ratio of federally-funded R&D to gross domestic product (GDP)

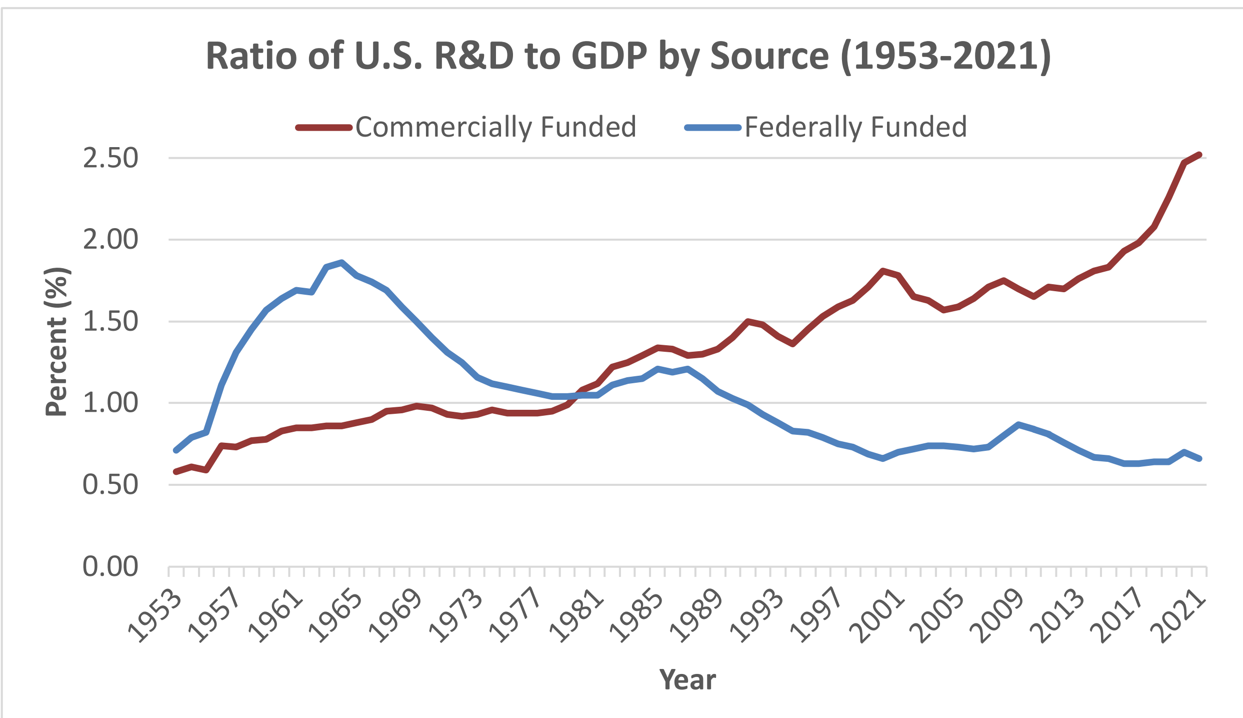

Figure 3 - Comparison of Federal to Commercial R&D Expenditures (1953-2021)

compared to the rapidly rising ratio of commercially-funded R&D, which surpassed the 1964 peak ratio of federally-funded expenditures in 2016 and continues to rise (National Center for Science and Engineering Statistics (NCSES), 2023). Clearly, the U.S.

innovation environment is changing, and the DoD needs to evolve its organizations and processes to keep pace. Congruent with the other efforts under the Defense Innovation Initiative, then-Under Secretary of Defense for Acquisition and Sustainment (USD(A&S)) Kendall released a revised version of the Better Buying Power (BBP 3.0) initiative with an overarching theme of "*Achieving Dominant Capabilities through Technical Excellence and Innovation"* (Kendall, 2015). This process-oriented guidance to the DoD's acquisition workforce aims to ensure that the DoD capitalizes on all available sources of technological innovation, including the increasing commercial technology sector. These sources better acquisition program cost management measures, reinvigorated long-range R&D planning, restructured incentives to attract and maintain DoD contractors, enhanced utilization of the Small Business Innovation Research (SBIR) program, and several other process improvement initiatives aimed at how the DoD engages with commercial industry (Kendall, 2015).

In a master's thesis for the Naval Postgraduate School, Gagnon and Van Remmen (2018) conduct a comparative analysis of the disparate communities comprising the DoD Innovation Ecosystem to determine which acquisition processes best contribute to innovation. The authors echo the concerns of the cumbersome acquisition processes highlighted throughout the reviewed literature, including Austin (2022), Carter and White (2001), Hunter and Crotty (2015), and Kotila et al. (2023). To combat this, the Fiscal Year 2016 NDAA expanded the DoD's authority to utilize Other Transactions (OT) as flexible contracting arrangements with industry that are not restricted by the same rules and regulations as FAR-based contracts. This authority gave rise to an expansive segment of the innovation ecosystem known as OT Consortia and numerous accelerator and connector offices internal to the DoD that utilize this contracting method to shorten the timeline needed to deliver new technologies (Gagnon & Van Remmen, 2018). One example of an accelerator is the Colorado-based Catalyst Accelerator, which focuses on establishing DoD partnerships in the commercial space industry and maintaining awareness of commercial space technology developments (Catalyst Accelerator, 2023). On the other hand, OT Consortia provide an organizational construct where commercial companies can align under specific technology areas for easier access to government contracts, funding, and assistance with navigating the government contracting bureaucracy. Examples of these OT Consortia include but are not limited to, 301 member companies aligned under the Medical Chemical Biological Radiological Nuclear (CBRN) Defense Consortium (MCDC, 2023), 141 member companies aligned under the Defense Automotives Technology Consortium (DATC, 2023), and 433 member companies aligned under the Maritime Sustainment Technology and Innovation Consortium (MSTIC, 2023).

The DoD Innovation Ecosystem growth did not stop there. Two additional organizational network constructs created within the innovation ecosystem include the Manufacturing Innovation Institute (MII) effort launched in 2012 and the Microelectronics Commons effort launched in 2023. MIIs are public-private partnerships focused on advancing domestic manufacturing technologies through resource and information sharing between the DoD and commercial manufacturing companies. The DoD's Manufacturing Technology (ManTech) office oversees nine MIIs totaling a network of over 1,700 organizations across the U.S. (DoD ManTech, 2023). Established through an existing OT consortium and in accordance with the Fiscal Year 2021 NDAA, the Microelectronics Commons aim to foster the growth of similar partnerships and information sharing between the DoD and commercial industry for microelectronics technology. Through this network, the DoD established eight regionally distributed hubs, most of which are aligned under academic institutions (Microelectronics Commons, 2023).

With the expansive network of organizations that are all contributing to innovation on behalf of the DoD, who is actually responsible for understanding and managing this ecosystem? Understanding the current state of the ecosystem is vital to effective management because, as Gagnon and Van Remmen (2018) highlight, the DoD is seeing duplication of effort and inefficient resource utilization within the ecosystem. A 2017 Defense Innovation Board (DIB) report echoes this concern, which states that “The Department has an ‘innovation archipelago’: many offices within DoD are engaged in excellent and important work on innovation, but each is an island, disconnected from the rest. This lack of communication and collaboration is hampering progress” (Defense Innovation Board, 2017, p. 1). Flagg and Corrigan (2021) also identify that innovation offices are scattered throughout the DoD, with each office established to address the needs within their specific niche, making collaboration and transparency across the ecosystem extremely difficult. Congress is also starting to take notice. The House Armed Services Committee (HASC) version of the Fiscal Year 2024 NDAA states that “While the committee is supportive of innovation organizations within the Department and military services, the committee believes that the unchecked proliferation of them could allow for significant duplication and confusion both inside and outside the Department” (H.R.2670 - National Defense Authorization Act for Fiscal Year 2024: Chairman’s Mark, 2023). The bill also calls for the DoD to produce a report to Congress with an organizational consolidation plan. It is clear that the DoD needs to understand this ecosystem fully and then actively manage it, and this work needs to be accomplished now.

The MITRE Corporation’s Acquisition in the Digital Age (AiDA) office maintains one data repository of organizations that comprise the DoD Innovation Ecosystem (MITRE AiDA, 2023). This database is helpful for exploring various organizations and identifying their functions, including accelerators, challenges, connectors, funding opportunities, incubators, and offices with government contracting authority. However, this database does not capture the total innovation ecosystem or its underlying hierarchy. Other data repositories exist, including locally generated products to fulfill the needs of specific offices and a crowdsourced "wiki" collection of organizations hosted on Golden.com (*Department of Defense Innovation Ecosystems - Wiki*, n.d.). While these data repositories can be helpful for some top-level information about organizations, they are incomplete, do not reflect recent ecosystem changes, and make no inferences about the underlying system connectivity and complexity.

During a keynote address at the Carnegie Mellon University Software Engineering Institute's Research Review in 2021, the USD(R&E) and DoD's CTO, Heidi Shyu, commented on the mapping of the DoD Innovation Ecosystem as one of the CTO office staff's three priority areas (Vergun, 2021). In response, the CTO staff created an extensive mapping of the Defense Innovation Ecosystem, including an organizational hierarchy. The map is hosted on a public-facing website titled Innovation Pathways, which aims to serve as a virtual front door for industry, academia, and DoD personnel to connect with and explore the ecosystem (OUSD(R&E), 2023). A screenshot of this interactive network is shown in Figure 1. While this network is the most extensive of any located data repository and includes hierarchical linkages, it is built primarily for understanding the "what" of the Defense Innovation Ecosystem. With additional data verification and further buildout of the underlying information and hierarchical connections, the ecosystem can be explored, including the first level of analysis required to address the Congressional request for an organizational consolidation. With this lens, this research project aims to provide the DoD with organizational insights toward addressing this information gap.

Chapter 3

Model Development

This chapter begins with an overview of the current DoD organizational hierarchy to baseline the understanding of the DoD organizational hierarchy and provide insight into the complexity involved in the DoD Innovation Ecosystem for modeling. Then, this chapter details the data collection methodology, the DoD Innovation Ecosystem model development process, and begins the visual data exploration on the network.

3.1 Understanding the DoD Hierarchy

The modern DoD hierarchy took shape following the conclusion of World War II through the National Security Act of 1947 and its subsequent amendments. This act unified the Department within the Executive Branch under a Secretary of Defense as a civilian leader of the U.S. armed forces. The DoD currently employs approximately 3.4 million employees, including service members and civilians, to sustain its global operations (*U.S. Department of Defense*, 2023; *U.S. Department of Defense (DoD) | Britannica*, 2023). Headquartered at the Pentagon in Washington, D.C., the entire DoD can be broken down into six primary functional areas, including:

(1) Secretary of Defense staff, known as the Office of the Secretary of Defense (OSD), with offices responsible for the overall management, oversight, policy, and resource allocations; OSD staff is organized by seven major staff elements, including Acquisition and Sustainment (A&S), Research and Engineering (R&E), Budget and Financial Management, Intelligence and Security (I&S), Personnel and Readiness (P&R), Policy, and Reform.

(2) Three military service departments to manage five branches of the military, including the Department of the Army (USA), the Navy and Marine Corps under

the Department of the Navy (DON), and the Air Force and Space Force under the Department of the Air Force (DAF).

(3) The Joint Chiefs of Staff (JCS), consisting of a Chairman of the Joint Chiefs of Staff (CJCS) and representation from the top unformed service member from each of the five military services, as well as a Joint Staff organization for cross-cutting collaboration and coordination between the military services.

(4) Eleven Unified Combatant Commands (CCMD), including the six geographic areas of U.S. Northern Command (NORTHCOM), U.S. Southern Command (SOUTHCOM), European Command (EUCOM), U.S. Indo-Pacific Command (INDOPACOM), U.S. Central Command (CENTCOM), and U.S. African Command (AFRICOM), and the five functional commands of U.S. Strategic Command (STRATCOM), U.S. Special Operations Command (SOCOM), U.S. Transportation Command (TRANSCOM), U.S. Cyber Command (CYBERCOM), and U.S. Space Command (SPACECOM) with missions that are not bounded by geographic borders.

(5) Twenty defense agencies, such as DARPA, DLA, Defense Threat Reduction Agency (DTRA), National Reconnaissance Office (NRO), Defense Health Agency (DHA), Missile Defense Agency (MDA), and the Defense Contract Management Agency (DCMA). These organizations perform missions that cut across the entire DoD or directly support whole-of-DoD mission areas.

(6) Eight DoD field activities responsible for the management of DoD administrative functions, such as the Defense Technical Information Center (DTIC), DoD Human Resources Activity, and the DoD Test Resource Management Center (TRMC) (DoD Chief Management Officer, 2020; Eanes, 2019).

A line and block diagram depicting this top level of the DoD organizational hierarchy is included below in Figure 4, which is adapted from information contained in DoD Directive

5000.01, *Functions of the Department of Defense and Its Major Components*, and the DoD Directorate for Organizational Policy and Decision Support Resource Guide (DoD Chief Management Officer, 2020; Eanes, 2019).

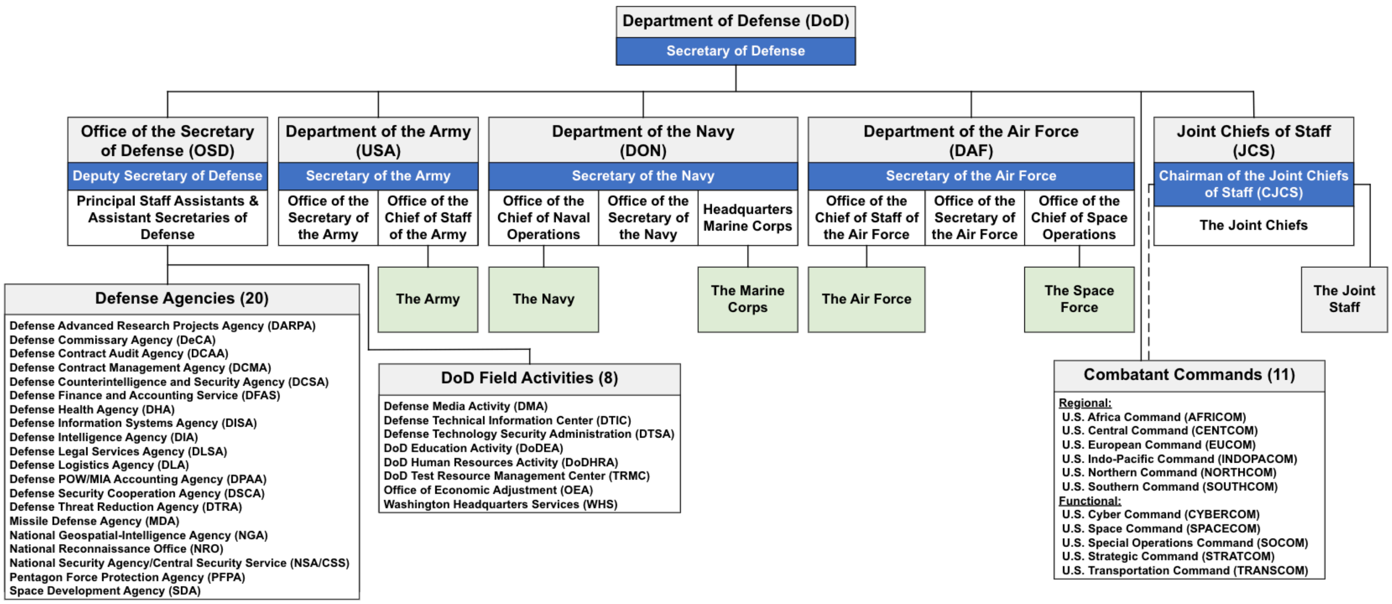

Figure 4 - Line and Block Diagram of the High-Level DoD Organizational Hierarchy

To further add to the complexity of the overall DoD hierarchy, each functional area and organization listed above maintains its own internal organizational structure and unique hierarchy. Clearly, the full scale and scope of the DoD are massive, and the hierarchical structure underpinning its organizational construct is unequivocally complex. With this organizational background under consideration, coupled with the overview of the various types of organizations comprising the DoD Innovation Ecosystem described in previous chapters, the data collection for the model development can begin.

3.2 Data Collection Methodology

The first step toward modeling the DoD Innovation Ecosystem is to locate and aggregate all relevant information about the organizations that comprise the model. For this research, the data needs are as broad as the ecosystem itself. While multiple databases exist, such as the MITRE Corporation AiDA website (MITRE AiDA, 2023), a

RAND study on the DoD Software Factories (*Personnel Needs for Department of the Air Force Digital Talent*, 2022), and the DoD CTO's Innovation Pathways website (OUSD(R&E), 2023), the available data includes inconsistencies in the application of the organizational hierarchy and is, therefore, not ideally suited to conduct an organizational network analysis. Information from these sources, conversations with subject matter experts familiar with the DoD Innovation Ecosystem, and data obtained through various open-source web pages was collected and consolidated in a spreadsheet. Namely, this database includes the names of any organizations considered part of the ecosystem, the go-by name or acronym, type of organization, DoD organizational affiliation or primary DoD sponsor, and the location of the primary office or headquarters.

For the purposes of this research, each organization is categorized along the eight organizational types described below. Insufficient data is available in several cases, so some assumptions are necessary for consistency across the model. Ultimately, the categorization does not affect the model regarding the network connectivity analysis outputs.

(1) Innovation Org: These organizations include offices dedicated to various innovation activities, such as technology acceleration, rapid prototyping, commercial technology adoption, small business engagement, digital transformation, and employing non-FAR-based contracting methods. Examples of organizations in this category include the DoD's Defense Intelligence Innovation Office (DI2O), the Navy's Innovation and Modernization Patuxent River (IMPAX) office, the Air Force's Center for Rapid Innovation (CRI), and the Army's 75th Innovation Command (75IC). Further, this category includes the nine DoD Manufacturing Innovation Institutes (MIIs) sponsored by the DoD Manufacturing Technology (ManTech) office.

(2) Governance: These organizations perform general oversight and management functions and drive the policy and strategy within the DoD. Also, this category

includes the organizations added to the model to complete the organizational hierarchy. In some cases, these organizations can also perform innovation activities or be directly responsible for implementing them, but this is not considered its primary role or function. Examples of organizations in this category include the Office of the Secretary of Defense, the military service departments, Naval Sea Systems Command (NAVSEA), Air Combat Command (ACC), and Army Cyber Command (ARCYBER).

(3) R&D: These organizations primarily perform an R&D role, such as the government research laboratories. In some cases, the dedicated higher-level organizations responsible for overseeing and managing R&D functions are also considered R&D organizations. Examples of organizations in this category include the Los Alamos National Laboratory (LANL), the Office of Naval Research (ONR), the Air Force Research Laboratory (AFRL), and the Army Research Laboratory (ARL).

(4) OT Consortia: These organizations include the established OT consortia groups as well as the consortium management organizations. As described in Chapter 2, each OT Consortium can include several hundred organizations. Therefore, the model does not extend to the specific industry organizations contained within each consortium. Examples of organizations in this category include the Medical Technologies Enterprise Consortium (MTEC), sponsored by the U.S. Army Medical Research and Development Command (USAMRDC) and managed by Advanced Technologies International (ATI), and the Space Enterprise Consortium (SpEC), sponsored by the U.S. Space Force Space Systems Command (SSC) and managed by National Security Technology Accelerator (NSTXL). Further, this category includes the eight Microelectronics Commons hub sites managed by NSTXL.

(5) Academia: These organizations include the numerous primary host universities associated with FFRDCs, UARCs, or other DoD innovation partnerships. Examples of organizations in this category include the Georgia Institute of Technology as host to the Georgia Tech Research Institute (GTRI) UARC, Carnegie Mellon University as host to the Software Engineering Institute (SEI) FFRDC, and the Massachusetts Institute of Technology as host to the MIT-Lincoln Laboratory FFRDC and the DAF-MIT Artificial Intelligence Accelerator (DAF-AIA) office.

(6) Software Factory: These organizations include the various software factories found throughout the DoD, which can vary widely in terms of their size and scope. Examples of organizations in this category include the Navy's Overmatch Software Armory, the Air Force's Kessel Run office, and the Army Software Factory.

(7) UARC: These include the 15 UARCs described in Table 2.

(8) FFRDC: These include the 10 FFRDCs described in Table 1.

In total, the research identified 462 organizations to include in the model. A summary of these organizations by their organizational category is included in Table 3 below.

Table 3 - Summary of Organizations in the DoD Innovation Ecosystem Model by Organizational Category

Category	Quantity
Governance	103
R&D	95
FFRDC	10
UARC	15
Academia	31
OT Consortia	60
Software Factory	23
Innovation Org	125
Total	**462**

After locating and consolidating the data for these 462 organizations, the next step in the model development is to capture the hierarchical structure. The model intent is for a directed network representing a hierarchical flow from the lowest level organization on one extreme to the Office of the Secretary of Defense on the other. Therefore, a spreadsheet of all source-target organizational pairs is necessary to represent this hierarchy. A source is an organization that reports to another organization, and a target is the organization to which it reports. Source-target pairs can represent any linkage or reporting relationship between two organizational entities. In this case, the linkages are classified as either primary or secondary. Primary linkages are any direct reporting relationships to a parent organization, whereas secondary relationships indicate any other (non-primary) hierarchical connections. For example, each UARC discussed previously maintains a DoD sponsor organization (primary link) while also maintaining a connection back to its host university (secondary link). As an example of deconstructing a hierarchy diagram into source-target pairs, Figure 5 below details the Air Force's AFVentures organizational hierarchy. Note that this is only a subset of all organizations included in the ecosystem model and is, therefore, not representative of all organizations or linkages into or out of these organizations.

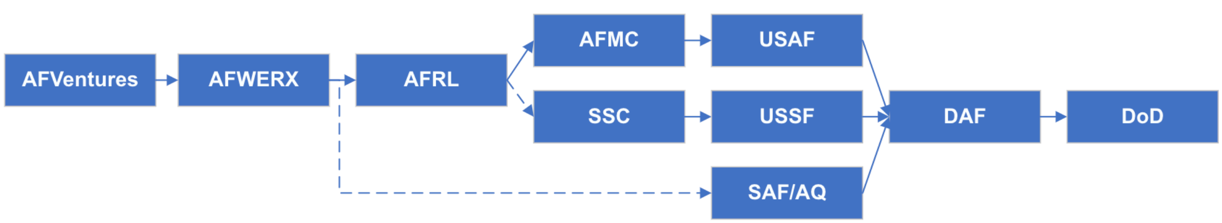

Figure 5 - Organizational Hierarchy for Air Force AFVentures Office

This hierarchy includes a primary linkage from AFVentures (source) to AFWERX (target). Then, it shows a primary linkage from AFWERX (source) to AFRL (target) and a secondary linkage from AFWERX (source) to the Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics (SAF/AQ). This source-target pairing is completed for the entire chain in Figure 5 and a list of all source-target pairs for this subset of the model is reflected in Table 4 below.

