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Joint All-Domain Command and Control (JADC2) Opportunities on the Horizon

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Abstract

Joint All-Domain Command and Control (JADC2) is an enormous effort in information sharing—sense, make sense, and act—to empower joint force commanders in warfighting. This effort will take advantage of materiel and non-materiel solutions as well as modify existing policies, authorities, organizational constructs, and operational procedures. The goal of JADC2 is to empower the U.S. military to join forces to seize, maintain, protect, gain information and knowledge, and maintain decision advantage and superiority. There are several challenges and questions raised by experts in the DoD including but not limited to: the need for the portfolio management of JADC2-related efforts, the decision-making authority structure within JADC2, affordability and specific budget allocation, and technical maturity of the proposed technologies as well as optimal technical system design and lifecycle management. This paper looks at JADC2 through an academic/scientific lens to identify multiple opportunities in which academic institutions in various domains (engineering, sciences, and social sciences) can contribute to creating a state-of-the-art, Joint All-Domain Command and Control system.

Keywords: Joint All-Domain Command and Control, JADC2, Systems View, MBSE

Introduction

The U.S. military operates in an ever-changing operational landscape, requiring quick adaptation to shifting circumstances. In such a dynamic environment, achieving and maintaining information superiority is of utmost importance. To this end, the Department of Defense (DoD) has established Joint All-Domain Command and Control (JADC2), an initiative, and concept aimed at improving Joint Force C2 capabilities (Hoehn, 2022). However, due to the significant diversity among the various sectors and departments within the DoD, the development and implementation of JADC2 require considerable effort to consider the distinct needs and perspectives of all stakeholders and agencies involved.

To guide and oversee the development and implementation of JADC2, a cross-functional team has been created which will work in collaboration with a Deputy Secretary of Defense–related staff that is comprised of Senior Executive Service (SES)–level members from various agencies, for example, the DoD, Office of the Secretary of Defense, Defense Advanced Research Projects Agency, Air Force, Army, and Navy (Hoehn, 2022). The main objective and focus of this team are to identify and implement command and control improvements in the form of an implementation plan.

This paper provides an overview of the current state of the JADC2 initiative, provides a set of suggestions, and identifies several opportunities to solve and improve some of the key challenges of JADC2 in multiple domains of technical, organizational, and data enterprise. This paper begins by providing an introduction and overview of the significant challenges pertaining to jointness and JADC2. It provides a brief overview of JADC2 history followed by a general conceptual overview of JADC2. The next section of the paper provides a set of technical and conceptual solutions and directions needed for research, development, and acquisitions of the technologies that would enable the DoD to achieve a resilient and elegant advanced solution to JADC2.

History and Progress

Before the JADC2 initiative, distinctive command and control systems (C2) were owned and operated by each force independently (Hoehn, 2022; McInnis, 2021; Theohary, 2021; Woolf, 2021). Historically, each military service has developed and acquired its own unique tactical command and control network, often incompatible across weapons systems, platforms, and operating domains. As a result, decision time cycles and the transmission of critical time-sensitive data for decision making were slow, redundant, and organizationally stove-piped (*Advanced Battle Management System*, 2022) and domains of air, land, sea, space, and cyberspace were treated separately (DoD, 2022; Feickert, 2022; O'Rourke, 2021; Theohary, 2021) in addition to geographically separated command units (*Advanced Battle Management System*, 2022; DoD, 2022; *Doctrine for the Armed Forces of the United States*, 2013). While multiple command and control systems owned by different forces enabled highly specialized and effective solutions to be developed and implemented, it also required significant efforts on all fronts and limited the threat reaction capabilities and information sharing between all forces (Feickert, 2022).

The legacy C2 systems come with the disadvantage of potential susceptibility to adversaries' anti-access and denial attacks. The adversaries' anti-access/area denial (A2/AD) tactics, including electronic warfare, cyber weapons, long-range missiles, advanced air defenses, and GPS denial, can affect our operational ability and decision cycle that relies on sensors and technologies (*Advanced Battle Management System*, 2022; Friedman, 2019; *Joint Doctrine Publication 5 Command and Control*, 2012; Kreisher, 2001). In addition, current threats are not limited to individual domains anymore, which makes it difficult to counter with dedicated and partially isolated solutions. Consequently, DoD leaders have expressed the need to expand

access to information in an extensive approach to increase overall agility and preparedness for contingencies from different directions (*Doctrine for the Armed Forces of the United States*, 2013; *Jointness - A Selected Bibliography*, 1993; Kirtland, n.d.; *Transforming the Joint Force*, 2003; Woolf, 2021).

The JADC2 initiative and the proposed shared infrastructure would reinforce and enhance the effectiveness of all armed forces and services. Such a shared foundation allows for simultaneous and consecutive operations, as well as continuous integration of capabilities across all domains. In recent years, major efforts have been undertaken to join specific areas of operation and exploit the advantages of combined information and technology, such as the AirLand Battle concept (Kirtland, n.d.), DARPA's Mosaic Warfare program, the Air Force Advanced Battle Management System (ABMS), the Navy's project Overmatch, and the Army's Project Convergence (Congressional Research Service, 2021b). Jointness efforts have also been reported in various forms in other countries, such as the Netherlands and India (Birch et al., 2020; Congressional Research Service, 2022; Nardulli et al., 2003). Additionally, JADC2 tests were conducted in 2019 and 2020 (McInnis, 2021). Due to the disproportionate increase in complexity, growing connectedness of networks of sensors, and novel and sophisticated joint technologies exceeding human cognitive capabilities, no particular solution has been widely implemented as of today.