Table 4 - Source-Target Pairs for AFVentures Hierarchy Example

Source	Target	Reporting Channel
AFVentures	AFWERX	Primary
AFWERX	AFRL	Primary
AFWERX	SAF/AQ	Primary
AFRL	AFMC	Primary
AFRL	SSC	Secondary
AFMC	USAF	Primary
SSC	USSF	Primary
USAF	DAF	Primary
USSF	DAF	Primary
SAF/AQ	DAF	Primary
DAF	DoD	Primary

This process is repeated for each of the 462 organizations in the model to construct the complete hierarchical structure of source-target pairs. The final table of source-target pairs developed for this research includes 581 total connections, consisting of 429 primary and 152 secondary connections.

3.3 Model Development

Numerous network modeling software options exist, which vary in their intended usage and functionality. This research project tested several network modeling options, assessing each for its usability, configurability, and built-in data analysis tools. While some software focuses on the quality and functionality of the user interface, others are more focused on data analysis. This research includes tests with Kumu (www.kumu.io), Polinode (www.polinode.com), and Gephi (www.gephi.org) utilizing a subset of the entire model dataset. Ultimately, this research employs Gephi for its wide range of configuration and display options. Further, the Gephi software provides suitable analytical functions to complete the planned organizational network analysis. Therefore, the collected research data is cleaned and organized to match the Gephi uploading format.

Utilizing the terms used by Gephi and consistent with other network modeling software, the 462 organizations in the model are organized into a nodes table, and the 581 connections are organized into an edges table. The nodes table includes the following data elements for each node: organization name, acronym or go-by name, the organization type (i.e., Governance, R&D), the service or agency of the organization or its primary sponsor for non-DoD organizations, the city and state of the organization's headquarters, and the corresponding latitude and longitude. In addition to all source-target pairs, the edges table includes edge weights for representing primary and secondary connections. Edge weights are applied for the complete network to give more weight to primary linkages over secondary linkages, reflecting a greater strength of connectivity and influence from primary linkages within the organizational hierarchy.

The initial data upload to Gephi produces the network model shown in Figure 6 below. While the Gephi software reorganizes the layout based on the node connectivity, this depiction of the model is before altering the appearance of the nodes and edges. The layout methodology uses a "Force Atlas" function in the Gephi software, relocating nodes

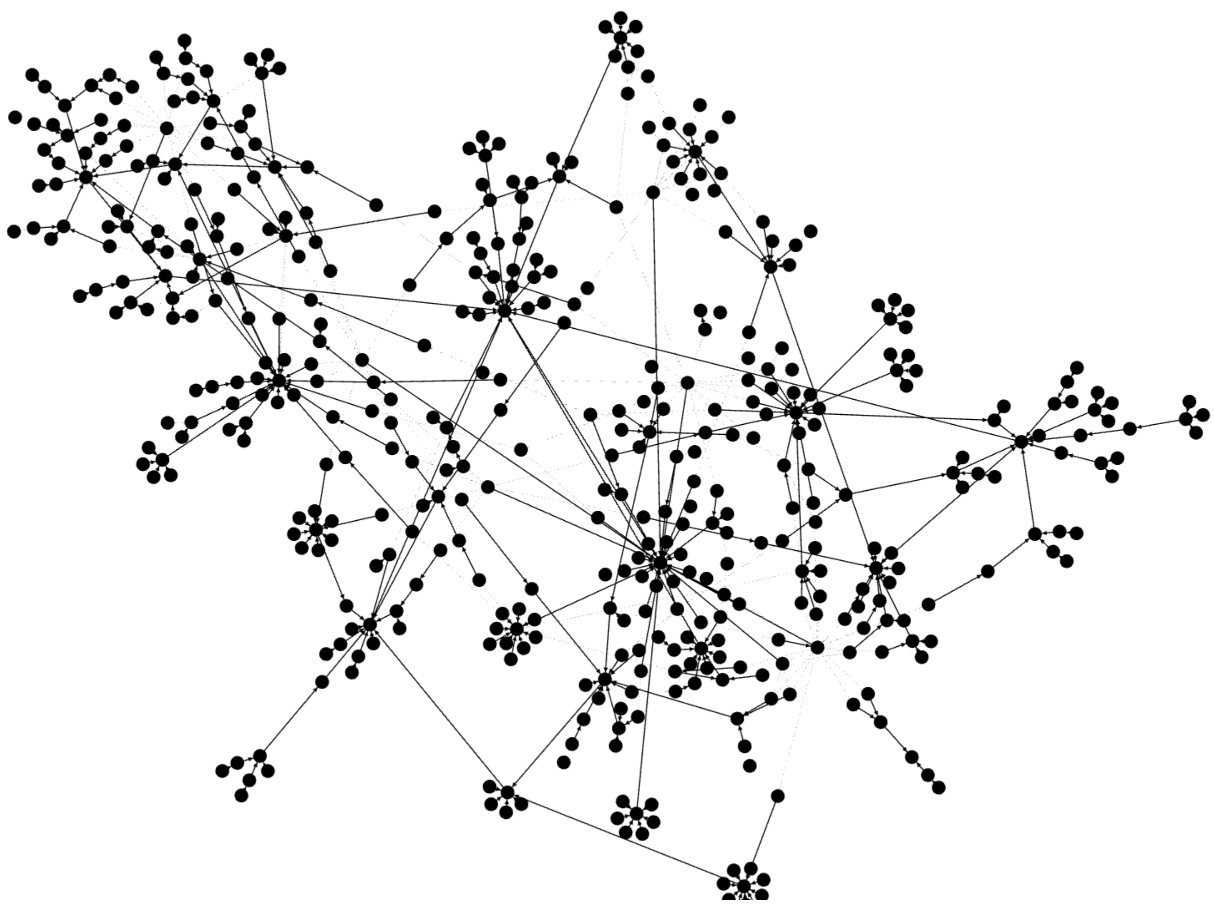

Figure 6 - Initial Model Output Showing Network Structure and Connectivity

based on their connectivity and keeping connected nodes pulled toward each other while allowing longer hierarchical chains to force other nodes to the periphery. It is clear from this initial model output that several nodes contain a large quantity of inputs. Further, numerous hub-and-spoke communities can be identified throughout the network, especially along the periphery. This layout logically tracks with the expectation for a hierarchical connection, but it is clear that this image alone is insufficient to draw significant conclusions from the network graph.

The Gephi software allows for the color and size of the nodes and edges to be altered across any categorical partition contained in the dataset. Additionally, the appearance of the nodes can be updated based on the output of the software's built-in organizational network analysis tools. The remainder of this chapter is dedicated to an initial exploration of the data visualization by altering the color of the nodes based on data contained within the research database, including the organizational alignment, organization type, and geographical location. This first-level analysis visually treats all nodes within the network as equal by not resizing or recoloring based on analytical results and instead looks specifically at categorical differences. Following a description of the organizational network analyses in Chapter 4, Chapter 5 returns to a data visualization exploration of the model where the node size and placement are altered based on the analytical results. This stepped approach provides a comprehensive review of the model and its underlying structure.

3.3.1 Organizational Alignment

The first visual alteration method recolors the nodes based on the organizational alignment within the DoD. For non-DoD entities, this alignment is based on the hierarchical alignment of the primary DoD sponsor organization. Non-DoD entities, in this case, refer to those organizations, such as OT Consortia, FFRDCs, and UARCs, which directly support DoD innovation, but their funding is through contractual agreements rather than direct DoD funding. The model partitions the nodes along the following seven categories, with the corresponding percentage share of the total number of organizations in the model included in parentheses following each partition description:

(1) DoD organizations, including OSD staff offices, defense agencies, and defense field activities (25.54%)

(2) The Department of Energy (DOE), including the three national labs at Lawrence Livermore (LLNL), Los Alamos (LANL), and Sandia (SNL) (1.08%)

(3) Academia, including the academic institutions that host FFRDCs, UARCs, or other innovation offices (6.28%)

(4) Combatant Commands (1.95%)

(5) The Department of the Army (USA) (17.53%)

(6) The Department of the Navy (DON), including the Navy and Marine Corps (20.56%)

(7) The Department of the Air Force, including the Air Force and Space Force (27.06%)

Figure 7 below takes the same network graph layout from Figure 6 and then partitions the node coloring into these seven organizational alignment categories. From this view, the organizational hierarchy becomes very clear, with the three military service departments and the DoD staff offices primarily aligned within their own clusters. It can also be noted how the DAF functions appear to be more isolated and interconnected between themselves, while the DON organizations are more loosely coupled and the USA organizations are even more distributed. Lastly, the academic institutions are spread throughout the network and not dominated by any particular service sponsor.

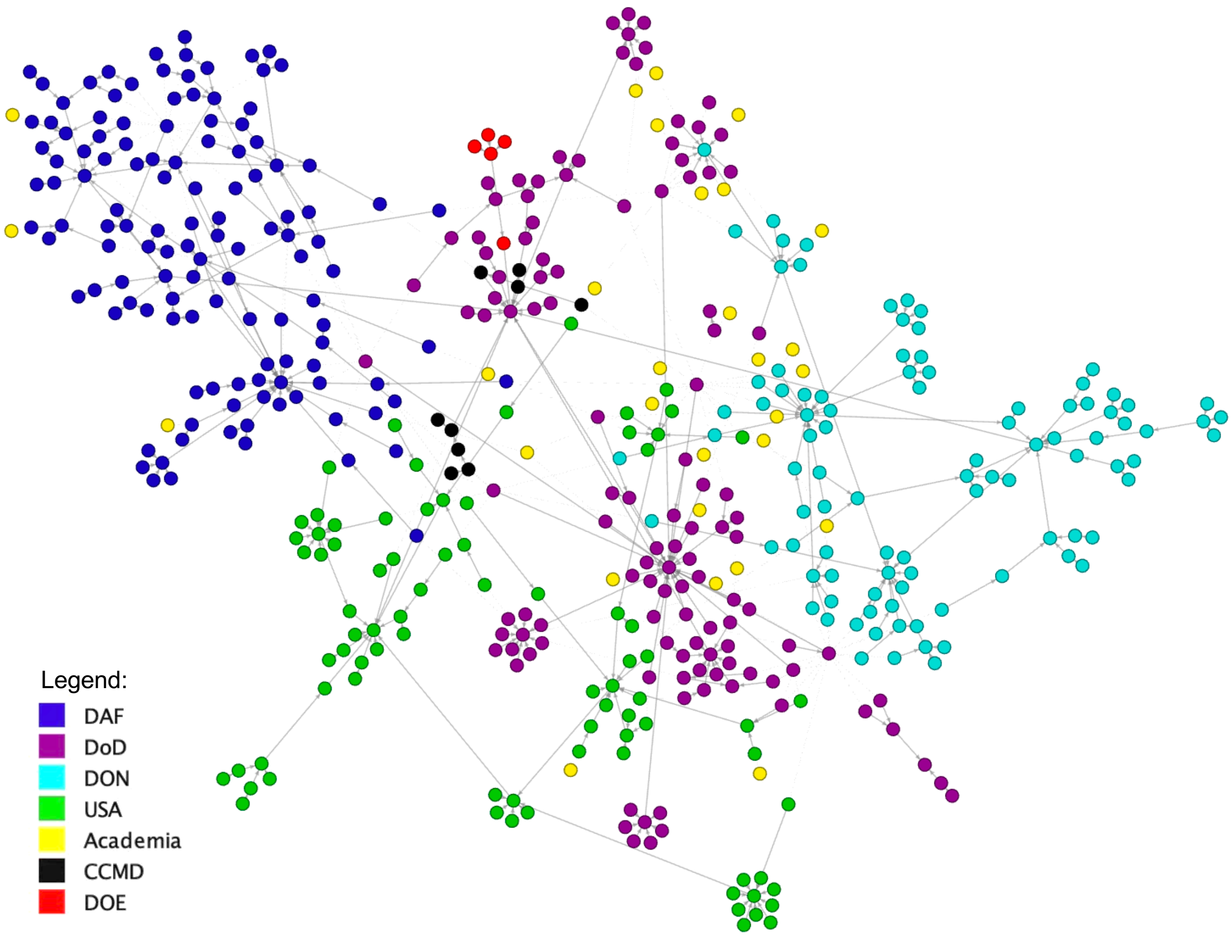

Figure 7 - Network Model With Nodes Colored by Organizational Alignment

3.3.2 Organizational Type

The second visual alteration method recolors the nodes based on the organizational type. The nodes are partitioned along the eight organizational categorizations described in the data collection methodology section above. This partitioning includes the following organization types, with their corresponding percentage share of the total number of organizations in the model included in parentheses:

(1) Innovation Organizations (27.06%)

(2) Governance (22.29%)

(3) R&D (20.56%)

(4) OT Consortia (12.99%)

(5) Academia (6.71%)

(6) Software Factories (4.98%)

(7) UARCs (3.25%)

(8) FFRDCs (2.16%)

As shown in Figure 8 below, this method of organizational partitioning does not result in clearly delineated boundaries or clusters. However, two intriguing takeaways are discovered through further analysis of this view of the network model.

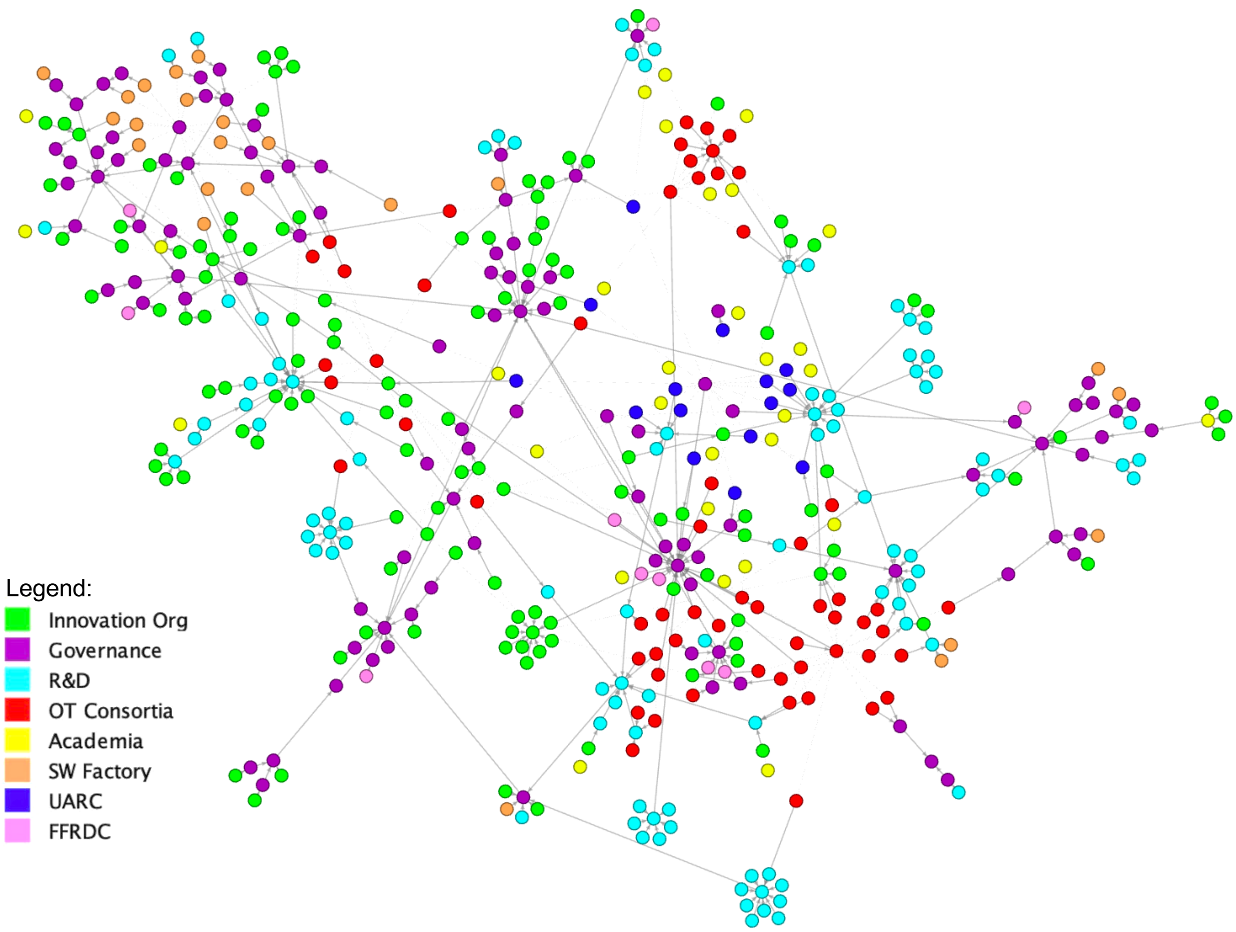

Figure 8 - Network Model With Nodes Colored by Organizational Type

First, the organization types are spread throughout the model, indicating that no department appears to dominate the quantity of DoD innovation or R&D organizations. If one of the services dominated, one would expect to see a more significant concentration of those node types within the organizational cluster areas reflected in Figure 7. The one exception is the apparent clustering of the red nodes, which signifies the OT Consortia organizations. When comparing Figure 8 back to Figure 7, one can note how the OT Consortia organizations are often aligned hierarchically through the DoD rather than the individual services. This finding is consistent with the OUSD(A&S) office maintaining the responsibility for overseeing OT agreements and associated policies.

Second, the green nodes in Figure 8, which signify the innovation organizations, can often be found at the end of hierarchical chains. One might argue that this is due to the innovation organizations signifying the termination point for the data collection methodology to build the ecosystem model. However, that is not the case, and there are only a few instances where innovation organizations have other organizations that report to them in the chain of command. For example, the Air Force's AFWERX office includes several supporting offices under the AFWERX chain of command, including the Prime, Spark, AFVentures, and SpaceWERX offices. However, AFWERX is unique, and these sub-organizations to innovation offices are not the norm throughout the network, as innovation organizations are often buried within the DoD hierarchy. This construct provides layers of potential bureaucracy up and down the respective chains of command. This bureaucracy is the antithesis of the agility and flexibility required of these organizations to be effective innovators.

3.3.3 Geographical Layout

The third and final visual manipulation of the network based on the information in the model database is a realignment of the network nodes based on the geographical location of each organization's headquarters. This manipulation uses the latitude and longitude information collected for each node and uploaded to Gephi in the nodes table. Then, using the GeoLayout add-on package for the Gephi software and altering the layout of the nodes based on their latitude and longitude data, the network maps shown in Figure 9 and Figure 10 below are generated. Figure 9 reflects all nodes in the model, including Alaska and Hawaii sites. Figure 10 focuses on the nodes within the contiguous U.S. for a closer view, given the overlap of nodes in several locations.

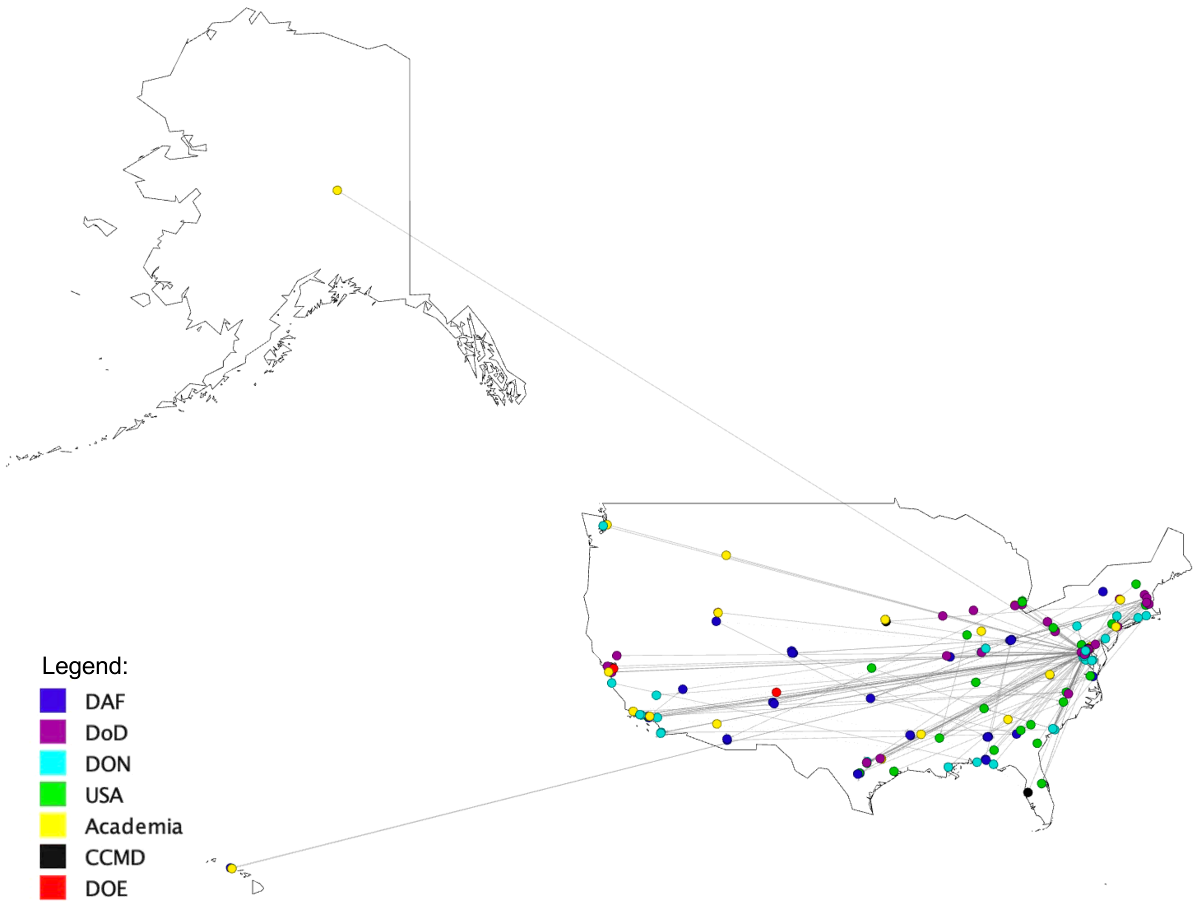

Figure 9 - Geographical Layout - Total Network, Colored by Organizational Alignment

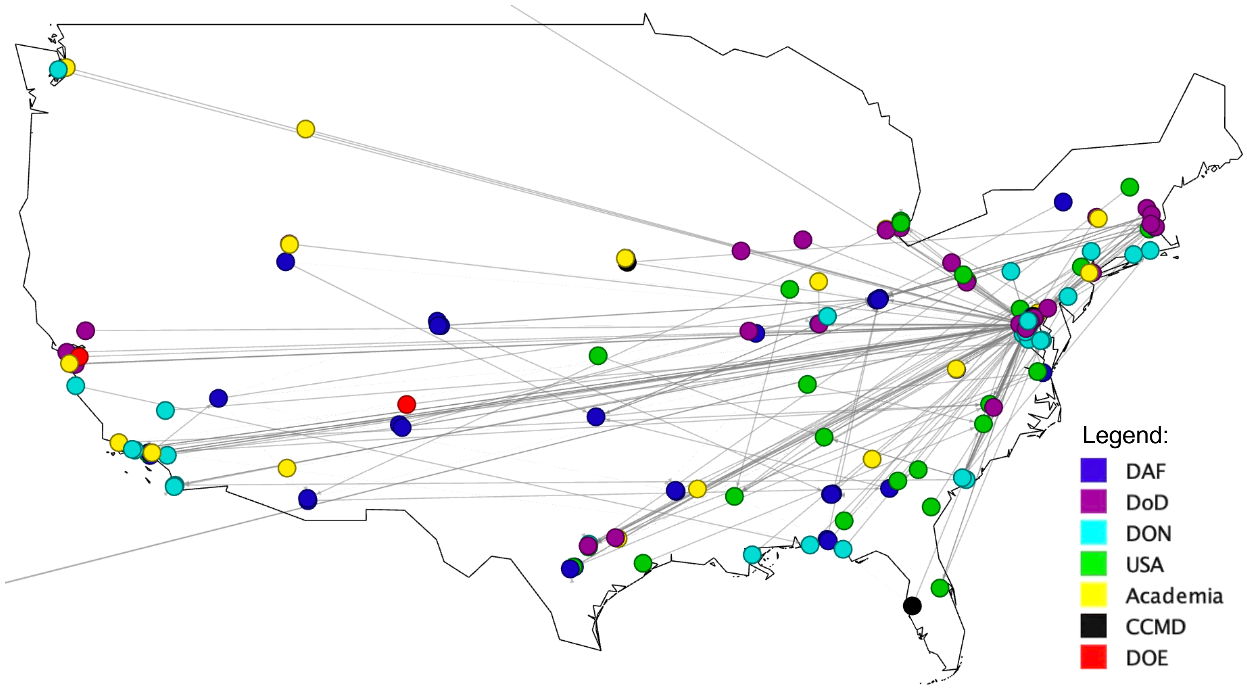

Figure 10 - Geographical Layout - Focused on Contiguous U.S., Colored by Organizational Alignment

Two key observations can be noted by viewing the ecosystem in this manner. First, the maps reflect that the DoD Innovation Ecosystem is extensive and spread across a large portion of the U.S. Since this is only a view of the headquarters locations and not all operating locations, the full extent of the DoD innovation network includes even more locations. Second, several regions serve as major innovation hubs for the ecosystem. These primary hub sites include the Silicon Valley and San Diego areas in California, the Austin and San Antonio areas in Texas, the Boston area in Massachusetts, and the largest regional hub located in the National Capital Region near Washington, D.C. Given that these locations enable co-location of several DoD Innovation Ecosystem offices with vital locations for industry and government operations, it makes sense that the innovation offices align in this manner. Further, this geographical layout signals that the DoD recognizes the influence of technology commercialization and is positioning organizations to facilitate commercial partnerships. However, with all of the nodes sized equally, it is hard to determine the relative influence that geography plays in the overall ecosystem. Using the organizational network analysis methods from Chapter 4, Chapter 5 will return to this geographical layout to investigate the impact of node sizing based on the analytical results.