Several challenges have been identified as follows:

- More approval steps are required to integrate multiple domains (Builder et al., 1999)
- Planners have insufficient expertise in or access to information on relevant multi-domain operations (Builder et al., 1999)
- Increased dependence on multi-dimensional operation communication systems (Builder et al., 1999)
- C2 legacy systems incompatibilities
- Presence of a single-domain or service-centric mindset as well as cultural and organizational biases (Builder et al., 1999)
- Integrating multiple domains increases risks to unifying efforts
- Managerial aspects and budget allocation (Alberts & Hayes, 2006)
- Interservice conflicts and competition (Alberts & Hayes, 2006)
- Overlapping organizational structures (Hoehn, 2022)

Such challenges not only affect the technical or cultural feasibility of JADC2 but also pose congressional challenges to budgeting and funding this major effort (Congressional Research Service, 2021b). The JADC2 program will address and respond to these challenges.

Joint All Domain Command and Control Concept and Framework

The JADC2 envisions Joint Force command and control capabilities for the future. It aims to establish a warfighting capability that can effectively sense, interpret, and respond at all levels and phases of the war, across all domains, and in collaboration with partners. The ultimate goal is to provide information advantage with unprecedented speed and relevance (Alberts & Hayes, 2003; Kirtland, n.d.). The JADC2 strategy employs a System-of-Systems approach, which integrates various capabilities, platforms, and systems, and is aimed at accelerating the implementation of necessary technological advancement and doctrinal change in the Joint Force C2. JADC2 will enable the Joint Force to use vast volumes of data and convert them to information and knowledge, employ automation and AI, utilize a secure and resilient, and adaptable infrastructure, and act inside an adversary's decision cycle (Builder et al., 1999). To address these efforts, an implementation plan has been developed and a team appointed to oversee the process. This team consists of cross-functional SES-level members

from the areas of Combatant Command together with Services, Defense Agencies, as well as Joint and OSD staff.

Sense, Make Sense, and Act

Sense: To ensure the usability and usefulness of joint data for all forces/services and Joint Force Commander, a common and shared sensing methodology and information management technologies are required. The approach requires that information collection and provision in an operational environment can be conducted and delivered to the receiving. JADC2 implements a novel data-sharing approach in combination with advanced information management technologies. These networks are created based on federated data "fabrics" and enable the Joint Forces to achieve information that can be used for decision-making. Through sensing and integration, it is possible to "discover, collect, correlate, aggregate, process, and exploit data from all domains and sources (friendly, adversary, and neutral)" and "share the information as the basis for understanding and decision-making" (Kirtland, n.d.).

Make Sense: The process of making sense involves analyzing, understanding, and predicting the operational environment as well as the adversary and friendly force actions. In this phase, data is transformed into information, and information churns into knowledge. Making sense requires the ability to fuse, analyze, and render validated information from all domains and the electromagnetic spectrum. One major requirement in this phase is to provide secure as well as accessible information execution. The capabilities developed by JADC2 will leverage Artificial Intelligence and Machine Learning (ML) to accelerate the joint force commander's decision cycle (Builder et al., 1999; Kirtland, n.d.). The technical and procedural advancements will also significantly enhance the Joint Force's ability to operate in a C2 degraded environment.

Act: To "Act" is to make and disseminate decisions to the Joint Force and its mission partners. This phase combines the human elements of decision-making with the technical means to perceive, understand, and predict the actions and intentions of adversaries, and take action. This step includes decision analysis, conveying the decision, and the execution phase. Novel decision support applications will be implemented between Joint Forces through advanced, resilient, and redundant communication systems, an accessible and comprehensive transport infrastructure, and flexible data formats to enable the rapid, accurate, and secure dissemination of decisions. "Act" also means providing the Joint Forces with proper training. Using a Mission Command approach, subordinate commanders are empowered to act with confidence and authority through understanding a senior commander's operational intent while retaining the ability to act when communications linkages are broken or when the urgency of operations precludes the time necessary to seek guidance. Mission Command provides the Joint Force the agility and trust needed to seize the initiative and maintain information and decision advantage (Kirtland, n.d.).

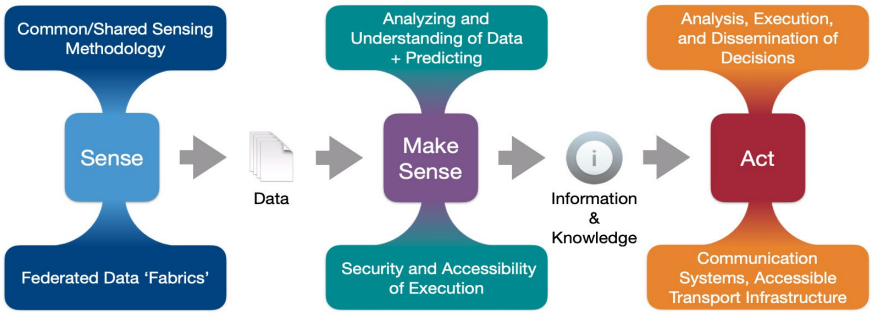

Figure 1. JADC2 Action Chain and Process

Lines of Effort (LOEs)

The JADC2 strategy is organized around five LOEs to guide Department actions in delivering capabilities, including data enterprise, human enterprise, technology enterprise, integrating with nuclear C2 and C3, and modernizing mission partners' information sharing. Each LOE is guided by an Office of Primary Responsibility represented by senior Flag/SES persons that can raise issues, interact with, and support the Joint Requirements Oversight Committee through its Joint Capability Board (Congressional Research Service, 2021a).

LOE 1: Establish Data Enterprise - The first LOE addresses the data structures and infrastructure. As a strategic asset, data must be effectively managed by JADC2 to enable it to seize, maintain, and protect information and decision advantage. To accelerate the decision-making process, joint forces must be able to discover and access any data and information from all warfighting domains at all levels of warfare. The following key data standardization objectives have been identified as critical to JADC2:

- Establishment of minimum metadata tagging criteria
- Adoption and use of standardized data interfaces
- Implementation of common data availability and access practices
- Incorporation of data security best practices
- Establishment of JADC2 conformant Information Technology (IT) standards
- Continued application of data strategic objectives (Visible, Accessible, Understandable, Linked, Trustworthy, Interoperable, Secure). (Kirtland, n.d.)

LOE 2: Establish the JADC2 Human Enterprise - The second LOE addresses the human and organizational performance in command-and-control capabilities using innovative tools such as Artificial intelligence and Machine Learning. This LOE is also tasked with reforming, realigning, or creating organizations with the structure, agility, and resources to more effectively combine the physical and informational strength of the Joint Force and its mission partners such that they are capable of exercising effective control of the Joint Information Advantage (JIA) operations (Kirtland, n.d.). The human enterprise will also address the professional development and training of the leaders as well as guide and support the development of JADC2 aspects of policies, concepts of operation (CONOPS), doctrine, and tactics, techniques, and procedures (TTPs) to optimize the advantages gained through new JADC2 capabilities.

LOE 3: Establish the JADC2 Technical Enterprise - The third LOE addresses enhanced shared situational awareness, synchronous and asynchronous global collaboration, strategic and operational joint planning, real-time global force visualization and management, predictive force readiness and logistics, real-time synchronization and integration of kinetic and non-kinetic joint and long-range precision fires, and enhanced abilities to assess Joint Force and mission partner performance (Kirtland, n.d.). The technical enterprise is required to provide secure, worldwide communications networks with sufficient speed and bandwidth to meet warfighting needs. LOE 3 also addresses the transport infrastructure of the JADC2, as well as essential minimum features necessary to ensure continuous C2 capability (communications system resiliency and diversity, multi-level security, elimination of single points of failure).

LOE 4: Integrate NC2/NC3 with JADC2 - JADC2 will have the capability to collaborate with nuclear C2 communication, and therefore the requirements for NC2 should be considered at the technical and human enterprise level (Kirtland, n.d.).

LOE 5: Modernize Mission Partner Information Sharing - The last LOE describes the institutional interoperability needs and organizational architecture for JADC2. The Joint Force Commander will establish and maintain a common understanding of the operational

environment through shared situational awareness with mission partners. Such integration is realized when data from each partner's C2 systems can be accessed, viewed, and acted upon by every other approved partner (Kirtland, n.d.). However, some challenging tasks in this LOE include emerging missions, large coalitions, and evolving technologies that present ongoing obstacles to achieving this goal.