In summary, this chapter provides an overview of the data collection methodology, the development of the DoD Innovation Ecosystem model, and the first level of model analysis through visual manipulations of the model based on information contained in the developed database. While this visual data exploration is helpful to begin understanding the ecosystem, it does not explore the effects of the underlying network connectivity. Chapter 4 applies five organizational network analysis methods to the network, and then Chapter 5 returns to the nodal network model for further data visualization exploration based on the results of these analytical methods.

Chapter 4

Organizational Network Analysis

This chapter begins with an organizational network analysis overview. Then, it describes and reviews the analytical results for each analysis method used in this research, including five network centrality measures: degree, weighted degree, eigenvector, betweenness, and closeness. Finally, this chapter provides an overview and assessment of the network through modularity.

4.1 Organizational Network Analysis Overview

Organizational network analysis methods explore the relationships and interactions between nodes in a network by examining various aspects of the network's connectivity structure. Networks are comprised of two primary elements: nodes and edges. In this research, each node represents a different organization within the DoD Innovation Ecosystem, and the edges represent the hierarchical connectivity between nodes. This model uses directional flow arrows for the edges, representing the hierarchical chain of command with the Office of the Secretary of Defense (OSD) at the top. Critical nodes in the DoD Innovation Ecosystem model are explored by investigating five commonly applied centrality measures: degree, weighted degree, eigenvector, betweenness, and closeness (Latora et al., 2017; Newman, 2018). While the first three centrality measures assess the quantity and strength of the nodes, the last two measures assess the network connectivity structure. Lastly, a modularity assessment of the model seeks the emergence of nodal clusters based on the underlying network structure. This chapter includes an overview of each organizational network analysis method applied to the ecosystem model and discusses the results of each analysis.

4.2 Degree Centrality

4.2.1 Degree: Overview

Degree centrality seeks to find nodes with strong influence and importance in a network by examining the quantity of edges. For a directed network, the degree measure can be further broken down into in-degree (flow toward a node) and out-degree (flow away from a node), with the direction of the edge arrows representing the hierarchical structure. The total degree measure for a node equates to the sum of its in-degree and out-degree, and a higher degree score indicates a higher level of connectivity. Mathematically, the degree centrality (C_D) of any node *v* in the set of nodes *V* for a directed network can be represented as:

$$\text{Degree Centrality} = C_D(v_i) =$$

$$\text{In-degree}(\mathrm{v}_i) + \text{Out-degree}(v_i) = \sum_{v_j \in V} A_{ji} + \sum_{v_j \in V} A_{ij}$$

In this equation, *A* represents the adjacency matrix, with A_{ji} representing incoming edges to v_i (in-degree) and A_{ij} representing outgoing edges from v_i (out-degree) (Brandes, 2001; Latora et al., 2017; Wasserman & Faust, 1994). An adjacency matrix was developed for the network model using the edge table of all source and target linkages. This matrix includes all nodes in both the rows and columns, then inputs a “1” for each corresponding cell linking two nodes if there is a source-target match and a “0” if not. Since the full 462-by-462 matrix is too large to include in this text format, a subset of the adjacency matrix is included below in Figure 11. For this matrix, the source node is depicted in the rows, the target node is depicted in the columns, and the edges are read from left to top. For example, this matrix depicts a connection from Node 1 to Node 0 and a connection from both Node 2 and Node 3 to Node 1. The in-degree is then found by the sum of a node’s column, the out-degree by the sum of the node’s row, and the total degree is the combination of the two.

Source \ Target	0	1	2	3	4	5	6	7	8	9	…	461	Out-Degree
0	0	0	0	0	0	0	0	0	0	0		0	0
1	1	0	0	0	0	0	0	0	0	0		0	1
2	0	1	0	0	0	0	0	0	0	0		0	1
3	0	1	0	0	0	0	0	0	0	0		0	1
4	0	0	0	1	0	0	0	0	0	0		0	1
5	0	0	1	0	0	0	0	0	0	0		0	1
6	0	0	0	0	1	1	0	0	0	0		0	2
7	0	0	0	0	0	0	1	0	0	0		0	1
8	0	0	0	0	0	0	1	0	0	0		0	1
9	0	0	0	0	0	0	1	0	0	0		0	1
…													
461	0	0	0	0	0	0	0	0	0	0		0	1
In-Degree	16	5	8	3	7	5	20	1	1	0		0	
Degree	16	6	9	4	8	6	22	2	2	1		1	

Figure 11 - Subset of Adjacency Matrix for Calculation of Network Degree

4.2.2 Degree: Analysis

The degree for each node was found using the adjacency matrix for the network model to compare and validate the degree outputs obtained from the Gephi software (Bastian et al., 2023). A graphical summary of the network's degree distribution is depicted below in Figure 12. This distribution shows that the network is heavily left-skewed, consistent with the expectations for a hierarchical network representation. This analysis shows that 187 nodes in the network lie at the end of their hierarchical chain, only having a single edge to their parent organization, with another 154 nodes only having 2 edges. Conversely, on the high end of the graph, there is only one organization with a

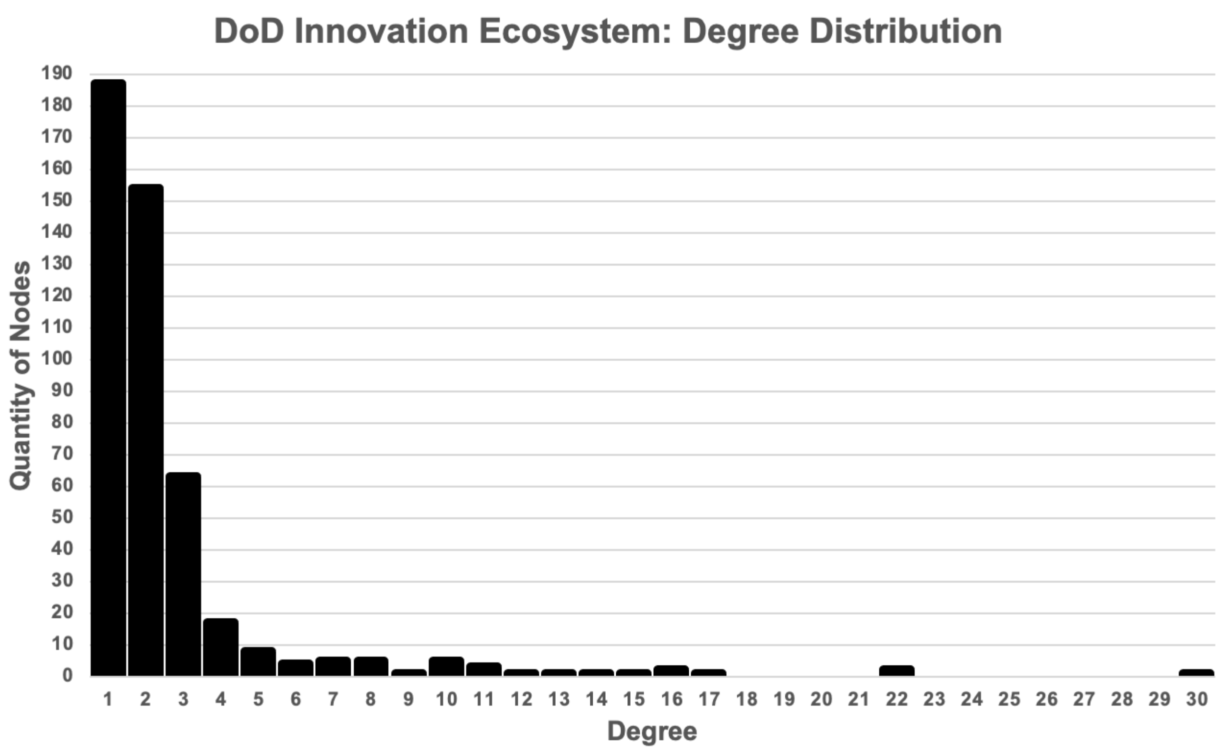

Figure 12 - Distribution of Degree Scores

degree score of 30 and two with a degree score of 22. The average node degree score for the whole network is 2.515, indicating a level of dependency across organizations beyond a strict hierarchical chain of command. The top ten nodes in the network in terms of their degree score are summarized below in Table 5.

Table 5 - Top 10 Organizations in the DoD Innovation Ecosystem Model by Degree of Connectedness

Rank	Organization	Type	Department	Degree Score
1	OUSD(R&E)/CTO	Governance	DoD	30
2	AFRL	R&D	Air Force	22
3	ATI	OT Consortia	DoD	22
4	ONR	R&D	Navy	17
5	OSD	Governance	DoD	16
6	ASD(S&T)	Governance	DoD	16
7	DAF CSO	Governance	Air Force	15
8	DoD ManTech	Innovation Org	DoD	14
9	NSTXL	OT Consortia	DoD	13
10	NAVSEA	Governance	Navy	12

Organization Acronyms: OUSD(R&E)/CTO: Office of the Undersecretary of Defense for Research & Engineering and Chief Technology Officer; AFRL: Air Force Research Laboratory; ATI: Advanced Technology International; ONR: Office of Naval Research; OSD: Office of the Secretary of Defense; ASD(S&T): Assistant Secretary of Defense for Science & Technology; DAF CSO: Department of the Air Force Chief Software Officer; DoD ManTech: Department of Defense Manufacturing Technology; NSTXL: National Security Technology Accelerator; NAVSEA: Naval Sea Systems Command

Half of this group of highly connected organizations are fulfilling governance and oversight functions, while the lead R&D organizations for the Air Force and Navy made the list. The DoD ManTech office is the only organization labeled an "innovation organization" within the model that made the list. The DoD ManTech office oversees the nine DoD Manufacturing Innovation Institutes, which explains the organization's high degree of connectedness. Lastly, two organizations that are part of the OT Consortia community made the list. ATI and NSTXL are prominent players in overseeing and managing OT agreements, and NSTXL also has a management role for the Microelectronics Commons Hub site agreements.

4.3 Weighted Degree Centrality

4.3.1 Weighted Degree: Overview

The degree measure is helpful to obtain one perspective of network connectivity, but it does not consider the strength of the connections. When including edge weights to quantify the strength of a connection, the weighted degree for each node can be determined. Primary linkages with a higher weighted reporting relationship affect the weighted degree of a node more than secondary connections. The formula for determining the weighted degree is similar to the degree formula but accounts for the edge weight rather than treating all edges as equal. Mathematically, the weighted degree centrality (C_W) of any node *v* in the set of nodes *V* for a directed network can be represented as:

$$\text{Weighted Degree Centrality} = C_W(v_i) =$$
$$\text{Weighted In-Degree}(v_i) + \text{Weighted Out-degree}(v_i) = \sum_{v_j \in V} W_{ji} + \sum_{v_j \in V} W_{ij}$$

In this equation, *W* represents the weighted adjacency matrix, with W_{ji} representing incoming edges to v_i (weighted in-degree) and W_{ij} representing outgoing edges from v_i (weighted out-degree) (Brandes, 2001; Latora et al., 2017; Newman, 2018; Wasserman & Faust, 1994). A weighted adjacency matrix is developed by applying the edge weights to each connection. For this model, an edge weight of 10 is applied for all primary hierarchy connections, and an edge weight of 7 is applied for all secondary reporting relationships. Using these edge weights, a sample of the full 462-by-462 weighted matrix is shown below in Figure 13. The weighted matrix is constructed similarly to the adjacency matrix, with the source node depicted in the rows, the target node in the columns, and edges read from left to top. For example, this weighted matrix depicts a primary (weight 10) connection from Node 1 to Node 0 and a secondary (weight 7) connection from Node 6 to Node 4. The weighted in-degree is found by the sum of a node’s column, the weighted out-degree by the sum of the node’s row, and the total weighted degree for any node by combining the weighted in-degree and weighted out-degree.

Source \ Target	0	1	2	3	4	5	6	7	8	9	…	461	Weighted Out-Degree
0	0	0	0	0	0	0	0	0	0	0		0	0
1	10	0	0	0	0	0	0	0	0	0		0	10
2	0	10	0	0	0	0	0	0	0	0		0	10
3	0	10	0	0	0	0	0	0	0	0		0	10
4	0	0	0	10	0	0	0	0	0	0		0	10
5	0	0	10	0	0	0	0	0	0	0		0	10
6	0	0	0	0	7	10	0	0	0	0		0	17
7	0	0	0	0	0	0	10	0	0	0		0	10
8	0	0	0	0	0	0	10	0	0	0		0	10
9	0	0	0	0	0	0	10	0	0	0		0	10
…													
461	0	0	0	0	0	0	0	0	0	0		0	10
Weighted In-Degree	160	50	80	27	61	50	200	10	10	0		0	
Weighted Degree	160	60	90	37	71	60	217	20	20	10		10	

Figure 13 - Subset of Weighted Matrix for Calculation of Weighted Degree

4.3.2 Weighted Degree: Analysis

A complete weighted connectivity matrix for the network is developed to compare and validate the weighted degree outputs obtained from the Gephi software. A graphical summary of the weighted degree distribution from the network is depicted below in Figure 14. The weighted degree distribution looks similar to the previously discussed unweighted degree distribution; however, closer examination of the data reveals that the incorporation

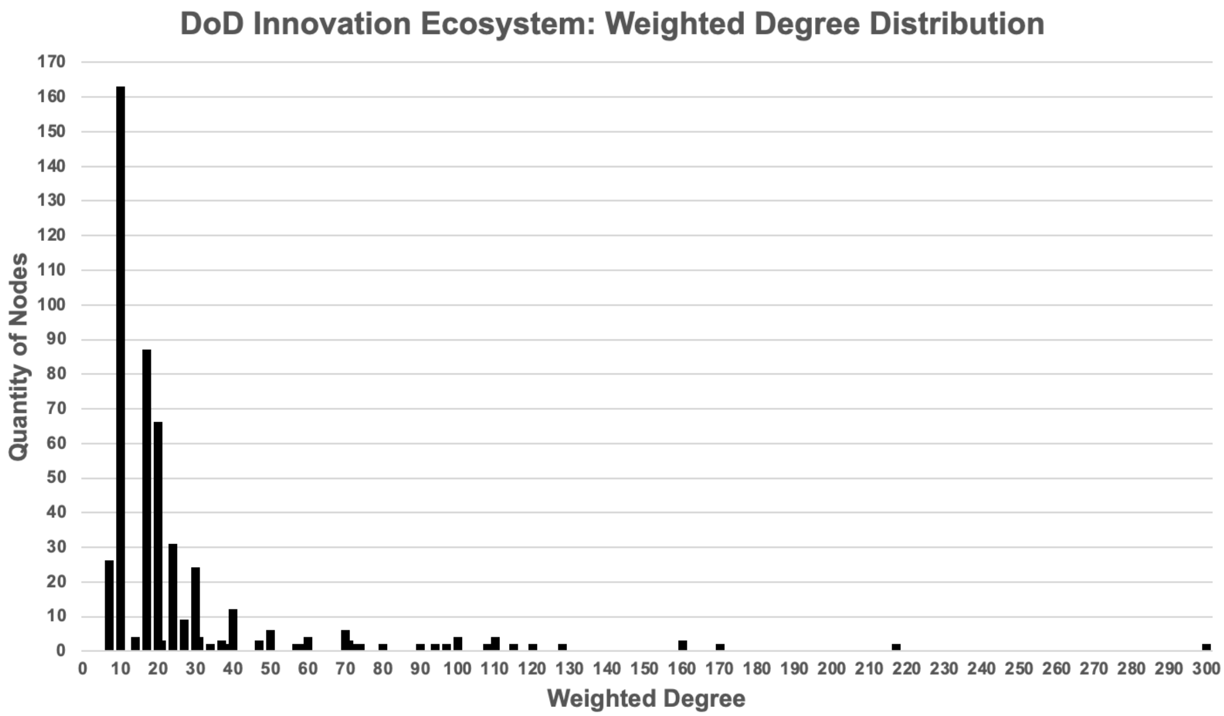

Figure 14 - Distribution of Weighted Degree Scores

of edge weights impacted the top ten nodes. The top ten nodes by their weighted degree score are shown below in Table 6, including several updates from the unweighted degree measure. Namely, two R&D command-level organizations made this weighted degree list, replacing DAF CSO and NSTXL. These two organizations have multiple secondary connections that decreased their ranking. The model includes secondary connections from every DAF Software Factory back to the DAF CSO office, and NSTXL has a secondary connection from each of the nine Microelectronics Commons hub sites.

Table 6 - Top 10 Organizations in the DoD Innovation Ecosystem Model by Weighted Degree of Connectedness

Rank	Organization	Type	Department	Weighted Degree Score
1	OUSD(R&E)/CTO	Governance	DoD	300
2	AFRL	R&D	Air Force	217
3	ONR	R&D	Navy	170
4	ATI	OT Consortia	DoD	160
5	OSD	Governance	DoD	160
6	DoD ManTech	Innovation Org	DoD	128
7	NAVSEA	Governance	Navy	120
8	ASD(S&T)	Governance	DoD	115
9	MRDC	R&D	Army	110
10	DEVCOM	R&D	Army	110

Organization Acronyms: OUSD(R&E)/CTO: Office of the Undersecretary of Defense for Research & Engineering and Chief Technology Officer; AFRL: Air Force Research Laboratory; ONR: Office of Naval Research; ATI: Advanced Technology International; OSD: Office of the Secretary of Defense; DoD ManTech: Department of Defense Manufacturing Technology; NAVSEA: Naval Sea Systems Command; ASD(S&T): Assistant Secretary of Defense for Science & Technology; MRDC: Medical Research and Development Command; DEVCOM: Combat Capabilities Development Command

This analysis identifies the primary centers of influence within the network in terms of their weighted hierarchical connectivity, with the DoD's CTO office remaining central to the DoD Innovation Ecosystem.

4.4 Eigenvector Centrality

4.4.1 Eigenvector Centrality: Overview

The eigenvector centrality assessment is a third measure of node centrality. This calculation on the network seeks to identify nodes of importance not solely based on their direct connections, as in the degree and weighted degree measures, but also by factoring in the importance of the nodes to which it is connected. Under this premise, a node with lower importance gains more prominence when connected to other nodes with high importance in the network. By investigating the degree centrality scores of a node's neighbors through the eigenvector centrality measure, additional insight can be obtained about how the highly influential nodes may impact other nodes in the network rather than looking at each node individually. Mathematically, the eigenvector centrality (C_E) measure can be represented as:

$$\text{Eigenvector Centrality} = C_E(v_i) = \frac{1}{\lambda} \sum_{v_j \in V} A_{ji} C_E(v_j)$$

In this equation, λ represents the dominant eigenvalue of the network and is calculated through a complex linear algebra sequence and, therefore, typically found via statistics software packages. A_{ji} is an entry in the adjacency matrix representing a connection between node v_i and v_j, and the term $C_E(v_j)$ represents that the eigenvector centrality for node v_i is dependent on the other nodes to which it is connected. Since the values for $C_E(v_i)$ and $C_E(v_j)$ affect each other, the process to determine the eigenvector centrality for any node in the network starts with the adjacency matrix and then iterates over it numerous times until the eigenvector centrality values stabilize. The nodes with higher eigenvector centrality scores signify their relative importance to the network when accounting for the importance of their neighboring nodes. To facilitate easier comparison of data across networks of any size, it is also common to normalize the output values to fall between zero and one (Latora et al., 2017; Newman, 2018).

4.4.2 Eigenvector Centrality: Analysis

The built-in algorithm from the Gephi software (Bastian et al., 2023) is applied to the network model to complete an eigenvector centrality assessment of the DoD Innovation Ecosystem. After 5, 10, and 50 iterations on the matrix, the results are examined for stabilized outputs. While minimal change is noted to the output values for each iteration level, the nodes reflecting the highest eigenvector centrality values remain constant. The graph in Figure 15 below summarizes the total output from the eigenvector centrality calculation on the network model after 50 iterations. This scatter plot shows the normalized eigenvector centrality values for all 462 nodes on the X-axis and the quantity of each score on the Y-axis.