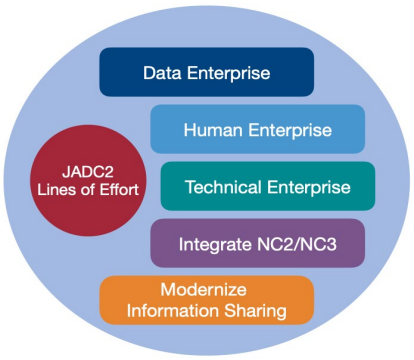

Figure 2. JADC2 Line of Efforts

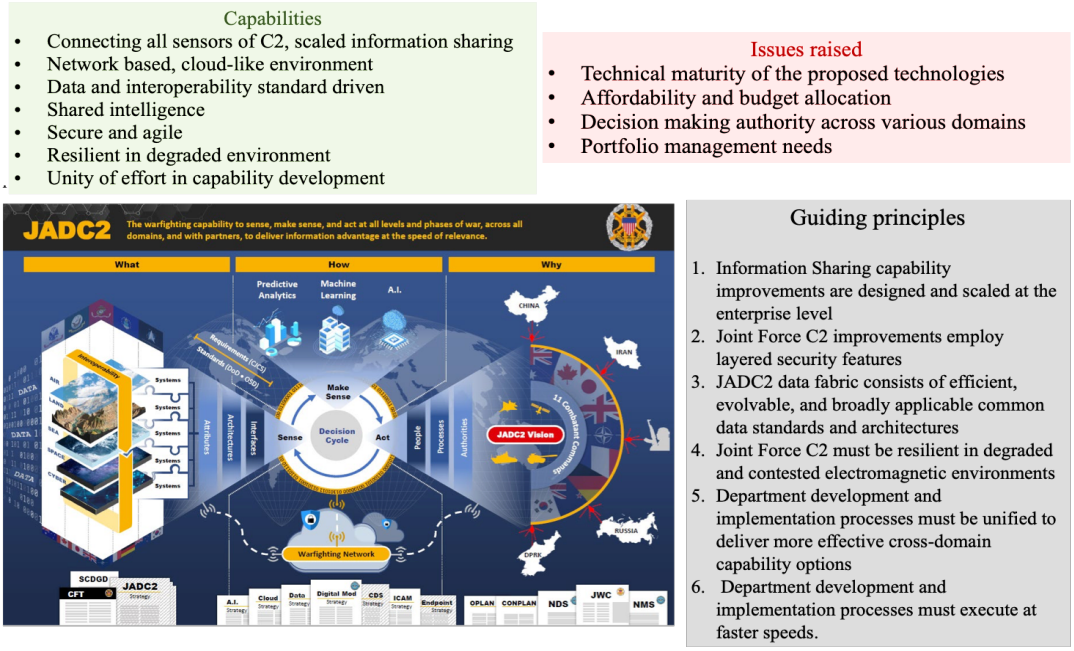

Figure 3. Summary of JADC2 Guiding Principles, Capabilities, and Issues Raised

Systemic and Lifecycle View of JADC2: Opportunities on the Horizon and Required Research

The Joint All-Domain Command and Control (JADC2) concept suggests joining sensors from all military services—Air Force, Army, Marine Corps, Navy, and Space Force— into a single network. Toward achieving this goal, the Department of Defense is pursuing the integration of a few emerging technologies including automation and artificial intelligence, cloud environments, and new communications methods. However, to integrate and infuse multiple new technologies into large legacy System-of-Systems (SoS), a systems and lifecycle approach

is essential to assure a sophisticated, cost-effective, low-risk, and highly capable, unique system that would provide an unparalleled unique set of capabilities to our military services.

There are multiple organizational, technological, sociocultural, and enterprise layers in JADC2 that are in perpetual interactions. The requirements for the JADC2 System of Systems are to integrate legacy systems into novel, disruptive, and cutting-edge technologies that need to be working smoothly together in a highly reliable, efficient, and cost-effective manner. Therefore, the authors propose a systemic approach to identify the opportunities and risks of such a complex system to assure the success of this great endeavor. In this section, the authors propose multiple systemic and lifecycle clusters of opportunities and risks that JADC2 is facing and provide direction of research and solutions for each identified opportunity.

This paper discusses five clusters of opportunities. The first opportunity is the need for novel culturally centered interoperable collaborative mechanisms between services/forces to ensure the formation of best practices in collaboration between the Air Force, Army, Navy, Marine Corps, Space Force, and other departments of defense services. The second opportunity discusses the imminent need for innovation and research in decision science, scenario analysis, and socio-culturally informed game theory modifications. The current game theory application is limited to rational and consistent actors, and the United States often is facing adversaries that are partially rational/or irrational and may have limited consistency in their behavior. The third opportunity discusses the need for complexity management of the growing network of interconnected sensors, decision-makers, and shooters. As the legacy system of sensor networks from all forces are united, the risk of excess network complexity rises and therefore there is an essential need for a resilient architecture for connecting legacy networks. The authors suggest a Universal Translator flexible network of hardware and software to connect all existing and future heterogeneous networks of sensors and assets. The fourth opportunity discusses the need for a novel and strong portfolio management framework for JADC2 Acquisition Programs (to manage, optimize, integrate, and fund JADC2-related projects and acquisition programs). JADC2 consists of multiple acquisition programs at software, hardware, and organizational level that are infused with current legacy and existing systems asynchronously and therefore would require high-level portfolio management to orchestrate multiple projects and tasks over the JADC2 lifecycle. And finally, opportunity 5 discusses the need for requirements and MBSE for JADC2 as an SoS in the following domains: materiel, non-materiel, policies, authorities, organizational constructs, and operational procedures (Nilchiani, 2022).

Opportunity 1: Create Novel Culturally Centered Interoperable Collaborative Mechanisms Between Services

All services and forces in the Department of Defense possess unique cultural and organizational heritage, history, and communication styles, and their assets are composed of legacy systems as well as the latest state-of-the-art in various technologies. One of the JADC2 lines of efforts (LOEs) is composed of human enterprise which involves the human and organizational aspects of the JADC2 implementation. However, the question remains what is the best organizational structure for the most optimal cooperation and collaboration between forces in JADC2? What potential force structure changes will be necessary to meet JADC2 requirements (Congressional Research Service, 2021b)?

The Department of Defense needs a unique one-of-a-kind approach to joining forces that recognizes the individuality and organizational identities of each joining organization, unique traditions, and values across various forces and departments. A successful collaborative solution calls for organic and optimal cooperation of different departments and forces while minimizing interdepartmental conflicts. Such a novel solution would require studies and research based on state-of-the-art organizational research on identity, historical and

anthropological studies of values and traditions of each of the forces, and proposing organic solutions that have emerged from voluntary and mutually agreed-upon collaborations. The JADC2's jointness factors and human enterprise needs to provide a unique organizational solution/blueprint that cannot be solved by technology alone. Figure 4 summarizes the first opportunity and relevant recommendations.

Suggestion: Invest in a unique, long-term, culturally informed solution/organizational blueprint of jointness that has dynamic longevity, versus limited, short-term "solutions" that do not solve core equities, roles, and functions.

Needed Academic Research: Organizational theory, Incentives to motivate jointness, organizational anthropology, and psychology to find the best and unique jointness and collaboration architectures.

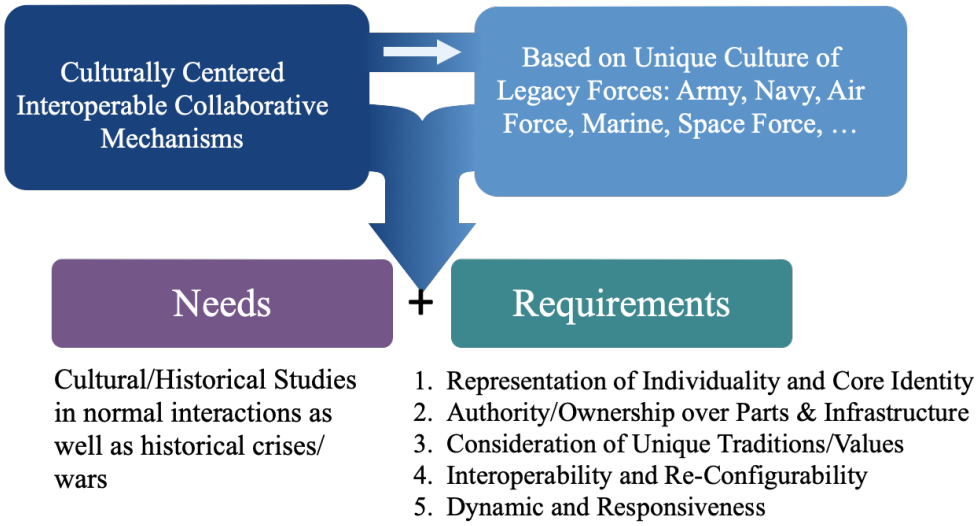

Figure 4. Conceptualization of Needs and Requirements for Organizational Solutions/Blueprints

Opportunity 2: Need for Innovation in Decision Analysis and Socio-Cultural Game Theory Modifications

At the core of JADC2, there are three actions of sense, making sense, and act on the collected and processed data from the sensors that are interwoven. Sensing and integrating provide the ability to discover, collect, aggregate, and process data from all domains and sources. Then using Machine Learning (ML) and Artificial Intelligence (Builder et al., 1999), the data gets fused, analyzed, and validated. The last step involves a critical decision-making process which is the focus of the suggestion on opportunity 2.

In the Act phase, joint forces engage in making and disseminating decisions to join forces and mission partners. A large portion of the tasks in this phase is to combine the following:

- Human elements of decision making
- Technological means to perceive, understand, and predict the actions and intentions of adversaries and take actions.

Game Theory explains the dynamics of situations where decision makers interact (Priebe et al., 2020) and has been used for decades in decision-making processes. The scientific focus of game theory addresses political, economic, and biological topics and phenomena predominantly (Priebe et al., 2020). The first major advances in game theory were made by Borel (1927; Alkire et al., 2018) in the 1920s together with von Neumann, who also later published one of the milestone publications in game theory, *Theory of Games and Economic Behavior* (Spirtas, 2018). More recently, game theory in economics has advanced dramatically by two Nobel laureates, John F. Nash (Michael et al., 2017) and John C. Hansanyi (1967).

Within the game theory, models are set up to represent the overall circumstances and dynamics which, four main aspects are defined: first, the decision makers, who are often considered players; second, the strategies and actions that each player/decision maker can choose; third the possible results and outcomes, that are linked to the action and strategic choices of the players; fourth, the payoffs respectively for each player in conjunction with the outcomes/results (Rapoport, 2012). In addition to these aspects, the players and decision makers within the scenarios are considered individually rational, meaning that the judgment of the payoffs in each player's perspective is rational and ordered, in addition to the assumption that each player assumes the other players to be rational (Rapoport, 2012). As a result, the players in the game can factor their knowledge and assumptions about other players into their strategy and can choose accordingly. Game theory allows for logical analysis of interest conflict situations as well as cooperation and therefore defines the theories of rational decision making in conflict situations (Lawlor, 2007).

Yet, the current approaches in decision analysis and game theory fall short of integration and use in JADC2. Game theory assumes rational and consistent actors/adversaries as the basis for strategies and decision analysis suggestions in conflict situations. However, not all actors/adversaries in game theory are ‘‘Rational." There is a critical need for novel research in socio-cultural game theory modification. This new science of decision analysis should take into account irrational and inconsistent players among adversaries from different socio-cultural backgrounds and create a modified game theory that strategizes based on new information.

In line with the need for modification of game theory, there is also a need for blueprints/systemic knowledge of adversaries' cultural norms, traditions, and mindsets, such as the underlying cultural norms and strategies presented in Sun Tzu (Bass et al., 2014; *JNT-501S Introduction to Joint Operations: Curriculum*, 2019) and to find the best decision analysis methodologies that take into account cultural differences, values, and approaches. *The Art of War* has been the authoritative military and political guide in the Far East for many centuries and translated and used in the West for the past century. There is a need for academic research to translate the principles of *The Art of War* into abstract rules and heuristics and create a framework that can enable a deep understanding of adversaries' actions and suggest the best strategies in action for JADC2. As an example, the five essentials for victory from Sun Tzu can be interpreted as follows:

1) Timing of the fight is essential (suggestions for minimizing engagement and optimizing the timing of decision points)
2) the ability to handle superior as well as inferior forces (scalability and ability to engage with adversaries of various scales and capability of forces)
3) applying the same operational principles across ranks in forces
4) preparation and taking adversaries when unprepared (which will point at surveillance and intelligence and accumulation of patterns and blueprints of operation)
5) military capacity and scalability of operations.