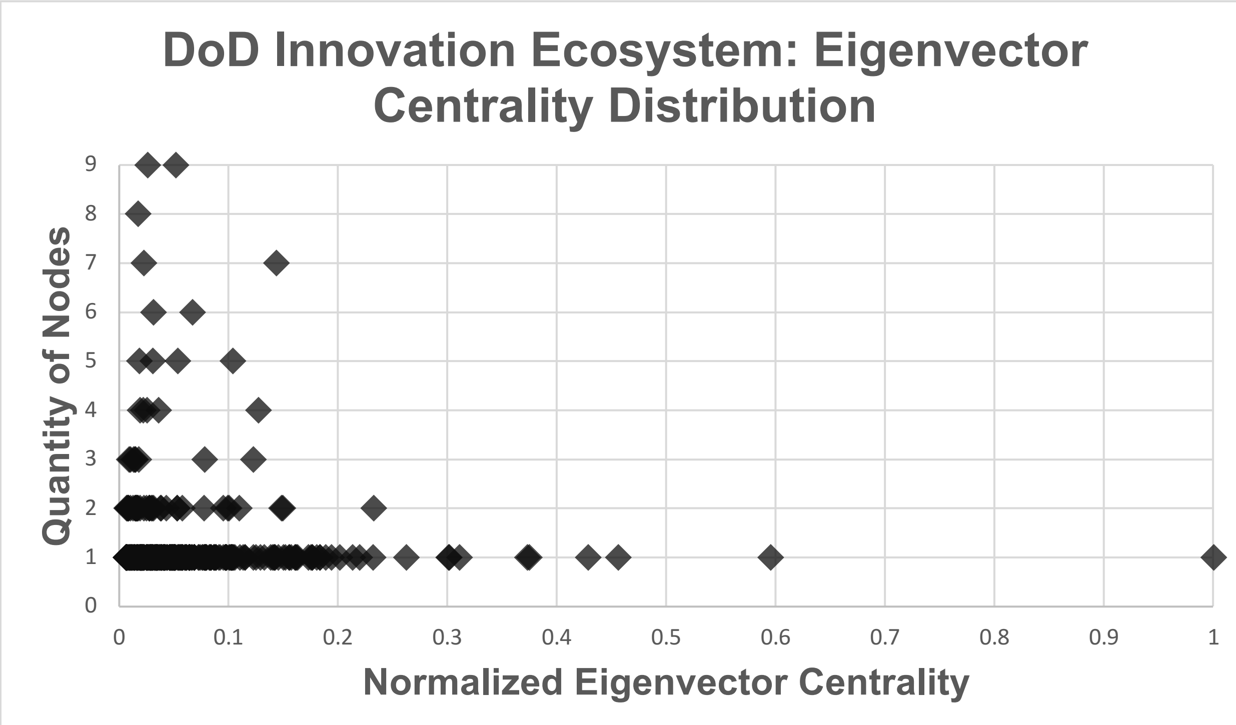

Figure 15 – Distribution of Normalized Eigenvector Centrality Scores

By examining the nodes with the highest eigenvector centrality (lower right portion of Figure 15), the network model includes one clear leader in this category and nine other nodes that stand out from the rest of the network. These top ten nodes in terms of their eigenvector centrality score are summarized in Table 7 below. As in the degree and weighted degree assessments, this network analysis measure identifies the DoD CTO office as the most significant node in the network model. However, the inclusion of the strength of neighbors in this assessment had a clear impact on the remainder of the top ten list. AFRL and CNO remain the only R&D organizations on the list, and DoD ManTech remains the only office labeled as an "innovation organization" on the list. Further, this assessment elevated several OT Consortia organizations in the rankings. As the DoD's organization responsible for managing the OT agreements (Mak, 2022), the CTO's influence as a strong neighbor to the OT Consortia organizations explains this rise.

Further, the model includes a primary linkage from each OT Consortia to their primary DoD sponsor and a secondary connection to the OT management company. This aspect of the model creates a strongly connected sub-hierarchy within the ecosystem that influences the outcome of this eigenvector centrality assessment.

Table 7 - Top 10 Organizations in the DoD Innovation Ecosystem Model by Normalized Eigenvector Centrality

Rank	Organization	Type	Department	Normalized Eigenvector Centrality Score
1	OUSD(R&E)/CTO	Governance	DoD	1
2	ATI	OT Consortia	DoD	0.595557665
3	OSD	Governance	DoD	0.456078704
4	ASD(S&T)	Governance	DoD	0.42848063
5	AFRL	R&D	Air Force	0.374811104
6	NSTXL	OT Consortia	DoD	0.372776658
7	DoD ManTech	Innovation Org	DoD	0.310747433
8	NAC	OT Consortia	DoD	0.30152904
9	ONR	R&D	Navy	0.301026531
10	SOSSEC, Inc.	OT Consortia	DoD	0.262145721

Organization Acronyms: OUSD(R&E)/CTO: Office of the Undersecretary of Defense for Research & Engineering and Chief Technology Officer; ATI: Advanced Technology International; OSD: Office of the Secretary of Defense; ASD(S&T): Assistant Secretary of Defense for Science & Technology; AFRL: Air Force Research Laboratory; NSTXL: National Security Technology Accelerator; DoD ManTech: Department of Defense Manufacturing Technology; NAC: National Armaments Consortium; ONR: Office of Naval Research; SOSSEC, Inc: System of Systems Enterprise Consortium, Incorporated

Each of these node centrality assessments produces different results for the top ten most central nodes in the DoD Innovation Ecosystem model. In the following two sections, the analysis extends to the node connectivity through betweenness and closeness centrality to obtain additional information from the ecosystem model.

4.5 Betweenness Centrality

4.5.1 Betweenness Centrality: Overview

The betweenness centrality analysis seeks to determine the importance of any node in a network by investigating its tendency to be on the shortest path between other nodes in the network. Following the mathematical notation established in the previous sections, as well as interpretations of the centrality formula representations by Brandes (2001), Wasserman & Faust (1994), Latora et al. (2017), and Newman (2018), a path between any starting node, *s,* and terminal node, *t*, is any progression of nodes and edges to flow through the network to connect node *s* to node *t*. The length of any path is determined by summing the edge weights along the path, and the distance between nodes *s* and *t* is determined by finding the minimum path length that connects these two nodes in the network. The following network example in Figure 16 ensures clarity in this terminology. In this example network, one possible path between starting node E and terminal node C is E-D-A-B-C. Assuming all edges have equal weights, this equates to a path length of four. However, an alternate and shorter path between nodes E and C is E-B-C, with a length of only two. Therefore, the distance, or shortest path, from node E to node C in this example is two.

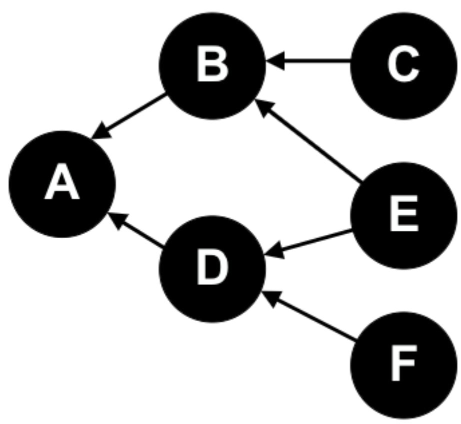

Figure 16 - Sample Network Diagram for Network Path Terminology

Building on this notation, the total number of shortest paths between any nodes *s* and *t* can be denoted as σ_{st}, with $\sigma_{st}(v)$ representing the number of shortest paths on which some node *v* in the complete set of nodes *V* lies. A node that lies on the largest quantity of shortest paths in the network must, therefore, be central to the network in terms of importance or influence and is measured as the node's betweenness centrality.

Mathematically, the betweenness centrality (C_B) for any node *v* in the set of nodes *V* can be represented as:

$$\text{Betweenness Centrality} = C_B(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

Since the betweenness assessment is a measure of how often a node falls on the shortest path between all other pairs of nodes, the bottom of the summation formula includes the caveat that this equation ignores any instances where node *v* is on the start or end of any shortest path length. Further, the results of this betweenness calculation are generally normalized to fall between zero and one to aid with interpretability and control for the network size (Brandes, 2001; Latora et al., 2017; Wasserman & Faust, 1994).

4.5.2 Betweenness Centrality: Analysis

Due to the complexity involved in determining and normalizing the betweenness centrality scores for this network, this research utilized the algorithm contained in the Gephi software (Bastian et al., 2023) to obtain the normalized betweenness centrality scores for the DoD Innovation Ecosystem model. For the 462 nodes in the network model, 192 nodes reported a betweenness centrality score of 0, indicating that they lie on the exterior of the network graph with no instances where the node lies on the shortest path between two other nodes. This value is higher than the 187 nodes stated previously to lie at the exterior of the network with a degree of connectedness score of 1 (Figure 12). Further analysis of these five additional nodes with betweenness centrality scores of zero reveals that they each contain primary and secondary out-connections but no in-connections. This construct equates to an in-degree score of zero and reinforces the betweenness centrality score of zero. A summary of the output for the remaining 270 nodes with non-zero betweenness centrality scores is summarized in Figure 17 below, with the scores on the X-axis and quantity along the Y-axis.

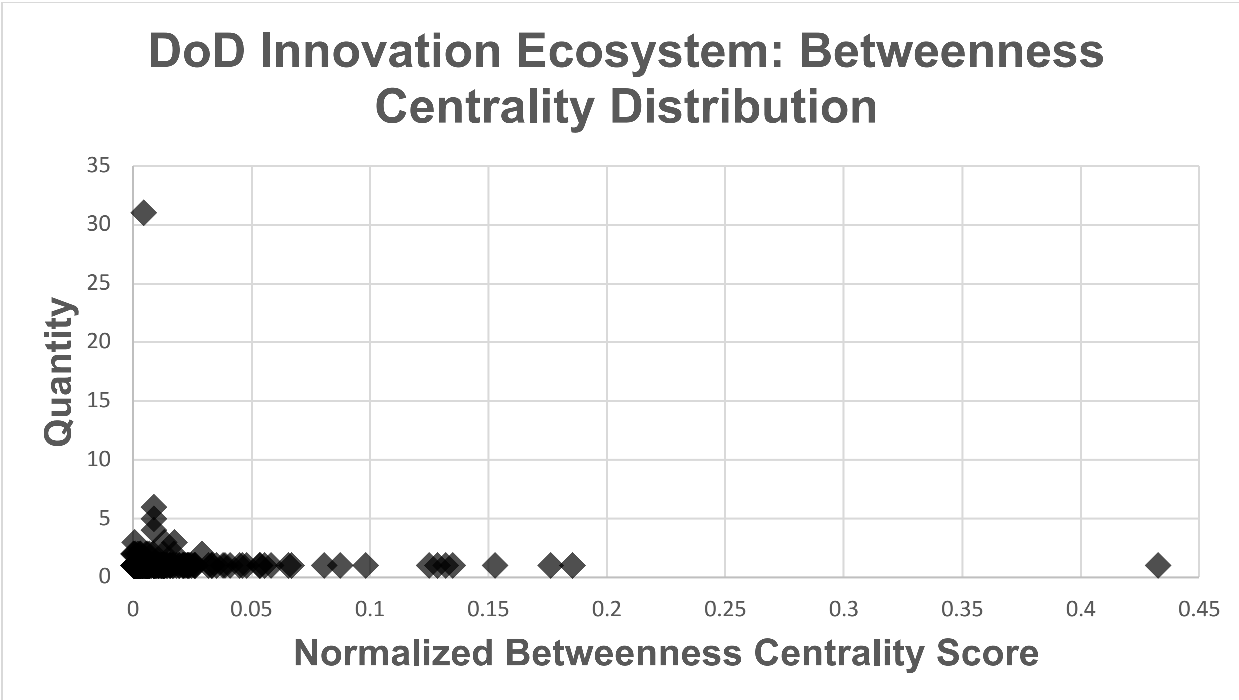

Figure 17 - Distribution of Normalized Betweenness Centrality Scores

Further examination of this output reveals similar results to previous assessments, with a clear leader and a handful of other organizations separated from the rest of the network (lower right of the graph). These standout organizations serve as hierarchical bridges for the network construction as most of the shortest path routes through the network go through them. The top 10 nodes in terms of their betweenness centrality score are summarized in Table 8 below.

Although not in the same order, the results of the betweenness centrality assessment are relatively aligned with the previous analyses, with the DoD's CTO office remaining at the top of each list. Additionally, this measure of centrality places more relative importance on the organizations at the top of their respective hierarchical branches, which explains the appearance of the lead offices for the three primary military service departments (Air Force, Navy, and Army). Another organization that rose in importance through this assessment, which is not highlighted by the prior analysis, is SOSSEC, Inc. This company is an OT Consortia management organization similar to ATI.

It was also interesting to note that AFRL is the only R&D organization to make the list, while no organizations in the model labeled "innovation organizations" make it.

Table 8 - Top 10 Organizations in the DoD Innovation Ecosystem Model by Normalized Betweenness Centrality

Rank	Organization	Type	Department	Normalized Betweenness Centrality Score
1	OUSD(R&E)/CTO	Governance	DoD	0.450312297
2	OSD	Governance	DoD	0.432583106
3	DAF	Governance	Air Force	0.185358428
4	DON	Governance	Navy	0.176291323
5	AFRL	R&D	Air Force	0.152766974
6	USA	Governance	Army	0.135012363
7	SOSSEC, Inc.	OT Consortia	DoD	0.131954508
8	ASD(S&T)	Governance	DoD	0.128415556
9	ATI	OT Consortia	DoD	0.124872936
10	USAF	Governance	Air Force	0.098275

Organization Acronyms: OUSD(R&E)/CTO: Office of the Undersecretary of Defense for Research & Engineering and Chief Technology Officer; OSD: Office of the Secretary of Defense; DAF: Department of the Air Force; DON: Department of the Navy; AFRL: Air Force Research Laboratory; USA: United States Army; SOSSEC, Inc: System of Systems Enterprise Consortium, Incorporated; ASD(S&T): Assistant Secretary of Defense for Science & Technology; ATI: Advanced Technology International; USAF: United States Air Force

The betweenness centrality assessment results indicate the breadth of innovation organizations spread throughout the DoD and the high degree of hierarchy present in the ecosystem rather than a dedicated innovation chain of command.

4.6 Closeness Centrality

4.6.1 Closeness Centrality: Overview

The closeness centrality is the final measure of this organizational network analysis. While the betweenness centrality seeks the frequency at which a node is located on the shortest path between two other nodes, the closeness centrality measures the average of the shortest paths for a node to all other nodes in the network. This data represents how quickly a node can reach any other node in the network, thereby signifying the nodes with the greatest ability to affect the network with minimal time or resources.

To determine the closeness centrality score of any node *v* in the set of nodes *V*, the formula quantifies the average length of the shortest paths to all other nodes. Mathematically, the closeness centrality (C_C) can be represented as:

$$\text{Closeness Centrality} = C_C(v_i) = \frac{1}{\sum_{v_i \neq j} d(v_i, v_j)}$$

In this equation, $d(v_i, v_j)$ represents the shortest path distance between nodes v_i *and* v_j. The farness of the node is represented by the sum of this distance from all other nodes, and the closeness is the reciprocal of the farness measure. When determining the closeness centrality, the nodes with the smallest values equate to the nodes most central to the network due to their smaller average distance to reach all other nodes. However, it is common to normalize the scores for easier comparison across networks of varying sizes. When normalized, the closeness centrality scores follow the convention of the previous analyses, where a higher score reflects nodes with more importance in the network (Brandes, 2001; Newman, 2018; Wasserman & Faust, 1994).

4.6.2 Closeness Centrality: Analysis

As in previous assessments, the closeness centrality scores for the DoD Innovation Ecosystem model were obtained via the built-in algorithm from the Gephi software (Bastian et al., 2023). A depiction of the distribution of the normalized closeness centrality assessment is shown below in Figure 18. This scatter plot includes all 462 nodes and graphs their closeness centrality score on the X-axis and the quantity that each score appears on the Y-axis. Although the distribution does not identify standout organizations as clearly as previous analyses, the distribution graph includes two standout organizations (lower right portion of the graph) and several other organizations with higher closeness centrality scores than most of the network.

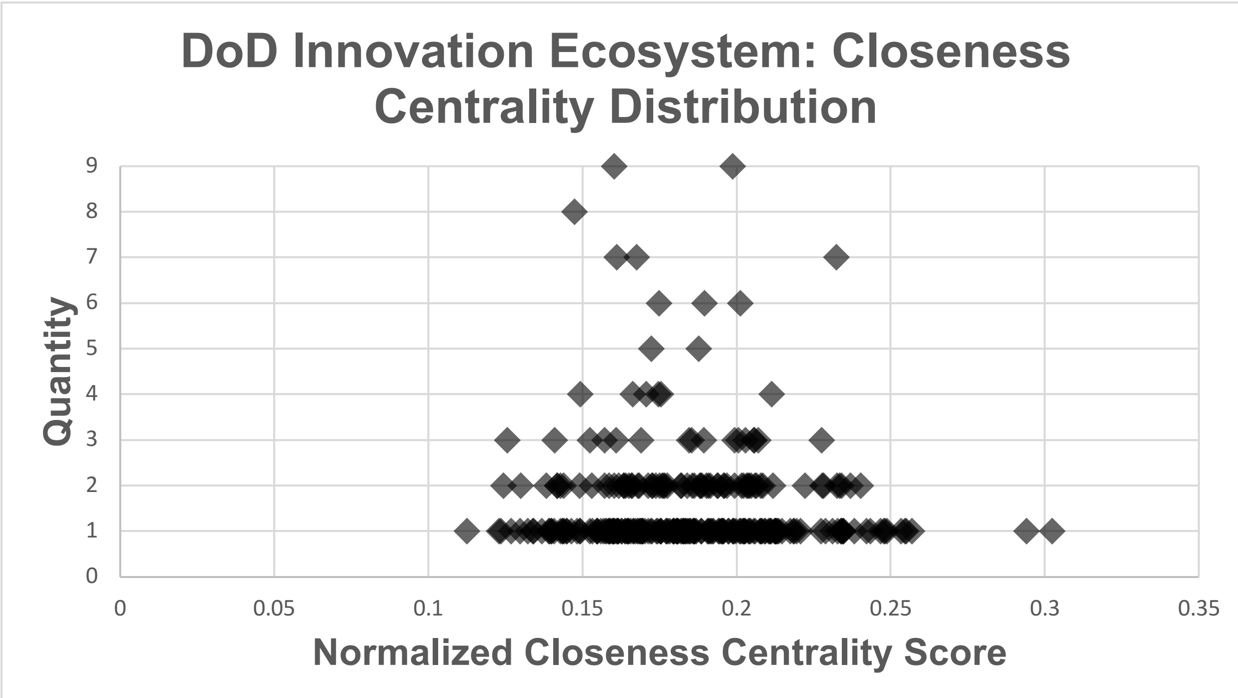

Figure 18 - Distribution of Normalized Closeness Centrality Scores

More details on the top ten organizations in terms of their closeness centrality score are contained below in Table 9. Several of the same organizations that surfaced through the previous analyses appear on this list, with OSD as the lead DoD governance organization joining the DoD CTO at the top. However, this analysis reveals a few other noteworthy takeaways, with the DefenseWerx organization making its first appearance at the top of the rankings and no R&D organizations on the list. In this analysis, DefenseWerx joins DoD ManTech as the only offices labeled as "innovation organizations" in the model to make the list. This ranking makes sense due to their position in their respective innovation chains of command and proximity to the lead DoD governance offices at the Pentagon. Further, DefenseWerx has ties to multiple innovation hubs, including the Air Force's Doolittle Institute, the Navy's Nautilus organization, the U.S. Special Operations Command SOFWERX office, and the Army's ERDCWERX and Cyber Fusion Innovation Center (CFIC) offices.

Table 9 - Top 10 Organizations in the DoD Innovation Ecosystem Model by Normalized Closeness Centrality

Rank	Organization	Type	Department	Normalized Closeness Centrality Score
1	OUSD(R&E)/CTO	Governance	DoD	0.302295082
2	OSD	Governance	DoD	0.294005102
3	SOSSEC, Inc.	OT Consortia	DoD	0.256824513
4	DAF	Governance	Air Force	0.254977876
5	ASD(S&T)	Governance	DoD	0.254415011
6	ATI	OT Consortia	DoD	0.253157606
7	NSTXL	OT Consortia	DoD	0.248651564
8	DON	Governance	Navy	0.247982786
9	DoD ManTech	Innovation Org	DoD	0.247583244
10	DefenseWerx	Innovation Org	DoD	0.246655966

Organization Acronyms: OUSD(R&E)/CTO: Office of the Undersecretary of Defense for Research & Engineering and Chief Technology Officer; OSD: Office of the Secretary of Defense; SOSSEC, Inc: System of Systems Enterprise Consortium, Incorporated; DAF: Department of the Air Force; ASD(S&T): Assistant Secretary of Defense for Science & Technology; ATI: Advanced Technology International; NSTXL: National Security Technology Accelerator; DON: Department of the Navy; DoD ManTech: Department of Defense Manufacturing Technology

The closeness centrality assessment seeks to identify the nodes with the shortest average distance to all other nodes in the network. Therefore, the nodes identified in this analysis are those that could most quickly reach any other node in the network. Given their respective roles in the DoD Innovation Ecosystem, the nodes that topped the closeness centrality list make sense logically.

4.7 Centrality Summary

The five centrality measures utilized in this chapter provide different perspectives on the nodes within the DoD Innovation Ecosystem model that are most critical to the ecosystem. In isolation, each measure seeks to obtain different information from the model but does not offer a consolidated perspective on the most influential organizations. Therefore, this section aims to highlight the consolidated total ranking of organizations across these five centrality measures. The ranked lists contain ordinal data, so the Borda

Count method, common in ranked vote tallying, is used to consolidate the rankings (Saari, 1985). Using the Borda Count method, a score is applied for each ranking with a maximum of 462 points for each #1 ranking, down to 1 point for an organization ranked at #462. This scoring is applied for each of the five ranked lists to determine an overall Borda Count score, with the highest Borda Count score equating to the top-ranked organization following all five assessments. A consolidated summary of the top 10 organizations in terms of their overall centrality ranking is contained in Table 10 below.

Table 10 - Consolidated Top 10 Central Organizations in the DoD Innovation Ecosystem Model by Borda Count Ranking

				Centrality Score Ranking					
Overall Rank	**Organization**	**Type**	**Department**	**C_D**	**C_W**	**C_E**	**C_B**	**C_C**	**Borda Count**
1	OUSD(R&E)/CTO	Governance	DoD	1	1	1	1	1	2310
2	OSD	Governance	DoD	5	4	3	2	2	2299
3	ATI	OT Consortia	DoD	2	4	2	9	6	2292
4	ASD(S&T)	Governance	DoD	5	8	4	8	5	2285
5	DoD ManTech	Innovation Org	DoD	8	6	7	13	9	2272
6	NSTXL	OT Consortia	DoD	9	17	6	11	7	2265
7	USA	Governance	Army	11	9	16	6	11	2262
8	DON	Governance	Navy	14	13	15	4	8	2261
9	SOSSEC, Inc.	OT Consortia	DoD	14	21	10	7	3	2260
10	AFRL	R&D	Air Force	2	2	5	5	62	2239

Organization Acronyms: OUSD(R&E)/CTO: Office of the Undersecretary of Defense for Research & Engineering and Chief Technology Officer; OSD: Office of the Secretary of Defense; ATI: Advanced Technology International; ASD(S&T): Assistant Secretary of Defense for Science & Technology; DoD ManTech: Department of Defense Manufacturing Technology; NSTXL: National Security Technology Accelerator; USA: United States Army; DON: Department of the Navy; SOSSEC, Inc: System of Systems Enterprise Consortium, Incorporated; AFRL: Air Force Research Laboratory

As stated in the individual assessment sections, the DoD CTO is the clear central leader within the DoD Innovation Ecosystem hierarchy. The DoD CTO received #1 rankings from each centrality assessment, resulting in the highest possible Borda Count score (462 x 5 = 2310). With the OSD governance role for the rest of the DoD and their place at the top of the organizational hierarchy, it makes sense that this office appears in the number two spot. Further, with the number of nodes and primary and secondary linkages associated with the OT Consortia hierarchy, it makes sense that the three leading OT Consortia management organizations are on this list (ATI, NSTXL, and SOSSEC, Inc.).

It can also be noted that the number of governance organizations in this list overshadows the innovation and R&D organizations. In order to understand where these innovation and R&D organizations landed in terms of their consolidated centrality ranking, Tables 11 and 12 below provide a summary of the top five innovation and R&D organizations, respectively, in terms of their overall Borda Count scores.

Table 11 - Top 5 Central Innovation Organizations in the DoD Innovation Ecosystem Model by Borda Count Ranking

				Centrality Score Rankings					
Overall Rank	**Organization**	**Type**	**Department**	C_D	C_W	C_E	C_B	C_C	**Borda Count**
1	DoD ManTech	Innovation Org	DoD	8	6	7	13	9	2272
2	DefenseWerx	Innovation Org	DoD	20	32	14	16	10	2223
3	Navy ManTech	Innovation Org	Navy	20	20	17	44	60	2154
4	DIU	Innovation Org	DoD	59	59	103	50	39	2005
5	AFWERX	Innovation Org	Air Force	20	22	51	26	237	1959

Organization Acronyms: DoD ManTech: Department of Defense Manufacturing Technology; Navy ManTech: Navy Manufacturing Technology; DIU: Defense Innovation Unit

Table 12 - Top 5 Central R&D Organizations in the DoD Innovation Ecosystem Model by Borda Count Ranking

				Centrality Score Rankings					
Overall Rank	**Organization**	**Type**	**Department**	C_D	C_W	C_E	C_B	C_C	**Borda Count**
1	AFRL	R&D	Air Force	2	2	5	5	62	2239
2	ONR	R&D	Navy	4	3	9	12	77	2210
3	DARPA	R&D	DoD	25	24	18	32	24	2192
4	DEVCOM	R&D	Army	11	9	50	24	159	2062
5	MRDC	R&D	Army	11	9	65	22	174	2034

Organization Acronyms: AFRL: Air Force Research Laboratory; ONR: Office of Naval Research; DARPA: Defense Advanced Research Projects Agency; DEVCOM: U.S. Army Combat Capabilities Development Command; MRDC: U.S. Army Medical Research Development Command

It is interesting to note the spread of organizational representation across these two lists, with the presence of organizations sponsored by the DoD and each of the three military service departments. This representation highlights that while the DoD may dominate the ecosystem in terms of oversight and governance, the presence of innovation and R&D is spread throughout the DoD, with no specific department dominating the innovation space.

This assessment provides an interesting insight into the DoD Innovation Ecosystem model, and the results are consistent with the underlying DoD hierarchy in terms of the organizations appearing at the top of the rankings. However, it is not clear which of the five centrality assessments best correlates to the overall ranking. The degree of correlation between the individual assessment rankings and the consolidated ranking can be determined using Spearman's rank-order correlation. This statistical measure is appropriate for correlated ordinal data. To determine the Spearman's rank correlation (r_s) for each of the five centrality measures, the following formula is applied to the rankings, where d_i denotes the difference between a centrality ranking and the final Borda Count ranking for each organization, and n denotes the number of samples, or the total number of nodes in the network in this case (Mukaka, 2012):

$$\text{Spearman's Rank Correlation} = r_s = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)}$$

A summary of the Spearman's rank correlation values obtained for each measure of centrality is included in Table 13 below, with the recognized convention of a Spearman correlation coefficient between 0.70 and 0.90 indicating high correlation, and 0.90 to 1.00 equating to very high correlation (Mukaka, 2012). With r_s = 0.901, this assessment indicates that the Eigenvector Centrality is very highly correlated to the consolidated ranking and is the best predictor for the overall centrality ranking in this model.

Table 13 - Spearman's Rank Correlation Coefficients for Five Centrality Measures

Measure	**Spearman's Rank Correlation Coefficient**
Degree Centrality	0.759
Weighted Degree Centrality	0.815
Eigenvector Centrality	0.901
Betweenness Centrality	0.802
Closeness Centrality	0.819

4.8 Modularity Assessment

As the final organizational network analysis method used in this analysis, modularization seeks to identify the emergence of network clusters based on the underlying connectivity structure. A modularity assessment seeks to cluster the nodes to maximize the connections within modules while minimizing connections between modules (Newman, 2018). The Gephi software includes a built-in modularization function based on the Blondel (2008) modularity optimization formula. The output includes a modularity score ranging from -1 to 1, with positive values signifying the presence of modules for non-random networks. As the modularity score approaches positive one, it signifies that more substantial community structures exist in the network.

Using the baseline software parameters, the modularity function identifies 15 communities in the model, ranging in size from 16 to 48 nodes per module, with a resulting modularity score of 0.789. By adjusting the input parameters to reduce the number of communities, the software outputs a revised module structure with seven communities and a modularity score of 0.715. Five of these seven communities range in size from 22 to 49 nodes per cluster, with the remaining communities containing significantly more, with 131 and 140 nodes. This revised analysis obtains a community quantity that aligns with the seven organizational alignment categories in the model while maintaining a similar modularity score. This adjustment enables a side-by-side comparison of the existing hierarchy and the results of the modularization function. Upon review of the results, it can be noted that the software identifies significant communities that predominantly follow existing organizational boundaries, with a few exceptions. The generalized breakout of communities is summarized in Table 14 below. These descriptions generally describe the module alignment but do not align with the described boundaries in all cases. For example, Module 6 includes most U.S. Army R&D organizations but also includes the DoD's Society of Automotive Engineers Industry Technology Consortium (SAE-ITC) and the New Jersey Innovation Institute (NJII).

Table 14 - Generalized Summary of Modularization Assessment

Module	Description	Quantity of Nodes
1	DoD R&E, FFRDCs, UARCs, and Navy R&D	140
2	Department of the Air Force	131
3	DoD, DOE, and CCMDs	49
4	U.S. Army Operations and DoD MIIs	49
5	Department of the Navy	37
6	U.S. Army R&D	33
7	Microelectronics Commons	23

In summary, this chapter presents the results of the organizational network analysis of the DoD Innovation Ecosystem model. The next chapter applies these analytical results to alter the model appearance by adjusting the node sizes, colors, and layout to seek new insights.

Chapter 5

Data Visualization

This chapter returns to the model developed in Chapter 3 to make visual alterations based on the organizational network analysis from Chapter 4, including visual modifications based on each of the five network centrality measures, how the centrality assessment impacts the geographical layout, and a visual analysis of the network based on the modularity assessment.

5.1 Degree and Weighted Degree Centrality Visualization

As the first visualization update to the model, the node sizing is updated based on the degree and weighted degree centrality assessment results, where a higher degree score results in a larger node size. Figure 19 below reflects the revised model representation based on sizing the nodes on the degree centrality score, and Figure 20 uses the weighted degree centrality score. These figures use the same organizational alignment color scheme established in Figure 7 for consistency and comparison. The network layout for these representations of the model is updated slightly from Figure 7 as a result of the adjusted node sizing and to avoid overlap. However, the node placement is kept relatively aligned with the prior representation to enable a side-by-side comparison of these figures.

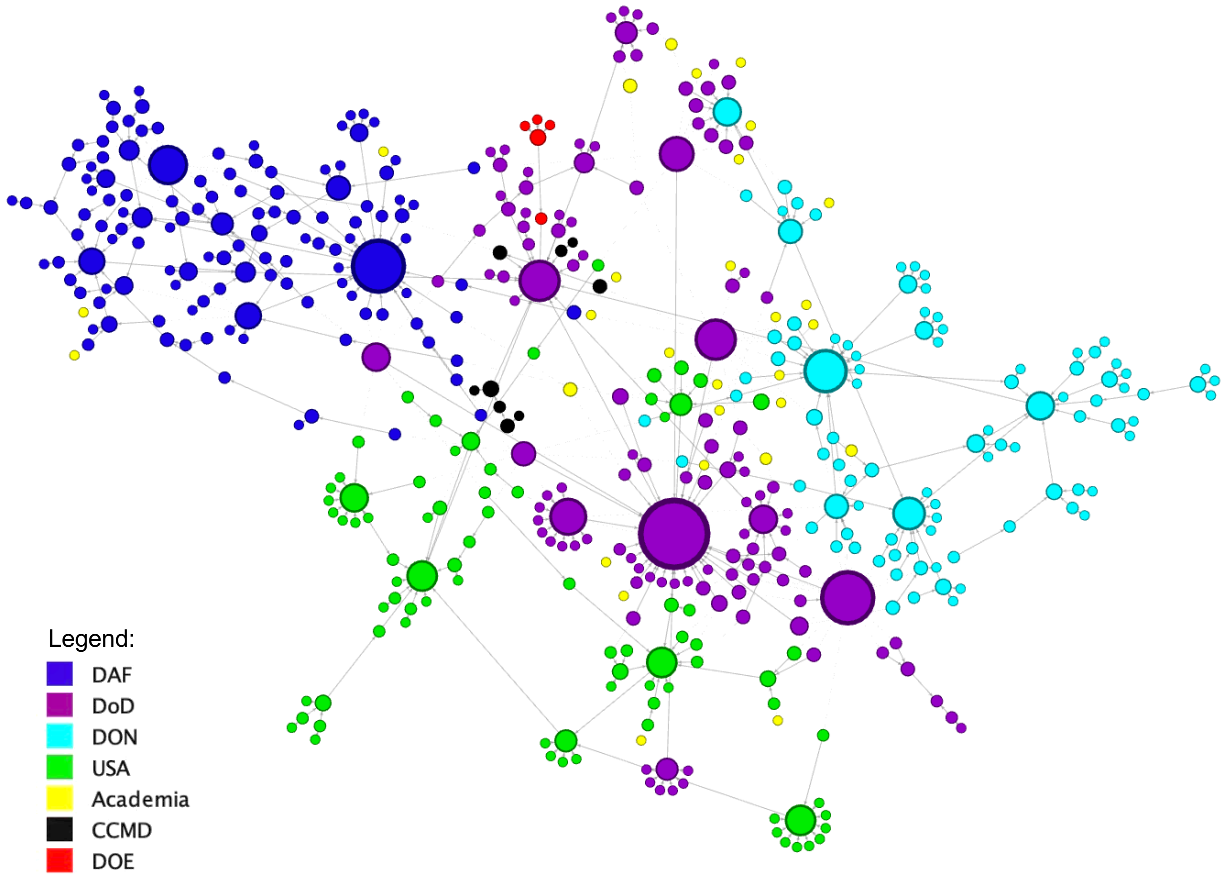

Figure 19 - Updated Node Size for Degree Centrality – Nodes Colored by Organizational Alignment

While this node size alteration is repeated for both the degree and weighted degree scores, the outputs only differed slightly for a small number of nodes. The red arrows in Figure 20 highlight the top five nodes most affected, which include the following organizations: ATI, SOSSEC, Inc., ASD(S&T), NSTXL, and the DAF CSO. This finding is consistent with the differences in the top ten rankings between the degree (Table 5) and weighted degree (Table 6) scores. It reflects the impact of secondary connections within the network rather than treating all connections equally.

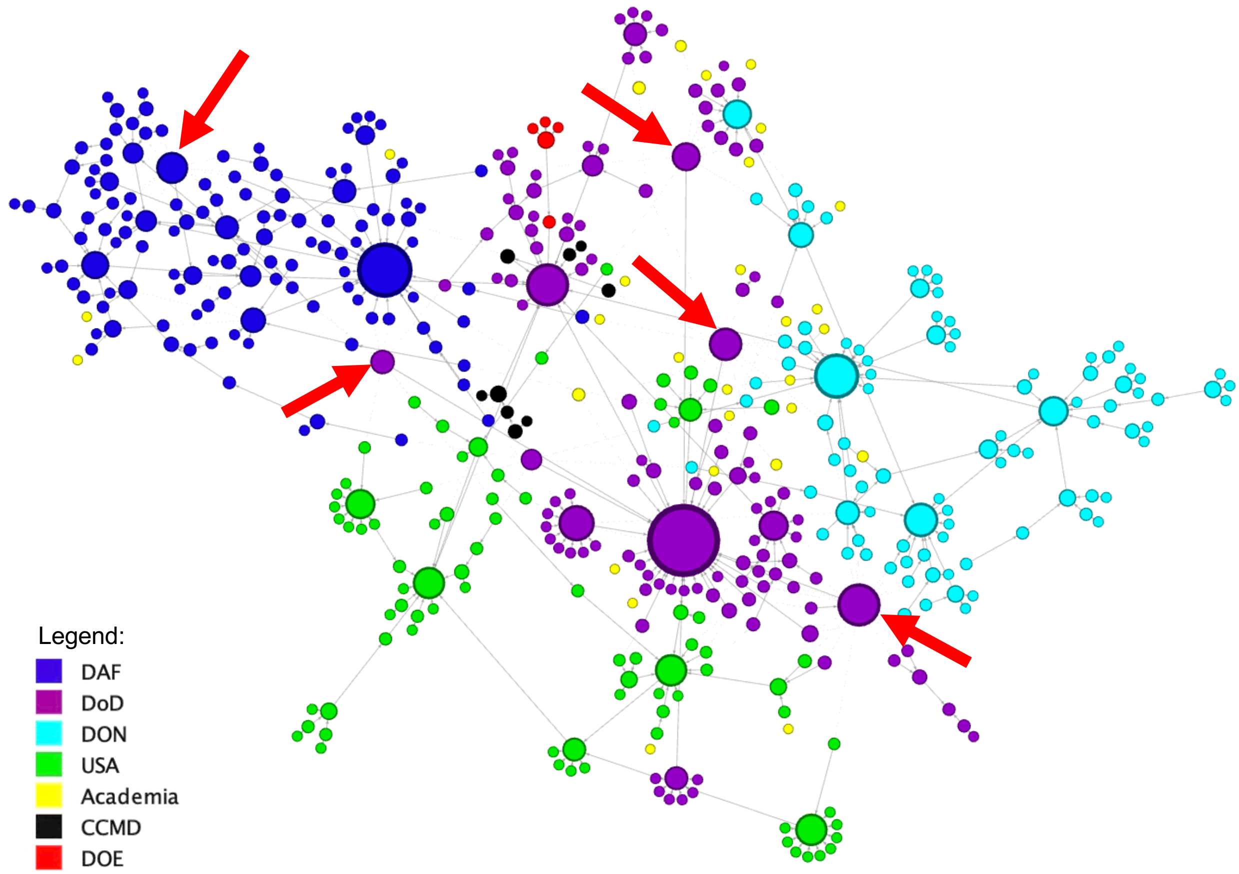

Figure 20 - Updated Node Size for Weighted Degree Centrality – Nodes Colored by Organizational Alignment

Although there is a minimal difference between Figures 19 and 20, these representations significantly improve the model from the view provided in Figure 7. By revising the model based on the degree and weighted degree centrality, the DoD CTO office, the large purple node in the bottom center of Figures 19 and 20, can be clearly seen as a central node to the network. Further, this node-sizing methodology allows for an updated visualization of the organizational hierarchy. The green nodes at the bottom of Figures 19 and 20 are the U.S. Army organizations, which reflect a more centralized command structure than the Department of the Air Force and the Department of the Navy. The U.S. Army command structure shows more consolidation at the organizational tiers, with several offices reporting through these hubs. Lastly, the revised sizing shows the connectivity to the hierarchical governance structure of the DoD offices more prominently.

The DoD is the second largest in terms of the number of nodes in the ecosystem and is central to the ecosystem's connectivity, which is evidenced by the number of large-sized purple nodes.

5.2 Eigenvector Centrality Visualization

The next visual alteration to the model looks at the impact of node sizing based on the results of the eigenvector centrality assessment. Recall from Chapter 4 that this centrality measure best represents the overall combined centrality ranking from the five assessments, with a Spearman's rank correlation coefficient of 0.901. Therefore, several explorations of the model using the results of this analysis.

Using the results of the eigenvector centrality assessment to drive the node sizing, with a higher centrality score equating to larger nodes, the resulting network model visualization is shown below in Figure 21. This visual alteration offers a different perspective on the network. Recall that this measure of centrality identifies nodes of importance not solely based on direct connections but also by factoring in the importance of connected nodes. With the DoD CTO, which is the largest purple node in the center of the network, reflecting such a high eigenvector centrality score, this raises the importance of the nodes to which it is connected. Looking at the series of other DoD offices in purple surrounding the DoD CTO office, their node sizing is starkly different from what is shown by modeling the degree and weighted degree scores in Figures 19 and 20, respectively. This visualization also significantly reduces the node sizing of the three military services, which are negatively impacted in this assessment by their more immediate connections to the nodes at the network's periphery. Therefore, this assessment emphasizes the underlying governance structure that supports the ecosystem rather than the innovation and R&D organizations that fall at the end of the hierarchical chains.

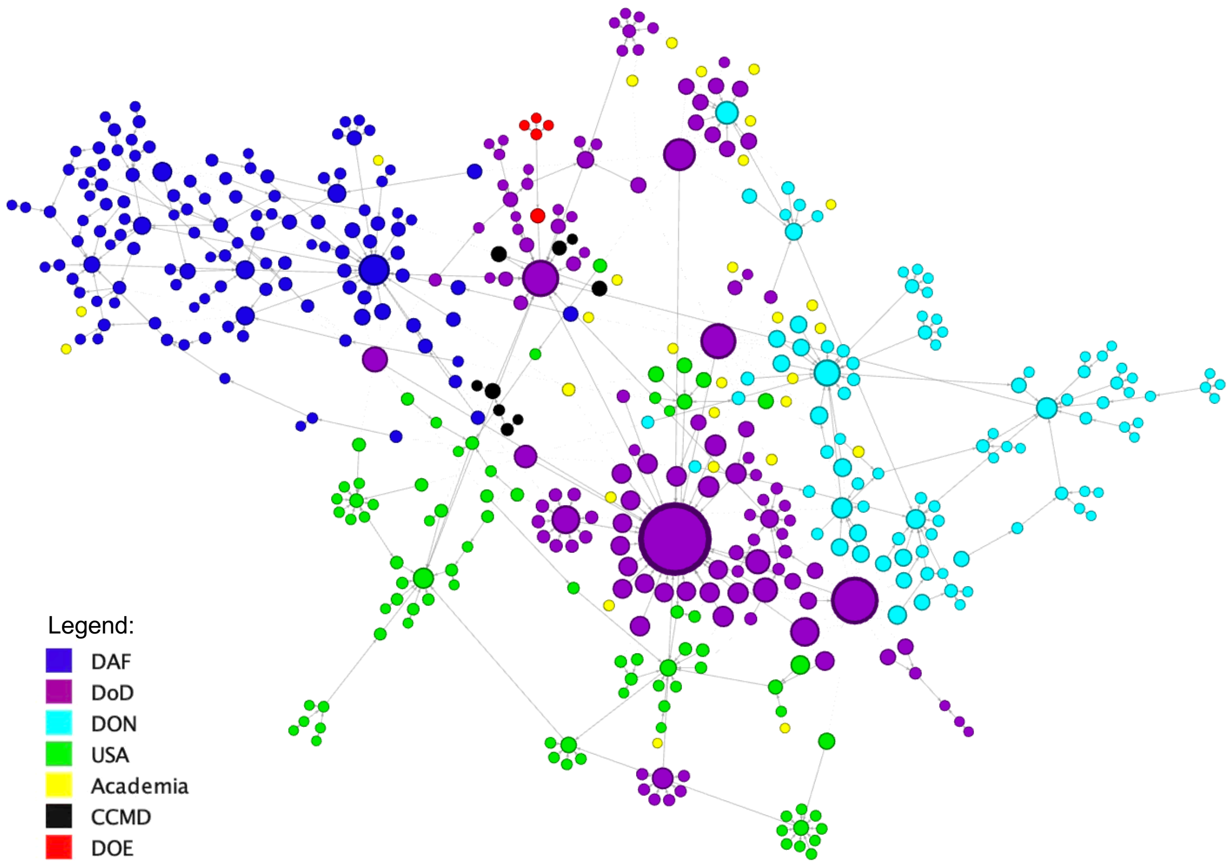

Figure 21 - Updated Node Size for Eigenvector Centrality – Nodes Colored by Organizational Alignment

This finding can be seen more clearly by coloring the nodes based on a gradient scale reflecting their eigenvector centrality score. In Figure 22 below, red signifies a higher eigenvector centrality score, and green signifies a lower score. It is evident when looking at this visualization of the model that the eigenvector centrality score highlights the nodes central to the network that are connected to other nodes with high importance. The non-green nodes in this visualization represent those organizations captured in Table 7, which lists the top ten organizations in the network model in terms of their eigenvector centrality scores.