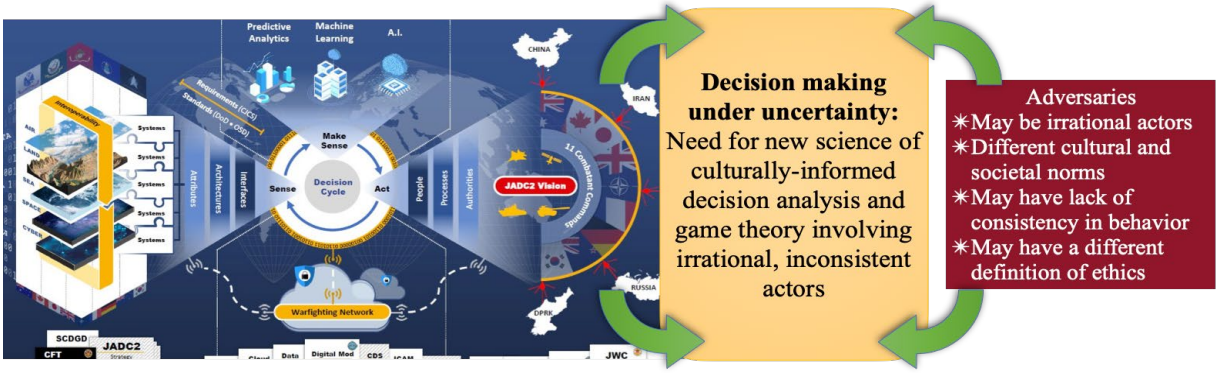

Figure 5. Conceptualization of the Need for Advancement in Modified Game Theory

Academic research that enables these advances are the following but not limited to the organizational theory, incentives to motivate jointness, game theory and modification for irrational and inconsistent actors/adversaries and extracting and understanding operational principles of various actors/adversaries that are culturally informed such as Sun Tzu.

Opportunity 3: Universal Translator System for Federated Heterogeneous Networks of Sensors: Complexity Management of the Growing Network of Interconnected Sensors, Decision Makers, and Shooters

One of the core technical challenges of JADC2 is the integration of the highly technical legacy sensor networks that are managed and operated by all forces/services. Each service owns a state-of-the-art in intelligence, surveillance, and reconnaissance sensor network that are not necessarily interoperable with other forces' tactical networks. Sense and integration are the ability to discover, collect, correlate, aggregate, process, and exploit data from all domains and sources (friendly, adversary, and neutral) and share the information for decision-making. The requirements for effective data integration must be considered from the earliest stages of data sharing and security and applied across the warfighting domains to deliver rapid collection, fusion, and customization of data (Kirtland, n.d.).

The heterogeneity of the tactical networks and assets of the DoD poses some challenges as well as great advantages to JADC2. The technological solutions for integrating multiple heterogeneous tactical networks are numerous, and many are suboptimal. Each solution uses a specific systems architecture and a combination of technical hardware and software solutions. However, in choosing the best technical solution for integrating a network of sensors, two systems characteristics are of critical importance: flexibility and complexity. Flexibility is the ability of the system to respond to various internal and external changes in a timely and cost-effective manner and is therefore critical for the JADC2 network of sensors, as various scenarios may rise that would need a prompt rearrangement of the interconnected networks. Increased complexity in architecture and technical solutions can also contribute to a fragile network that is prone to errors and attacks on the network, and therefore the complexity of the technical solution should be controlled (Chullen & Nilchiani, 2021; Nilchiani & Pugliese, 2017; Priebe et al., 2020; Pugliese et al., 2018).

As JADC2 looks for the best technical solutions for merging the network of sensors, there are multiple factors that should be considered:

- Need for compartmentalization and federation of complex networks, especially to accommodate the culturally centered interoperable collaborative mechanisms.

- Need for firewalling (protection by isolating from the rest of the networks) and multi-layered security of critical portions of the network, if the need arises (e.g., to separate service-specific functions from joint functions, or if the network goes under attack by an adversary)
- Ownership and management of the integrated networks of sensors: The choice between equal ownership on all interconnected networks versus keeping the primary ownership of each network by forces and sharing when needed (military Services, allied, and coalition)
- How to avoid vulnerabilities from monolithic jointness? Should the heterogeneity of each network remain intact?
- How to isolate adversaries sabotaging efforts, firewall their attacks on our networks, and respond?
- How to avoid and halt intentional/malicious propagation in the network? Noise propagation can delay sensor reading and interpretation of results and affects the effective decision-making process.

The excess network complexity and connecting leads to risks of errors (error propagation and from cross-Service misunderstandings) and vulnerability to attacks from adversaries. The technical solution should address managing complexity on a regular basis and incorporate flexibility and the ability to reconfigure the heterogeneous networks of sensors if the necessity arises. Multiple DoD initiatives related to JADC2 efforts have been working on technical solutions, including Mosaic Warfare (DARPA), Advanced Battle Management System (ABMS; Air Force), Project Convergence (Army), Project Overmatch (NAVY), Fully Networked Command, Control, and Communications (FNC3; Office of the Secretary of Defense), and Fifth Generation (5G) Information Communications Technologies (DoD Chief Information Office). DARPA's Mosaic Warfare program has specifically focused on the need for flexibility and responding to ever-changing environments and scenarios and therefore studying solutions that are responsive to rearrangement and change in situations and environments rapidly.