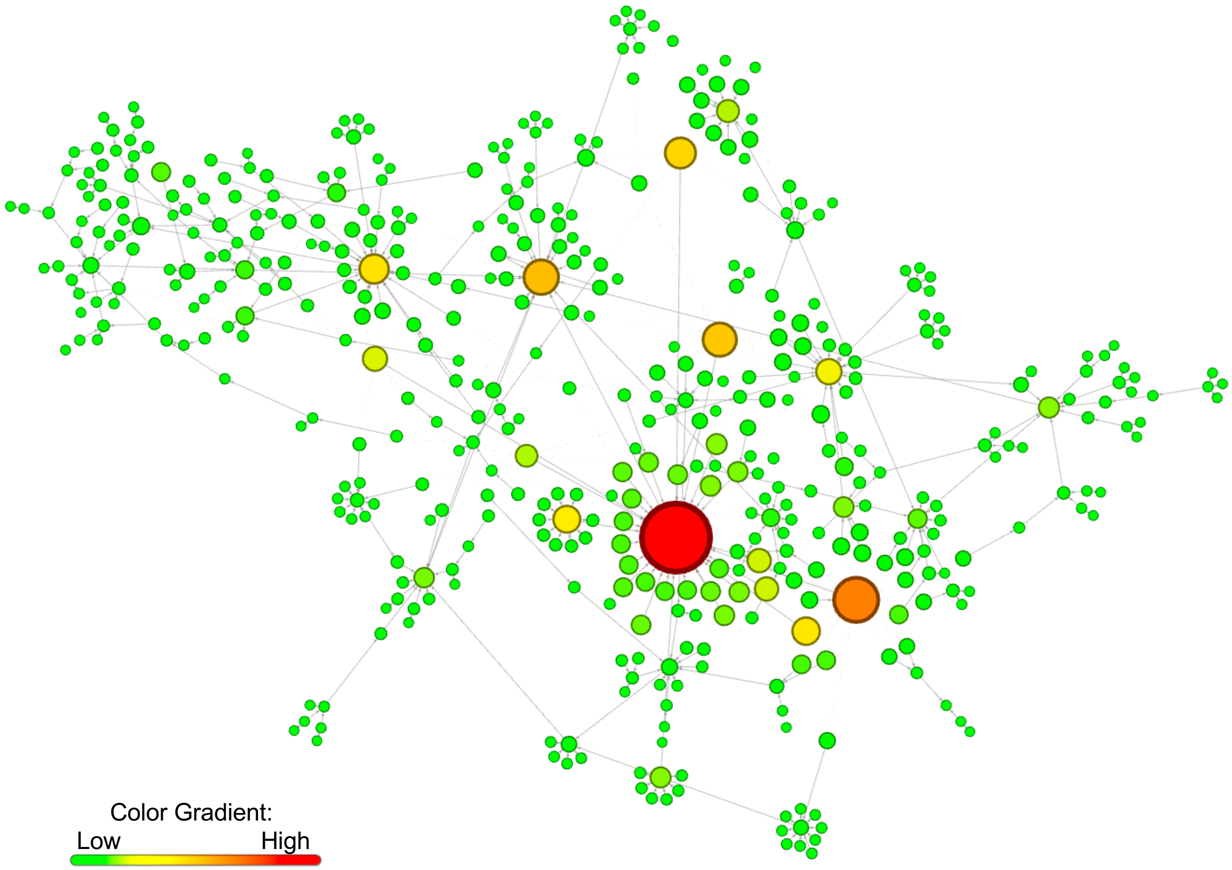

Figure 22 - Updated Node Size for Eigenvector Centrality – Nodes Colored by Centrality Score

Using the eigenvector centrality scores to size the nodes, it is also helpful to highlight several organizational communities within the network that highly influence this analysis based on their hierarchical structure. The first of these sub-networks that are highly connected hierarchically is the OT Consortia. Figure 23 below highlights the OT Consortia organizations in red, while all other organizational types are grayed out. Using this color scheme, the size and centrality of the OT Consortia in terms of hierarchical connectivity can be seen more clearly. The OT Consortia influence on the model is due in part to the overall consortia management through DoD offices but also due to the use of primary connections to the primary DoD sponsor and secondary connections to the consortium management company. This construct represents reality in terms of the hierarchical relationships, but it also likely results in the elevation of this sub-network in terms of the eigenvector centrality score rankings.

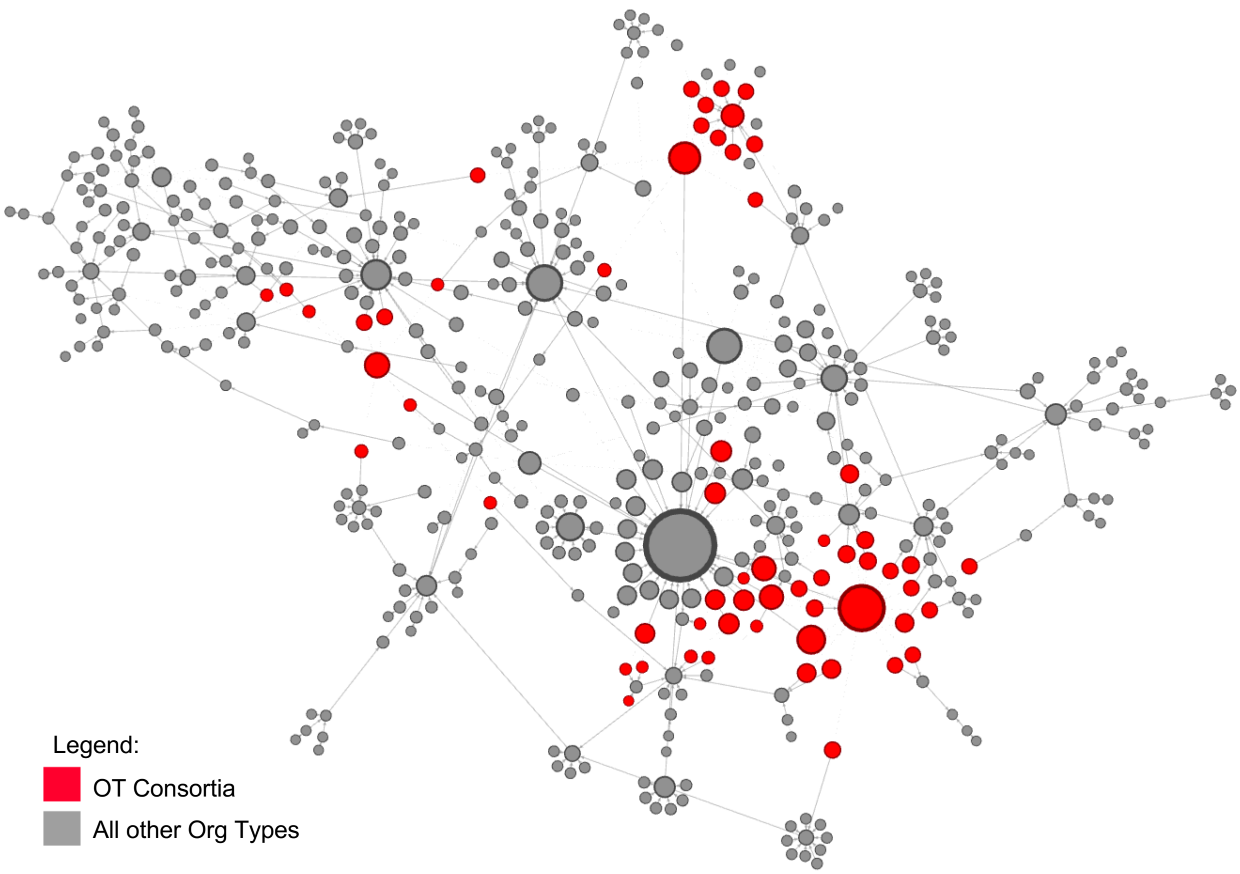

Figure 23 – Highlight of OT Consortia Connectivity Based on Eigenvector Centrality Assessment

Another essential organizational type in this network is the large number of organizations labeled “Governance.” Some of these organizations directly influence, oversee, or are responsible for policy and strategy for innovation and R&D, while others are solely added to the model for consistency and completeness in building the organizational structure. The size and impact of governance organizations on the network are evidenced by coloring only the governance organizations and graying out all other organization types, as reflected in Figure 24 below. In several instances, multiple levels of governance organizations can be observed in a direct chain connecting two other nodes. For example, one of these hierarchical chains can be seen in the lower left portion of Figure 24, which represents the connection from the U.S. Army headquarters, through Army Forces Command (FORSCOM), to XVIII Airborne Corps, to 3rd Infantry Division

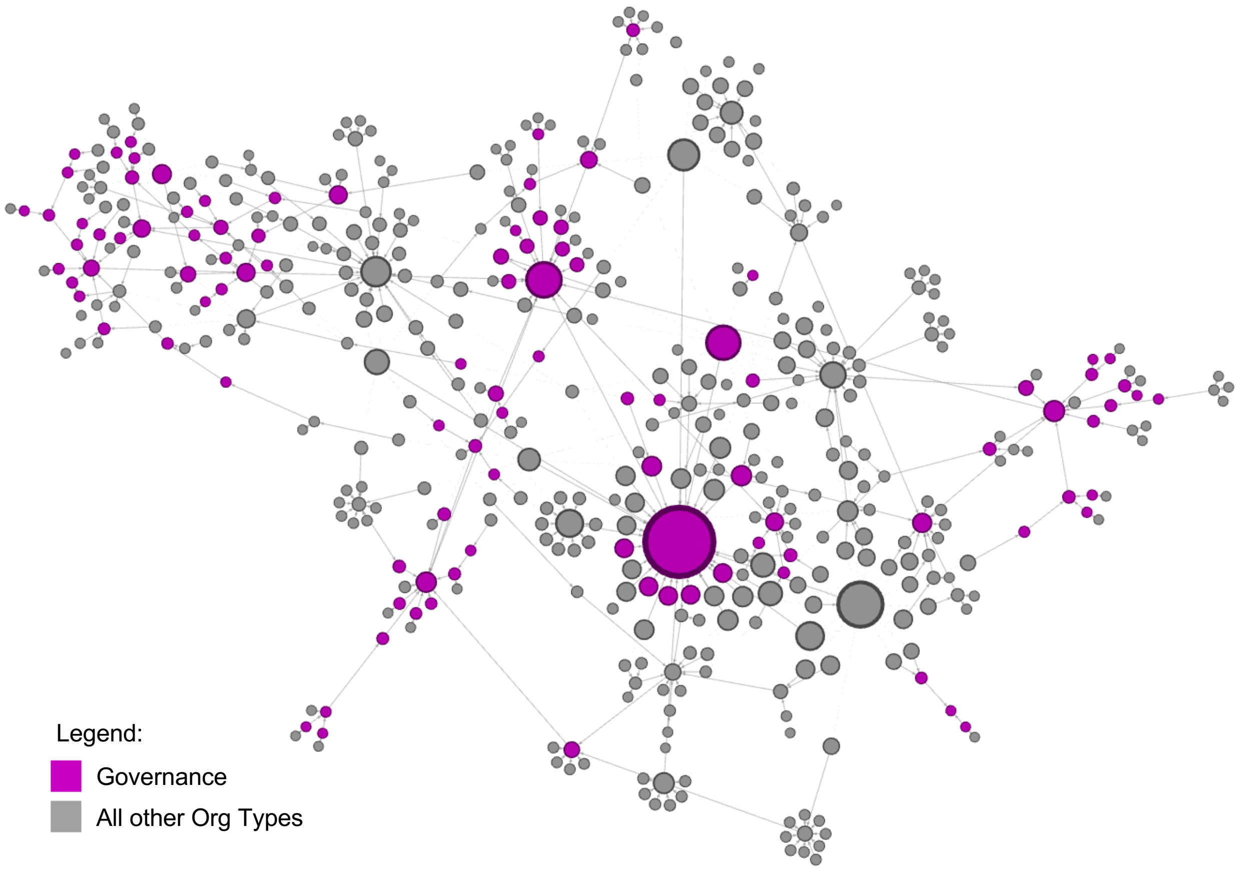

Figure 24 - Highlight of Governance Organization Connectivity Based on Eigenvector Centrality Assessment

and 101st Airborne Division, to reach three Army innovation offices. The concern with this type of hierarchy is that this level of bureaucracy could stifle effective innovation unless this chain of command is actively managed or communication pathways are developed to enable the free-flowing of information from those innovation offices to other parts of the network.

5.3 Betweenness Centrality Visualization

This section explores the model based on visual alterations from the results of the betweenness centrality assessment. This section is a shift away from the prior assessments based on the individual nodes and instead starts to analyze the model based on the length of the edge paths. Recall that the betweenness centrality measures how frequently a node is on the shortest path between two other nodes. Nodes on the ends of hierarchical chains obtain a zero betweenness centrality score as they are not located between any other nodes. Returning to the previously established color scheme based on the organizational alignment, then sizing the nodes based on the results of the betweenness centrality assessment, the model depiction below in Figure 25 is created.

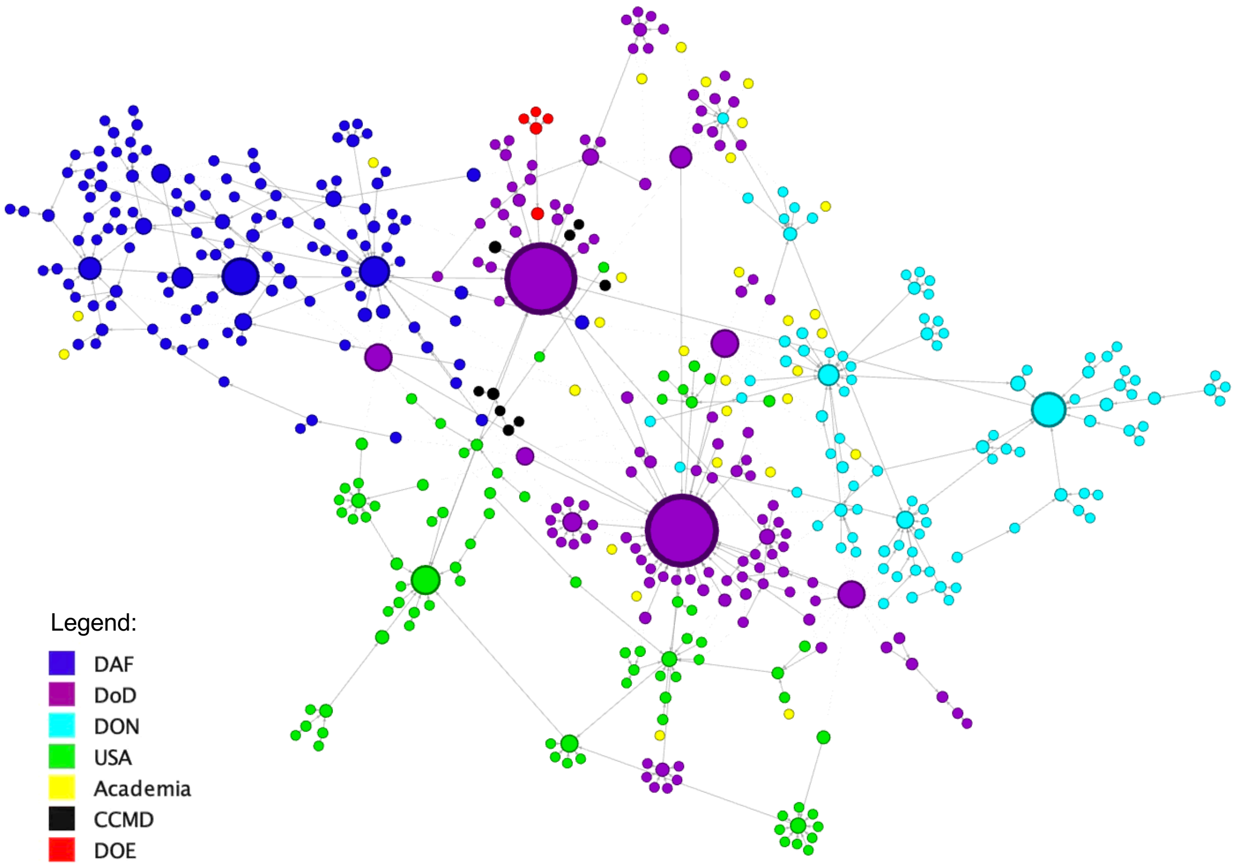

Figure 25 - Updated Node Size for Betweenness Centrality – Nodes Colored by Organizational Alignment

As a representation based on organizational hierarchy, this assessment gives greater weight to those organizations at the top of the chain of command. These organizations are more likely to have higher betweenness centrality scores as they are where disparate sub-hierarchies will first connect, such as OSD representing the top organization in the DoD Innovation Ecosystem hierarchy. For example, the U.S. Army and U.S. Navy offices have their own inter-service hierarchies, which may only link where the Department of the Army and the Department of the Navy connect through OSD. The two large purple nodes in Figure 25 reflect this output and are consistent with the betweenness centrality results reported in Table 8, where the lower purple node is DoD CTO, and the higher purple node is OSD.

Since the betweenness centrality measure assesses edges, it is helpful to visualize betweenness centrality through an alternate network layout. One of the built-in layout functions in the Gephi software uses the Fruchterman Reingold algorithm to create an alternate network geometry. This layout algorithm treats the edges like springs, which forces highly centralized nodes toward the center of the network geometry and decentralized nodes toward the periphery to find a balanced end state (Miguel et al., 2017). The result of this alternative network depiction of the betweenness centrality using the Fruchterman Reingold layout is shown in Figure 26 below.

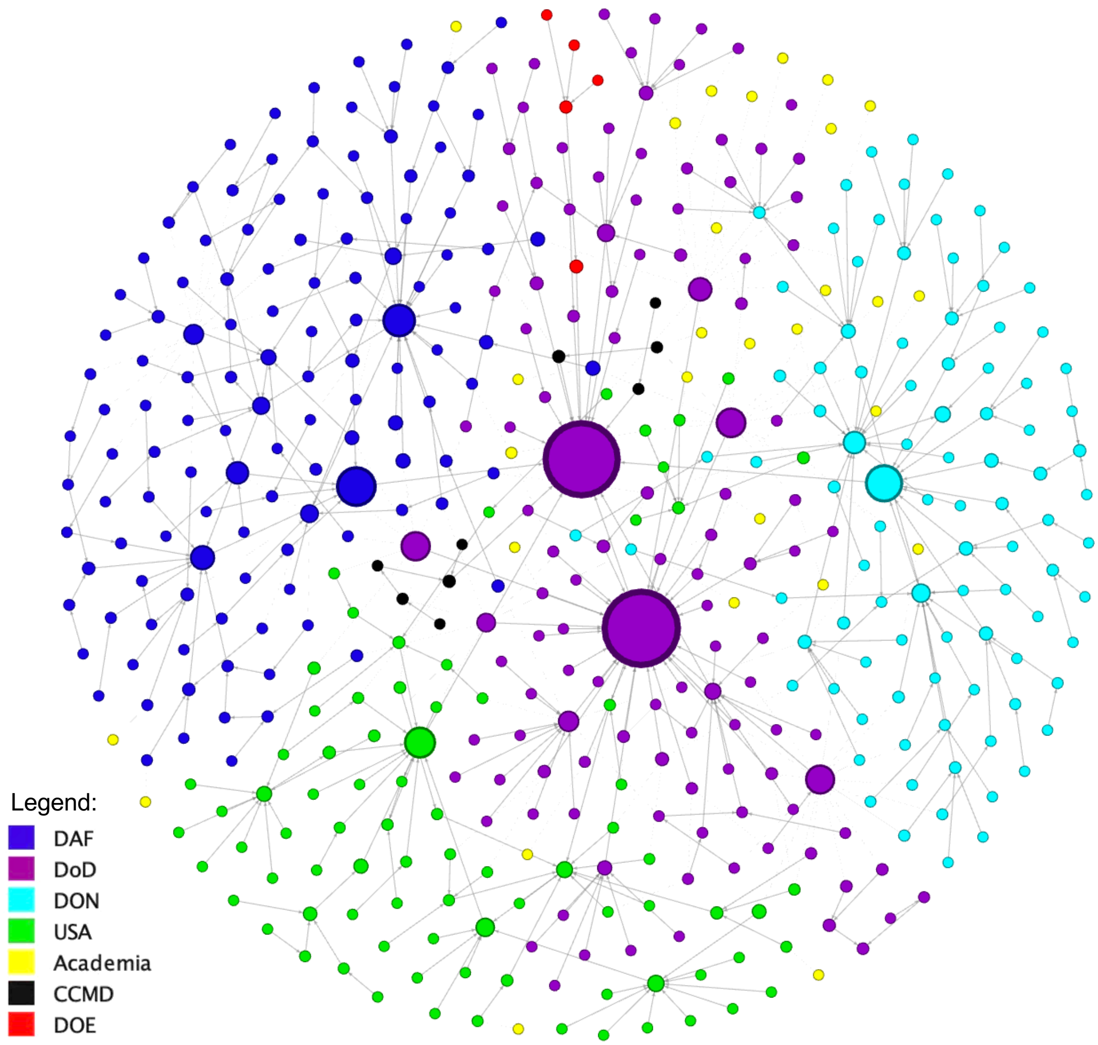

Figure 26 - Node Size Based on Betweenness Centrality in Fruchterman Reingold Layout

It is interesting to note in this Fruchterman Reingold layout how the military services maintain their overall connectivity grouping while the DoD organizations in purple cross through the model's center. This structure is indicative of the organizational hierarchy represented by the model. Additionally, the number of edges flowing to and from the large purple nodes, representing OSD and DoD CTO, can be seen more clearly in this view.

Following a similar gradient scale to that used in the eigenvector centrality analysis in the previous section, the node coloring for the Fruchterman Reingold layout is updated based on the betweenness centrality scores, with red indicating a high score and green indicating a low score. The resulting model depiction is shown in Figure 27 below. Using

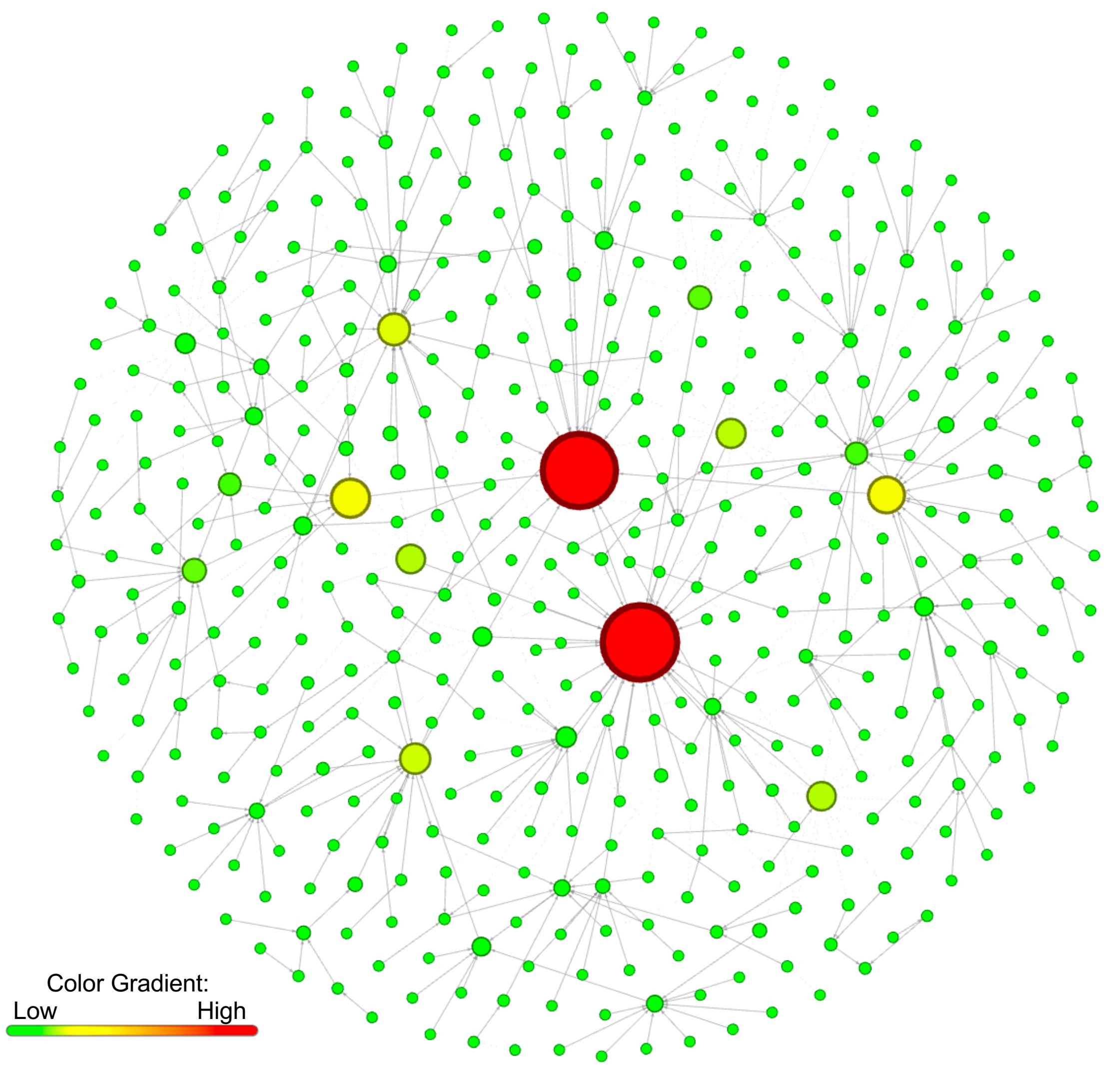

Figure 27 – Betweenness Centrality Fruchterman Reingold Layout – Nodes Colored by Centrality Score

this view, it is interesting to note the number of green nodes with low betweenness centrality compared to the small number of nodes on the high end. This uneven distribution reflects the left-skewed nature of the data output representation shown in Figure 17. Further, when comparing Figure 26 to Figure 27, the lead department organization office for each military service can be identified as a significant node for betweenness centrality, consistent with the data presented in Table 8.

5.4 Closeness Centrality Visualization

The following model visualization focuses on closeness centrality. This is another measure of centrality that looks at the edge paths through the network but quantifies a node's centrality based on the average length of the shortest path to every other node in the network. Using the similar model and layout parameters in Gephi as each previous centrality assessment, but instead sizing the nodes based on their normalized closeness centrality score results in the network model depicted in Figure 28 below. Consistent with the data distribution shown in Figure 18, the result of the closeness centrality was far less distributed than the other measures of centrality, which results in many more large-sized nodes and less differentiation based on node size alone. However, the impact of long hierarchical chains on the closeness centrality score for an organization becomes very apparent in this view.

Returning to the previously discussed Army FORSCOM hierarchy in the bottom left portion of the network diagram in Figure 28, one can clearly see the closeness centrality degradation at each step down the hierarchy. Since closeness centrality represents how quickly information can flow through the chain of command from one node to any other node in the network, this finding reinforces the need to actively manage these long hierarchical chains to avoid overburdening organizations in bureaucracy. It is also interesting to note how the dark blue DAF organizations appeared previously as highly

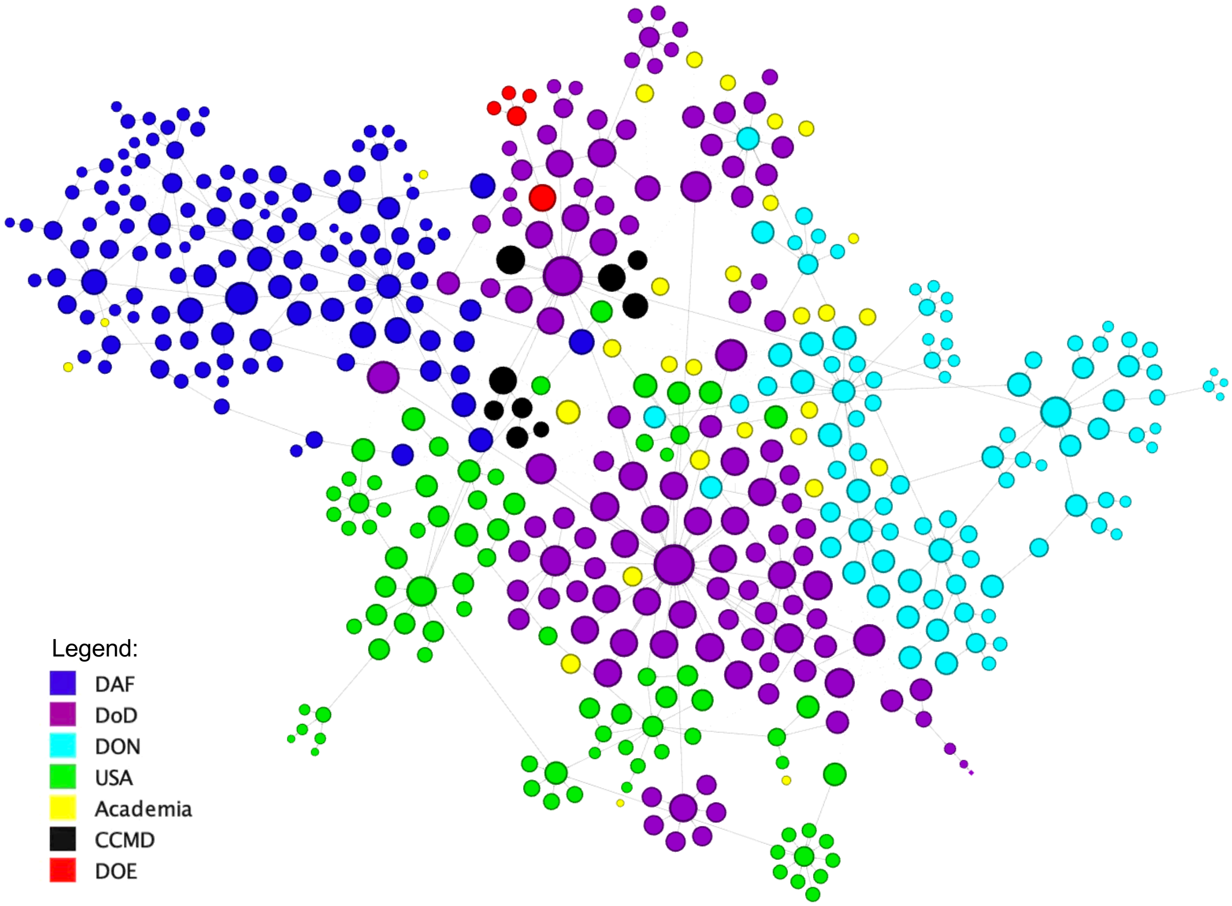

Figure 28 - Updated Node Size for Closeness Centrality – Nodes Colored by Organizational Alignment

connected in their own sub-network. However, when looking at the output of their closeness centrality in Figure 28, these DAF organizations appear less central to the overall DoD Innovation Ecosystem. This finding is likely due to the levels of hierarchy represented in the model, with organizations like AFWERX aligned under AFRL even though AFWERX maintains a direct reporting relationship to the Assistant Secretary of the Air Force for Acquisition, Technology & Logistics (SAF/AQ).

Similar to the betweenness centrality, closeness centrality assesses the edge path lengths. Therefore, reviewing the closeness centrality in a Fruchterman Reingold layout is helpful. Maintaining the gradient color scale to reflect red nodes with higher normalized closeness centrality scores and green to indicate lower scores, the resulting network graphic is depicted in Figure 29 below. It is interesting to note how the rank-ordering for the closeness centrality, reflected in both the node size and color, closely aligns with the Fruchterman Reingold algorithm for the network layout with the smaller green nodes pushed to the periphery while the larger red, orange, and yellow nodes pushed toward the interior.

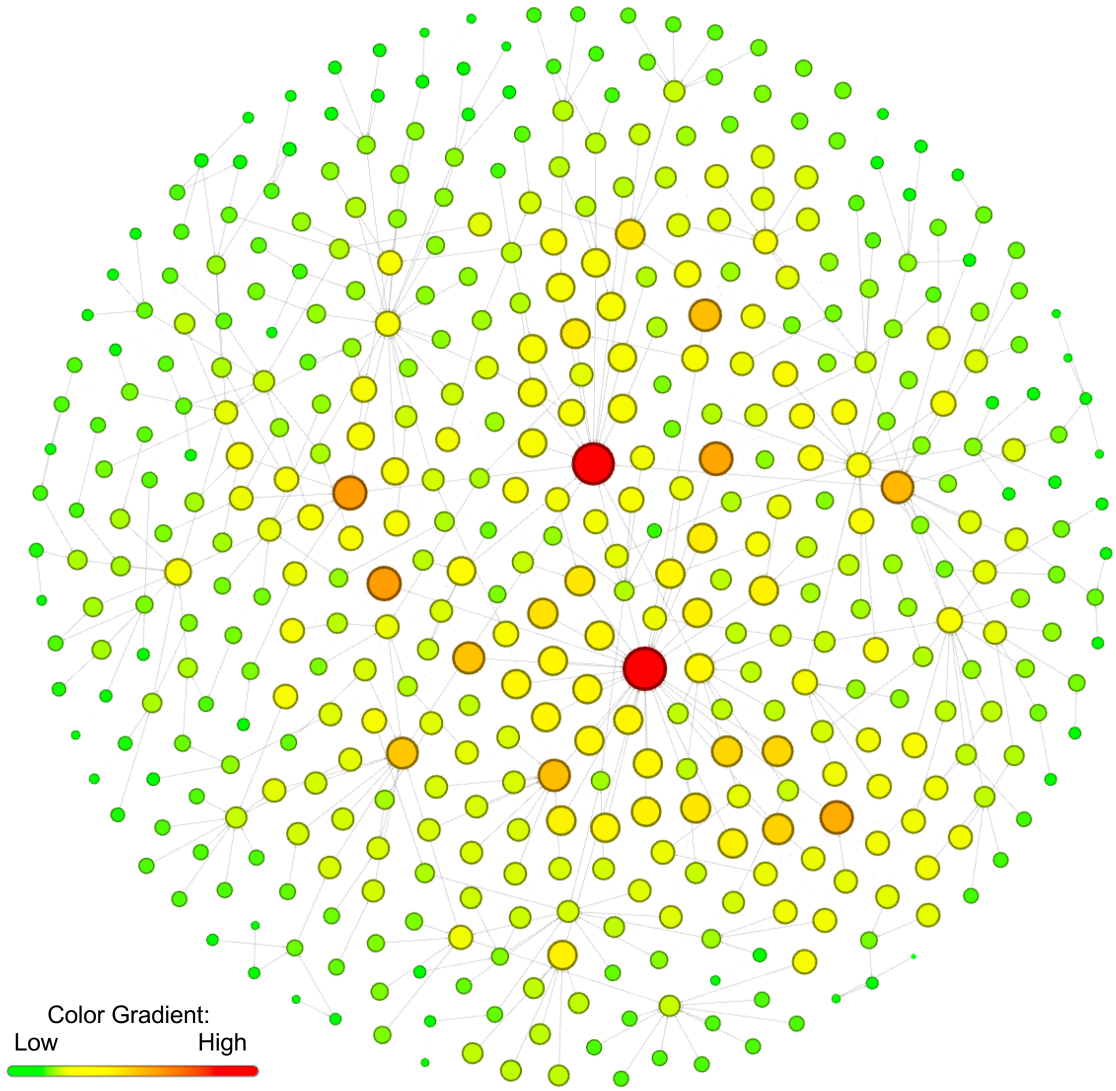

Figure 29 - Closeness Centrality Fruchterman Reingold Layout – Nodes Colored by Normalized Centrality Score

5.5 Revised Geographical Layout

The geographical network layout presented in Figures 9 and 10 keeps all node sizing equal. This section explores how the geographical layout view changes when incorporating the analytical results to alter the node appearance. As the best-correlated centrality measure to the consolidated centrality ranking, this assessment uses the eigenvector centrality results to resize the nodes. The result of resizing the nodes based on their eigenvector centrality score and overlaying it on the U.S. map is shown below in Figure 30. This exercise makes the Washington, D.C., regional hub significantly more

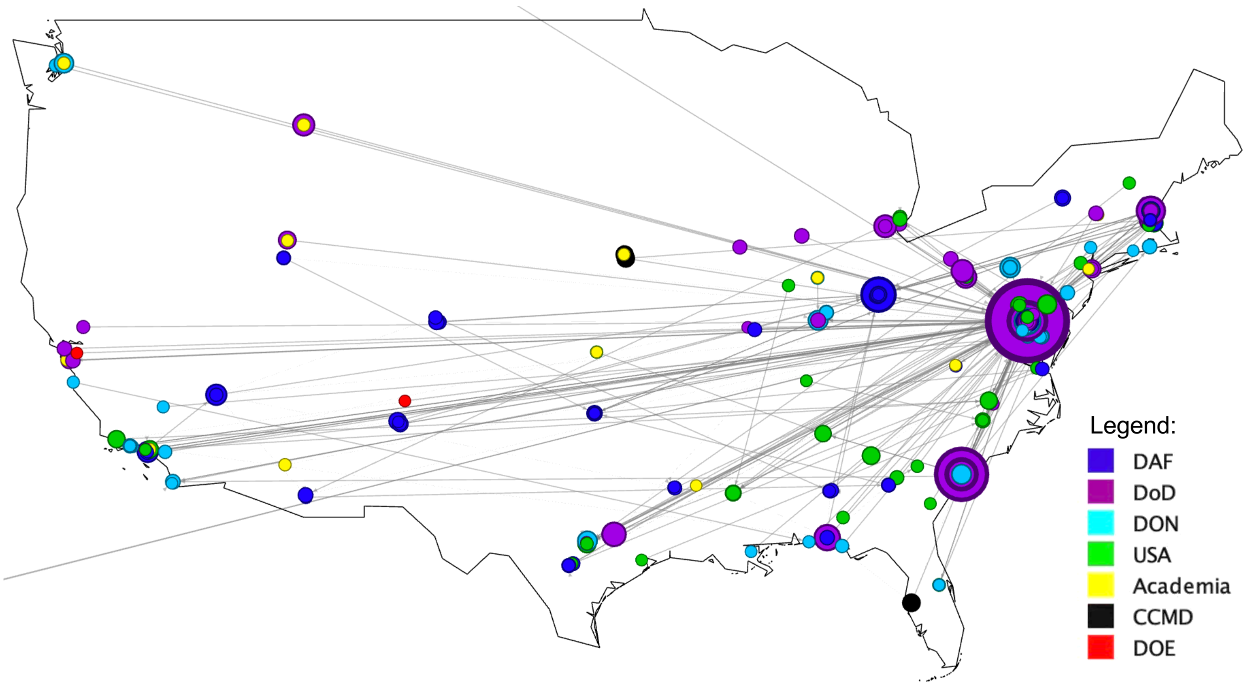

Figure 30 - Revised Geographic Layout - Nodes Sized by Eigenvector Centrality, Colored by Organizational Alignment

apparent when comparing this updated map to the one presented in Figure 10. This finding makes sense as the high-level governance offices are located in the Pentagon, and the eigenvector centrality measure considers the relative central importance of neighbor nodes.

The surprising discovery in this revised geographic view is the significant highlight of the Charleston, South Carolina area. This area was not highlighted as an important regional hub to the ecosystem by Figure 10 but is home to the U.S. Navy's Naval Information Warfare Center (NIWC) Atlantic office. Nearby Summerville, South Carolina, is also home to the OT Consortia management company Advanced Technology International (ATI), ranked second in the network in terms of its eigenvector centrality score (Table 7). Other key takeaways from this revised geographical view include the more prominent presence of DefenseWerx in Niceville, Florida, and the DAF offices in the Dayton, Ohio area, which is home to AFRL, the Air Force Material Command (AFMC) headquarters, and the Air Force Life Cycle Management Center (AFLCMC) headquarters.

Alternatively, a few additional insights are gained when using the weighted degree centrality scores to resize the nodes, as shown in Figure 31 below. The areas previously highlighted as central hub locations in the network remain, with the National Capital Region being the most prominent. Additionally, the Charleston, South Carolina, Niceville, Florida, and Dayton, Ohio, areas still reflect an update from the hub locations identified by Figure 10. However, two new locations emerge, with Vicksburg, Mississippi, and Crane, Indiana, now more clearly identified than in previous views. Vicksburg, Mississippi,

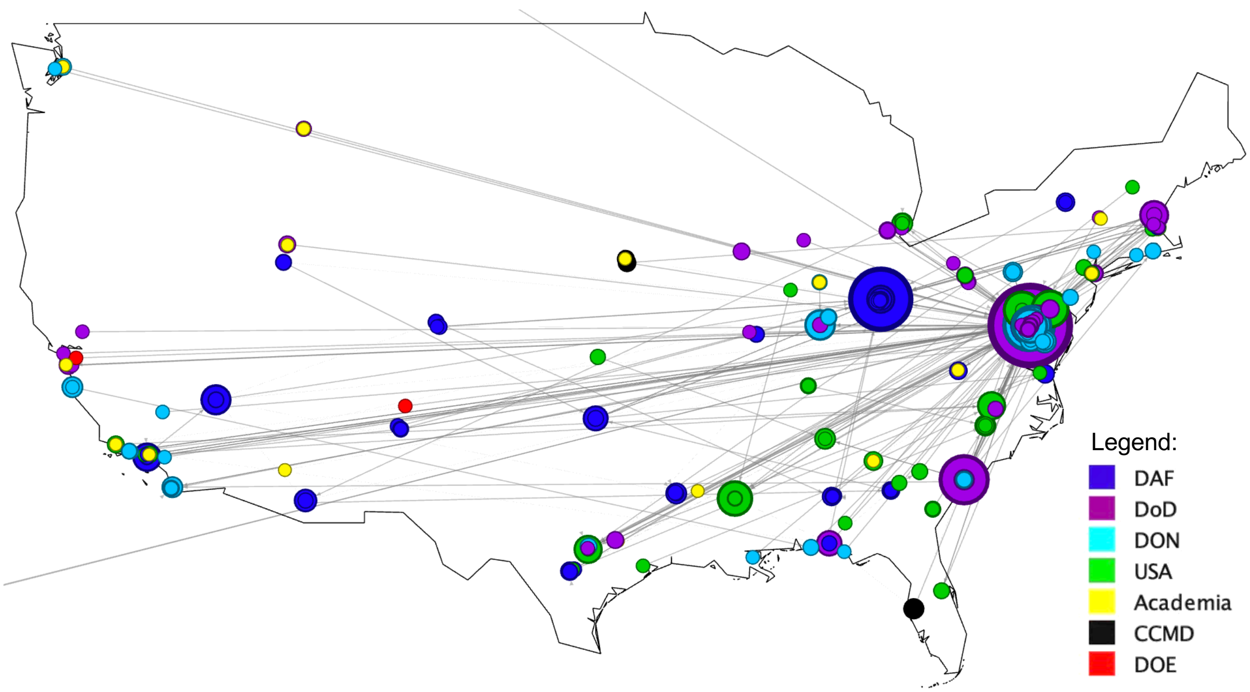

Figure 31 - Revised Geographic Layout - Nodes Sized by Weighted Degree, Colored by Organizational Alignment

is the home to the U.S. Army's Engineering Research and Development Center (ERDC), the ERDCWERX innovation office, and several research laboratories. Crane, Indiana, is home to the U.S. Navy's Naval Surface Warfare Center Crane Division and the DoD's Joint Hypersonics Transition Office (JHTO). Without resizing the nodes for these different centrality measures, these important geographic hub locations in the ecosystem may not have been otherwise identified.

5.6 Modularity Visualization

The last visual alteration on the network model explores the organizational alignment based on the results of the modularity analysis. Figure 32 below uses the same network layout utilized in multiple previous assessments with the node sizing based on the eigenvector centrality but colors the nodes based on their community alignment, as summarized in Table 14.

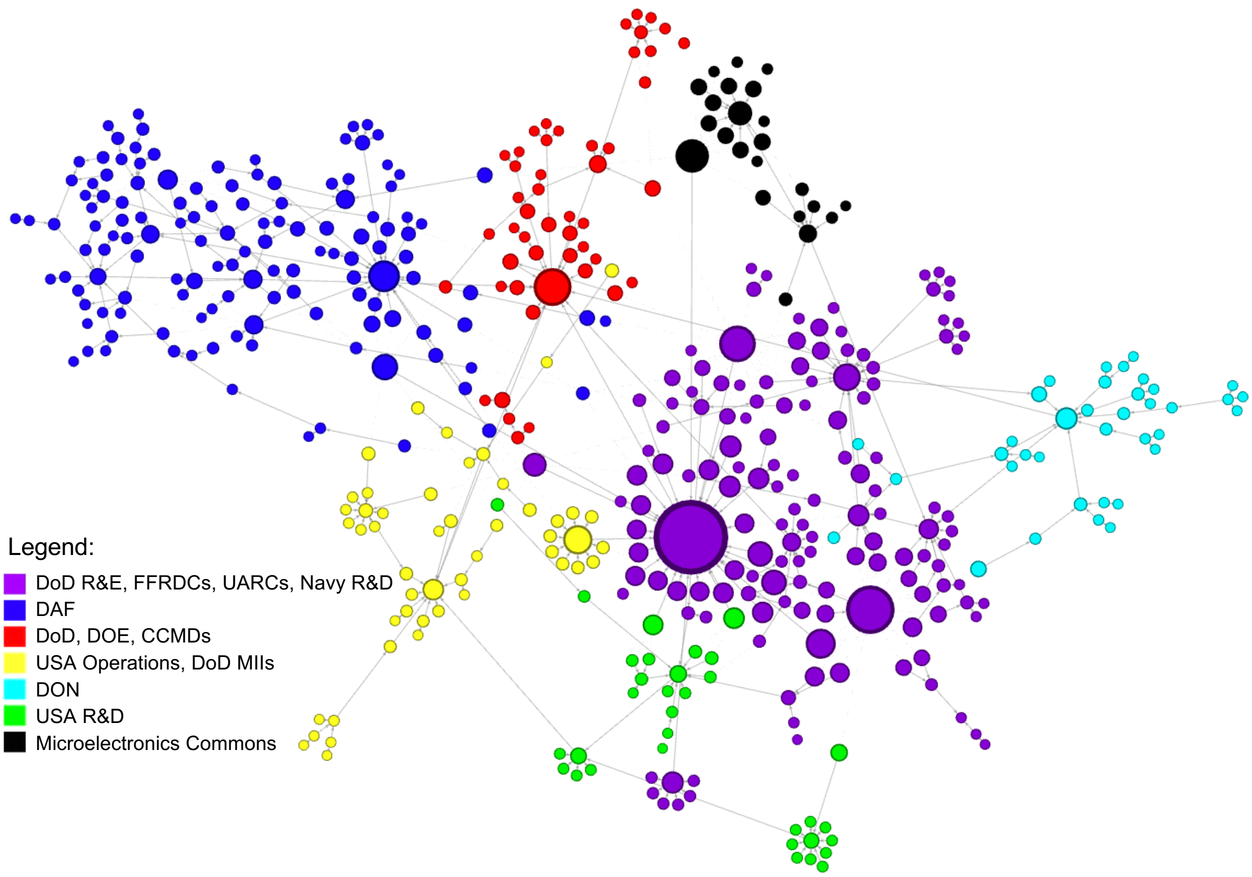

Figure 32 - Modularity Visualization with Nodes Colored by Community Alignment

When comparing this model depiction to the one shown in Figure 21, it is interesting to note how the DAF offices remain grouped, while the U.S. Army organizations are split between operations and R&D. It is also interesting how the Navy R&D organizations align with the DoD R&E enterprise rather than to the other Department of the Navy offices.