Technical Solution: Universal Translator System for Federated Heterogeneous Networks of Sensors (Rosetta Stone)

The technical solution for joining networks from all forces (Army, Navy, Air Force, Marine, Space Force) requires achieving a system-of-systems that is more resilient, flexible, and responsive to demands and produces greater information and insights in different scenarios that the DoD is facing. Often, over connecting all sensors and assets of all forces/services could pose some substantial problems including but not limited to 1) slowdown in sensor and information transfer, 2) increased risk of errors and issues in the collection and transfer of data, 3) network vulnerability in the face of cyber attacks and loss of ability to swiftly isolate and contain attacks.

The authors suggest the exploration of a novel concept of a universal translator infrastructure. This Universal Translator would consist of a combination of embedded hardware and software distributed nodes that will act as the interface translator between federated network sensors and assets across all five forces/services as well as all DoD agencies. Figure 6 shows the Universal Translator network concept.

The characteristics of the Universal Translator are as follows:

- Translation between different legacy systems takes place at certain physical hardware and software nodes which are positioned between two or more heterogeneous networks of sensors, belonging to different forces.
- There will be no need to invest in making all sensor assets from different forces into a unanimous frequency and standard. The Universal Translator will provide the translation

between networks, and legacy systems can continue their normal functions with no interruption.

- Universal Translator can consist of multiple nodes as well as redundancies that can operate as a fractionated network of translators and can be easily expanded, modernized, and upgraded with the latest state-of-the-art in technological advances in the future, and rearranged to create new network functions and topography on demand. This concept will provide a high degree of flexibility, adaptation, and upgradability, as well as an added layer of security and protection for all assets and sensors across all forces.
- Universal Translator nodes will act as a bottleneck between two separate networks and can act as a firewall mechanism. If necessary to turn off or isolate a sensor network under attack, certain translator node(s) can be turned off which will revert the isolated network to its original function.
- The Universal Translator network can be embedded with various security layers, giving each force's network extra protection and the ability of Mosaic Warfare (DARPA) novel network rearrangement and protocols.
- Each force can yet command their original assets (network of sensors) as the primary owner of the assets as well as share their data through permission and activation of the Universal Translator to the other forces. Data from various forces can be shared without the need to share the detailed blueprint and architecture behind each network.

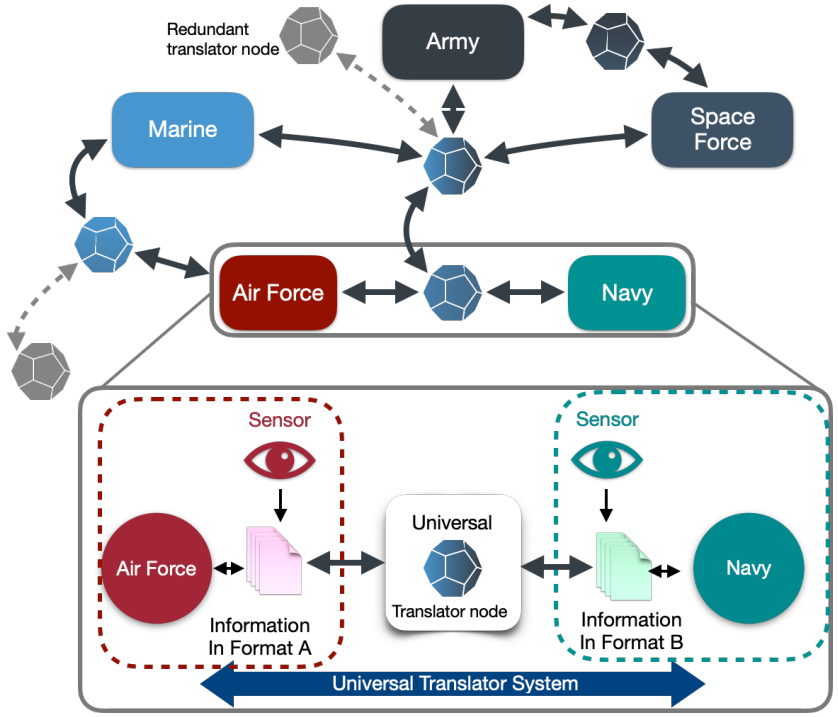

Figure 6. Concept of Universal Translator/Rosetta Stone Infrastructure With a Detailed View of the Universal Translator Infrastructure and Software Translating Data Between Two Agencies/Forces (Nilchiani, 2022)

Suggestion: Invest in a Universal Translator system for federated heterogeneous networks of sensors that can preserve service-specific functions yet interface seamlessly with joint functions and also operate independently from the rest of the network if under attack.