As an alternate view of the modularity assessment, Figure 33 below makes the comparison between the existing organizational alignment and the calculated communities more apparent. This image includes the module boundaries identified by Figure 32 but overlays them with the node color scheme based on the existing organizational hierarchy from Figure 21.

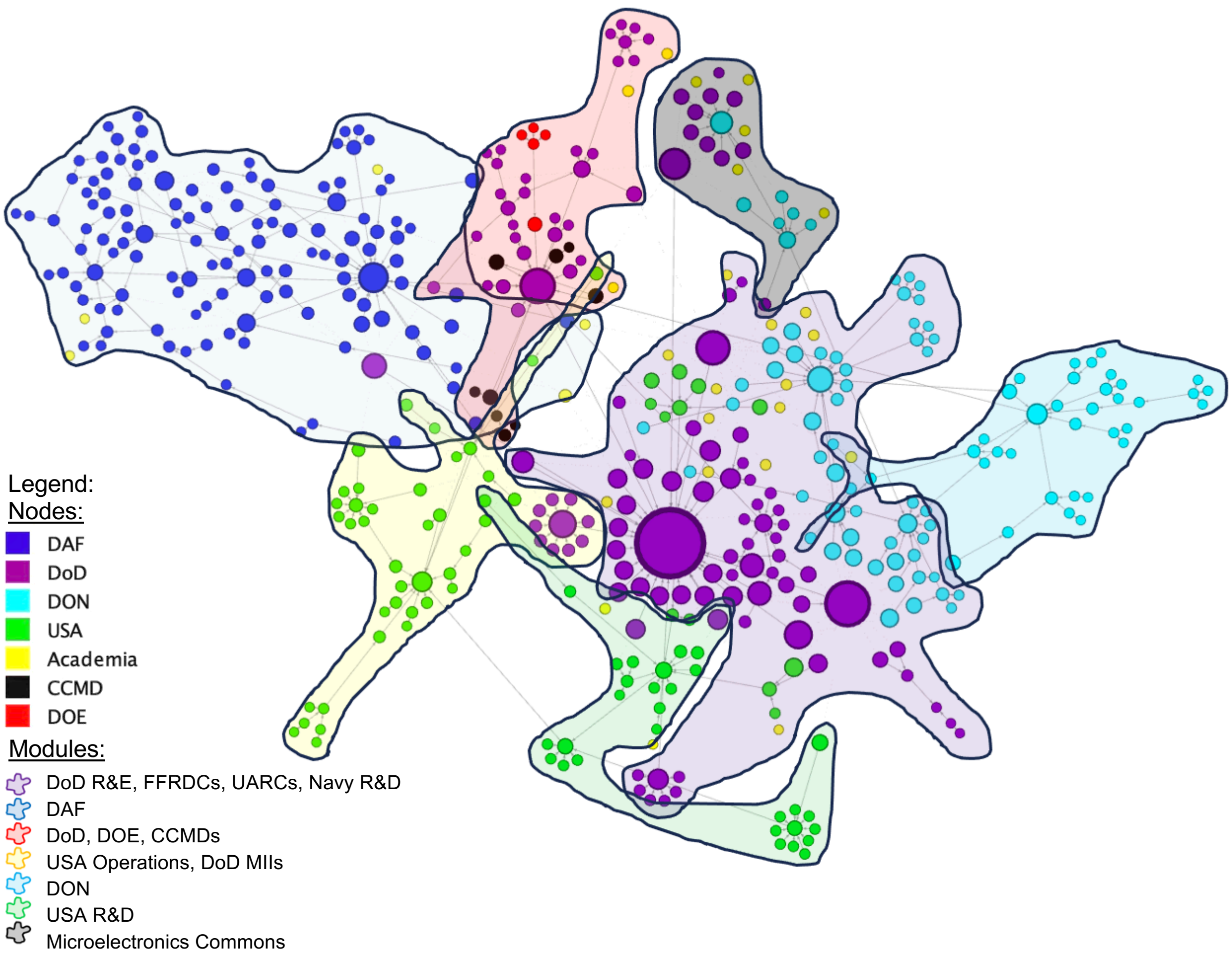

Figure 33 - Modularity Communities Overlaid on Organizational Alignment

Although this graphic appears complex initially, it offers several key insights. First, the modularity function takes into account the weighted connectivity. Therefore, primary connections carry more weight toward community alignment than secondary connections. While some nodes are pulled to one location on the network layout due to having multiple connections, the primary hierarchical chain most heavily impacts the community alignment. For example, the yellow module in Figure 33 includes a long section on the top to capture two U.S. Army nodes that appear closely aligned with the DoD. This chain connects the Training and Readiness Accelerator (TReX) Consortium with NSTXL via a secondary connection as the consortium management organization (large purple node in the black-shaded module). However, the primary connection is through the U.S. Army's Program Executive Office for Simulation, Training, and Instrumentation (PEO-STRI) as the DoD sponsor for this OT Consortium.

Second, the graphic in Figure 33 highlights how tightly connected the DAF community is within the ecosystem, while the DON organizations are more integrated with other offices within the DoD. This finding is consistent with the observations from the closeness centrality graphic, which shows the DAF organizations being less central to the overall network due to the service's tight internal hierarchical connectivity. While this may facilitate a strong innovation culture within the DAF, it could hinder the open sharing of information across the ecosystem and degrade the effectiveness of DoD-wide innovation efforts.

Lastly, it is surprising to note what the community cluster assessment does not capture. Due to the number of connections and hierarchy comprising the OT Consortia organizations, one could assume that the OT Consortia would generate a prominent community of their own. Figure 34 applies the same community overlay from Figure 33 but instead applies it to the graphic highlighting the OT Consortia organizations from Figure 23. By doing this exercise, it can be clearly seen how the OT Consortia are spread throughout the identified communities rather than being grouped together. This observation reflects how the established OT Consortia model represents a broad range of DoD needs while each consortium focuses on specific technology areas. The integration of these consortia throughout the DoD is indicative of a robust industrial base willing to support DoD innovation efforts.

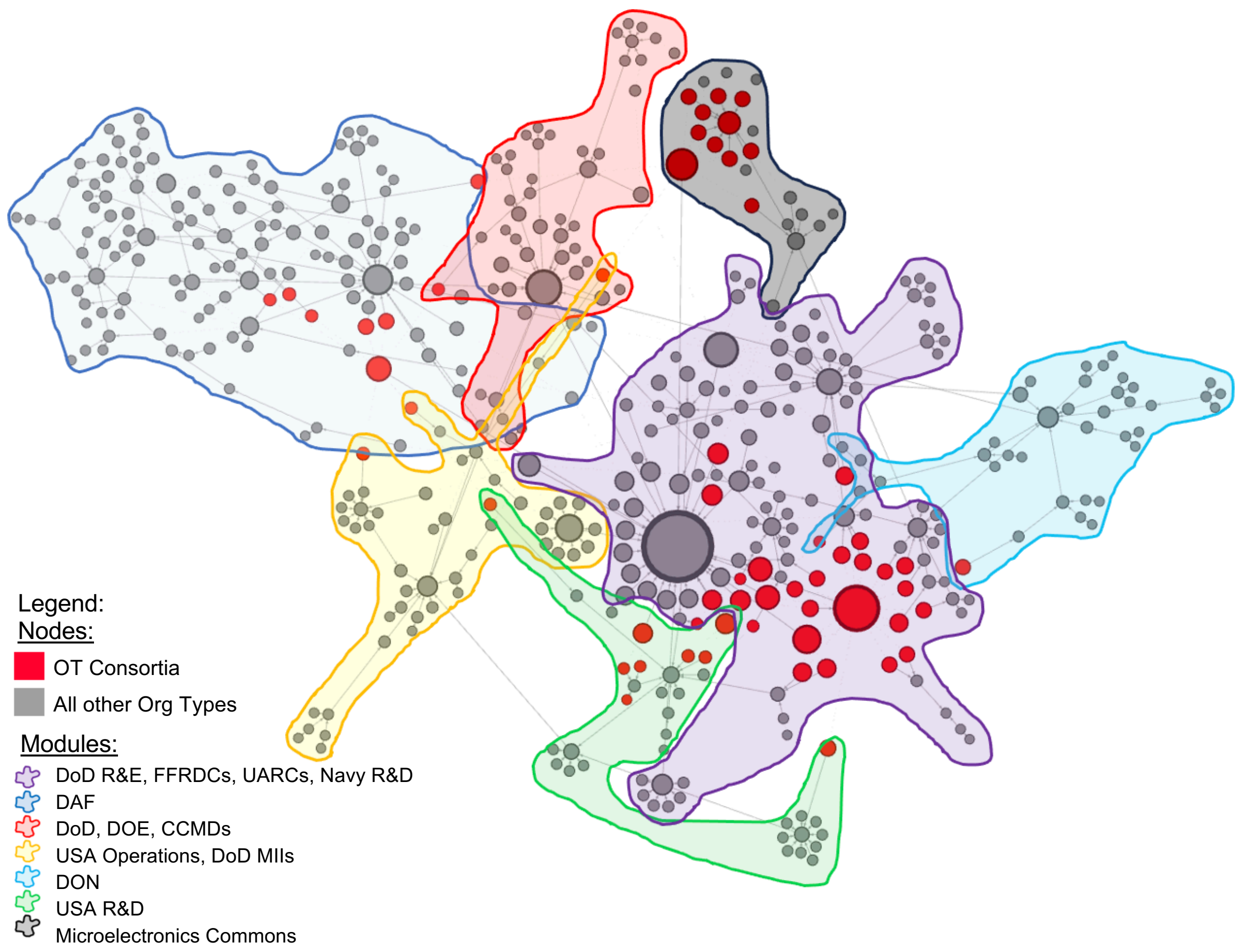

Figure 34 - Modularity Communities Overlaid on Network Highlight of OT Consortia

In summary, this chapter applies the various organizational network analysis methods from Chapter 4 to revise the model visualizations. This visual exploration of the model resulted in numerous interesting and surprising findings by exploring the impact of varying node size, color, and placement based on these analytical results. This combined analytical and visual approach to assessing the complex DoD Innovation Ecosystem model provides key insights into how the ecosystem is currently organized and how these hierarchical chains could impact overall effectiveness. It also identifies organizational communities based on the underlying hierarchical structure.

Chapter 6

Conclusion

This thesis provides an in-depth organizational network analysis of the complex and sprawling DoD Innovation Ecosystem. This research includes the development of a hierarchical network model of the ecosystem by consolidating available open-source information on the organizations and their respective hierarchies. Using this model, a series of organizational network analysis methods are applied. These methods include the node centrality measures of degree, weighted degree, and eigenvector centrality, and the path centrality measures of betweenness and closeness. Further, this analysis includes a review of network modularity for community detection based on the underlying connectivity rather than organizational alignment within the current DoD hierarchy.

6.1 Research Questions Addressed

This research addresses the three research questions identified in Chapter 1 by first developing a DoD Innovation Ecosystem model, then conducting an organizational network analysis on the model, and finally manipulating model visualizations based on the analytical results. The research questions and associated responses follow:

Research Question 1: What is the current state of the DoD Innovation Ecosystem?

The DoD Innovation Ecosystem is undoubtedly large and complex. However, one could argue that this expansive ecosystem is necessary to advance defense technologies across the full spectrum of military capability requirements. While commercial industry can focus their R&D toward their specific technology specialization, the DoD must maintain a large and diverse R&D capability across the entire technology spectrum while also maintaining the ability to capitalize on potential dual-use technologies developed through commercial R&D. The data collection methodology outlined in Chapter 3 identifies 462 different organizational nodes to construct the innovation ecosystem hierarchy. As summarized in Table 3, this includes 125 innovation organizations, 95 R&D organizations, and 23 software factories, with organizational functions as broad as the technologies they cover. This innovation and R&D enterprise is supported by 31 academic institutions, 10 FFRDCs, and 15 UARCs. Additionally, the research model includes 60 organizations responsible for overseeing and managing the DoD's OT Consortia, representing standing agreements with thousands of commercial industry companies across a massive and diverse portfolio of technologies. Lastly, the research identifies 103 governance organizations that drive the strategy, policy, oversight, resource allocation, and overall ecosystem management.

The research also highlights how innovation efforts are distributed relatively evenly throughout the DoD, including a spread in quantity and organizational types across the various DoD offices and military services. This even breakout of organizational alignment as a percentage of the total number of organizations includes 25.54% of innovation ecosystem organizations aligning under the DoD, 27.06% under the Department of the Air Force, 20.56% under the Department of the Navy, and 17.53% under the U.S. Army. Reviewing this breakout in conjunction with the spread of organizational types, as reflected in Figure 8, suggests that no service or agency dominates the innovation ecosystem.

Research Question 2: What insights can be gained by exploring the ecosystem's connectivity?

This research conducts multiple assessments on the DoD Innovation Ecosystem's connectivity, as detailed in Chapter 4 and reflected visually through Chapter 5. This analysis includes three measures of node centrality (degree, weighted degree, and eigenvector), two measures of path centrality (betweenness and closeness), and a modularity assessment. Further, the research observes the effect of these centrality measures when viewing the ecosystem geographically. While the research identifies several takeaways through these assessments, two main findings emerge.

First, the visual depictions of the different centrality measures on node size and color represented through Chapter 5 demonstrate how long hierarchical chains impact these measures. This finding is indicative of how levels of bureaucracy could negatively impact the flexibility and efficiency of innovation organizations. As shown in Figure 8, innovation organizations often fall at the end of these hierarchical chains, which adds layers of bureaucracy to connect these organizational efforts with the policy and governance organizations at the top of the hierarchy. One specific example that best reflects this point is reviewing Figure 24 and the subsequent discussion about a long hierarchical chain within the U.S. Army command structure. The concern is that bureaucracy can stifle effective innovation unless this long chain of command is actively managed or communication pathways are developed to enable the free-flowing of information from those innovation offices to other parts of the network.

Second, the visual exploration in Chapter 5 looks at how the centrality assessments impact the geographical network depiction. In the Chapter 3 review of the geographical layout in terms of node quantity (Figure 10), multiple regional hubs are identified, including the Silicon Valley and San Diego areas in California, the Austin and San Antonio areas in Texas, the Boston area in Massachusetts, and the largest regional hub located around Washington, D.C. However, new regional hubs emerge when updating the node appearance based on the results of the centrality assessments. Sizing nodes based on the eigenvector centrality (Figure 30) identifies Charleston, South Carolina, Niceville, Florida, and Dayton, Ohio, as three additional prominent locations in the ecosystem. Sizing nodes based on weighted degree (Figure 31) identifies Vicksburg, Mississippi, and Crane, Indiana, as two additional important regions. This insight would not have been otherwise identified without assessing the impact of centrality on the geographical network layout.

Research Question 2a: Where are the organizational nodes of high connectivity and influence in the system?

The organizational network analysis in Chapter 4 combines the results from the five different centrality measures to assess which nodes in the network have the highest level of influence based on their hierarchical connectivity. The consolidated list of the top ten organizations (Table 10) includes five governance organizations, three OT Consortia organizations, one innovation organization, and one R&D organization. The clear leader within the network regarding its hierarchical connectivity is the DoD CTO office, which makes sense as it is the organization responsible for the overall oversight, governance, and policy for the DoD Innovation Ecosystem. This assessment also shows the influence of the OT Consortia on the network model due to the highly connected nature of this organizational construct. When looking specifically at the top innovation organizations in terms of connectivity (Table 11) and R&D organizations (Table 12), it is interesting to note the spread of organizational representation from the DoD and each of the three military service departments. This conclusion reflects a balanced ecosystem where no service dominates the ecosystem in terms of centrality. Although the ecosystem is highly complex, this assessment indicates a highly diverse ecosystem that spans the full spectrum of DoD technologies and innovation practices.

Research Question 2b: How well does modularity by connectedness align with the DoD organizational structure?

As reflected through the centrality and modularity assessments in Chapter 4, the DAF and the U.S. Army appear to operate with more hierarchical isolation than the DON. The DON has numerous offices that appear more tightly integrated with other organizations across the ecosystem. This finding is most evidenced by the modularity assessment, which keeps the U.S. Army organizations together, albeit in two different communities. Figure 33, which overlays the calculated communities on the current organizational alignment, also shows how the DON connectivity structure and proximity to several DoD organizations result in their hierarchy splitting across three different communities. Further, this modularity assessment reflects a very tightly coupled hierarchy within the DAF. While this may signal a strong innovation culture within the DAF, it could indicate that Air Force innovation offices operate in relative isolation from the rest of the DoD. If so, this could hinder the open sharing of information across the ecosystem and degrade the effectiveness of DoD-wide innovation efforts. As this research only reviews the innovation ecosystem based on its hierarchical structure, further analysis is required to substantiate this claim. Specifically, this aspect of the ecosystem can be better understood by assessing network centrality based on the frequency, type, and means of information sharing across organizations rather than being solely based on the hierarchical structure.

Research Question 3: What system improvements can be made to streamline innovation?

As this research focuses on the DoD Innovation Ecosystem based on its hierarchical connectivity, this section limits the recommendations to only those observations noted through this analytical research. As reflected in the DoD Innovation Ecosystem model, the innovation ecosystem contains a complex network of interconnected organizations that spread across the DoD. With so many innovation organizations falling at the end of their respective hierarchical chains, it may be challenging to maintain the necessary speed, flexibility, and autonomy to evolve, thus limiting their ability to remain fully responsive to the rapidly changing technological environment. This premise is especially true given the increased speed of technology commercialization, where the DoD must maintain close partnerships with an ever-increasing base of potential suppliers. The DoD should develop communication pathways for successful practices to proliferate through the ecosystem and facilitate the removal of any unnecessary layers of bureaucracy that could hinder innovation. While not the subject of this research, forums to share and collaborate across the ecosystem likely already exist, which would be an excellent place to start exploring these collaboration opportunities.

Further, this research stopped at the OT Consortia organization level and did not dive into the industry partners that comprise them. The DoD should perform a detailed analysis of the OT Consortia management model, including a review of all the industry organizations participating in these consortia, particularly seeking those organizations that participate across multiple consortia. The ecosystem model reflects the heavy influence of the OT Consortia on the DoD Innovation Ecosystem's organizational hierarchy and the spread of OT Consortia management across the DoD. Therefore, this construct deserves significant attention and active management to cover the right technology areas and avoid unnecessary redundancy and waste.

6.2 Research Limitations

One limitation of this research is in the selected scope. While this DoD Innovation Ecosystem model includes all innovation, R&D, and SW Factory organizations found during the research, the FFRDCs, UARCs, and Academia partnerships that support them, the extensive network of OT Consortia, and any governance organizations necessary to generate the complete innovation hierarchy through the DoD, this model is still incomplete in several ways. First, the full impact of the organizations and their connectivity could be further refined by including all operating location offices for each of these organizations rather than solely using the headquarters offices. By doing this, larger organizations with multiple operating locations would generate higher measures of centrality and reflect a better picture of the entire geographic scope of the network. Second, the model could extend to capture the corresponding offices within the commercial industry, including all companies participating in the OT Consortia. Lastly, the model scope could extend beyond organizational hierarchy to assess organizational behavior and how that impacts centrality and importance to the network.

This research utilizes the existing hierarchical connectivity to build and assess the DoD Innovation Ecosystem model. Nearly one-quarter of all organizations identified in the innovation ecosystem model are labeled as governance (103 of 462 nodes). Further, governance organizations accounted for five of the top ten organizations in terms of their consolidated centrality scores (Table 10). This level of bureaucracy may not be surprising to anyone familiar with the U.S. Government. However, it could also be a product of this research taking an organizational hierarchy approach to building and assessing network connectivity. Organizations that appear central to the ecosystem based on the organizational hierarchy may not equate to those organizations in the network that have the most impact, generate the highest quality outputs, or best influence the military's technological edge. Further, this hierarchical approach does not consider the funding level of each organization. One would likely develop new insights on the organizations and geographical regions of impact within the ecosystem by investigating each organization's budget and overall economic impact.

6.3 Future Research

This research provides an initial assessment for understanding the complex DoD Innovation Ecosystem, but it is only a start. Future research recommendations to further advance the understanding of this network include an assessment of technological gaps and redundancies, the potential for organizational realignment, and a detailed assessment of the full extent of the OT Consortia construct.

The DoD can ensure that the requisite resources are applied where most needed by reviewing the innovation and R&D organizations based on their respective technological focus areas. Further research in this area could highlight to the DoD if technological gaps critical to the future of military capabilities need to be addressed.

Further, this analysis could identify potential redundancy and waste areas that negatively impact the DoD's effectiveness. This is not to say that the DoD should only identify one office per technological area for R&D, but rather to be able to identify if the DoD is adequately organized to advance the 14 critical technology areas identified by the 2023 National Defense Science and Technology Strategy. Further, coupling this assessment with a review of the organizational budgetary data could inform the DoD if the limited R&D resources are being appropriately applied to achieve its strategic goals.

Building on the first level of modularity assessment conducted in this research, additional research should be conducted on the organizational alignment of the DoD's Innovation Ecosystem. This research could focus on the impact of different centrality measures beyond organizational hierarchy, including a review of the type, frequency, and quality of communication across the ecosystem. Analyzing the modularity community alignment based on organizations that most frequently communicate or have the most significant influence regarding effective information sharing could develop an interesting argument for organizational consolidation or realignment to streamline innovation.

Lastly, further research should be conducted to perform an organizational network analysis on the full scope of the OT Consortia. By extending the research out to the large number of industry companies that are involved, the DoD could gain a better understanding of how the OT Consortia are organized, which consortia are most utilized or under-utilized, how the current consortia model aligns with the DoD R&D offices and critical technology areas, and the extent to which companies are aligned under multiple consortia. This understanding would ensure that the industry partners identifying their willingness to work with the DoD are not overburdened by the bureaucracy or lost within the DoD Innovation Ecosystem hierarchy.

It is through research such as this thesis and the recommended future research that the DoD can be sure it is adequately postured to generate, maintain, and sustain its technological edge through innovation. By first understanding what comprises the DoD

Innovation Ecosystem, the DoD can better employ the system for the greatest impact. The pace of technological change shows no sign of slowing down, the level of commercial investment and advancement of next-generation military capabilities is likely to continue, and the DoD's ability to maintain partnerships and rapidly adopt dual-use technologies will drive the future of military capability acquisition practices. The DoD's failure to innovate at an ever-increasing pace will degrade the ability to effectively maintain peace and deter aggression. The DoD cannot falter in this endeavor; the future of national and global security is at stake.

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