Opportunity 4: Portfolio Management of JADC2-Related Acquisition Programs

In *Joint All-Domain Command and Control: Background and Issues for Congress* (Hoehn, 2022), there are several clusters of questions raised regarding managing JADC2-related efforts, budget, cost estimates, and requirements. Among those questions were JADC2 spending priorities, initiatives as well as management of JADC2-related efforts. The solution to managing multiple JADC2-related efforts is to adopt the best practices in portfolio management from the industry and create a comprehensive DoD portfolio management framework to manage multiple efforts. By studying the best of industry innovations on portfolio management, innovative System-of Systems, and enterprise-level frameworks can be created that empower joint staff of JADC2 to manage, optimize, integrate, and fund JADC2.

JADC2 consists of multiple efforts in data, human, and technical enterprise that fit within hardware, software, business, and major acquisitions. Dealing with multiple concurrent capability acquisitions needs a System-of-Systems-based framework that integrates multiple programs, and a portfolio management approach that funds, manages, and integrates multiple potentially asynchronous acquisition programs for JADC2. The portfolio management framework will need to incorporate the shared governance structure (architecture of governance) for JADC2-related projects.

Academic Research: Portfolio management framework for multiple acquisition programs, Shared governance architecture

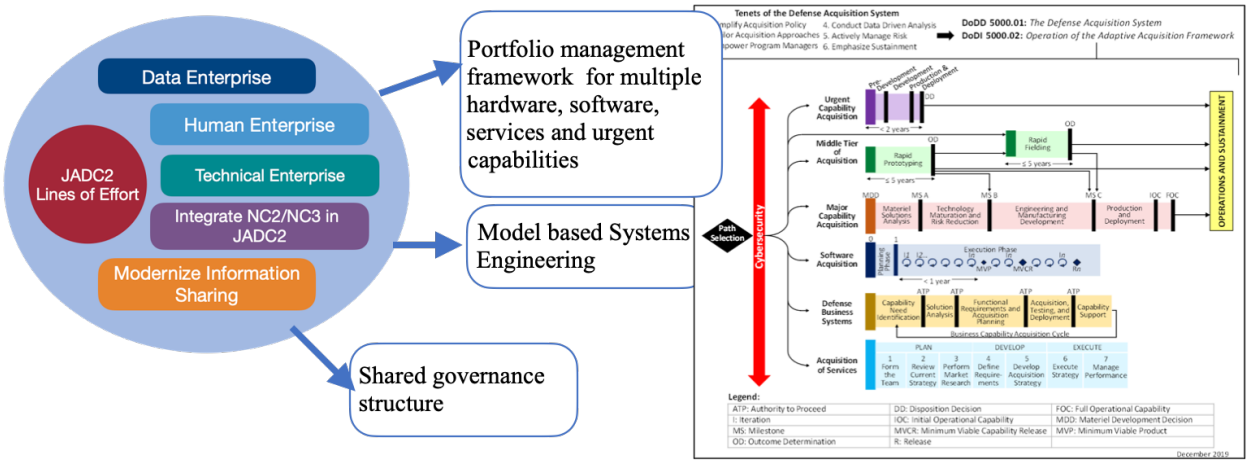

Figure 7. Conceptualization of the Need for Portfolio Management for All JADC2-Related Acquisition Programs

Opportunity 5: Needs, Requirements, and MBSE for JADC2 as a System of Systems

Joint All-Domain Command and Control (JADC2) is a System of Systems that operates in domains of materiel, non-materiel, policies, authorities, organizational constructs, and operational procedures and therefore in need of systems engineering tools and methodologies to assure the most optimal system of systems. Model based systems engineering (MBSE) can help in responding optimally to categories of questions regarding the acquisition of individual technologies/programs, lifecycle management, and periodic upgrade and infusion of novel technologies to JADC2, as well as ownership and management of various sensors and assets in JADC2.

MBSE can help identify joint-specific systems, needs, and requirements, and guide the acquisition process for a portfolio of programs and technologies. Technical questions about how sensor networks of various forces and services will be connected, the architecture, and the concept of operation are enabled by the systems approach. MBSE can also find optimal solutions to lifecycle-related questions of JADC2 including identifying new disruptive technologies and integration with current legacy systems, as well as complexity management of the growing interconnected sensor and asset networks of JADC2.

MBSE can also provide suggestions and solutions for network ownership and architecture for various assets. For example, can jointness be achieved and implemented successfully while respecting primary ownership of each force over their assets/sensors? Using the concept of universal translator, each service can retain its primary ownership and command over its assets and sensors and share a secondary ownership of all assets on a need basis. In extreme scenarios, the primary owner can sever their assets from the rest of the network to protect their assets or other services assets and operate independently if need be.

Summary

This paper provides an overview of the current state of the Joint-All Domain Command and Control and suggests a set of recommendations and opportunities through the lens of academic research and development (R&D). This set of opportunities emphasizes the need for research and development and gaps in knowledge, technologies, procedures, and capabilities that can empower JADC2 as a resilient, agile, adaptive, and strong shared command and control platform.

The following opportunities were proposed in the paper: *opportunity 1*: novel culturally centered interoperable collaborative mechanisms between forces (organizational and cultural studies; *opportunity 2*: necessity for innovation in decision analysis and game theory (modified based on adversaries' socio-cultural nuances); *opportunity 3*: need for complexity management and best system architecture design for the growing network of interconnected sensors, decision makers, and shooters (the authors suggests a Universal Translator network concept of hardware and software to connect all existing and future heterogeneous network of sensors and assets of the DoD, which will empower rearranging, reorganizing, expanding, and infusing the latest advances in technologies as they become available); *opportunity 4*: need for a novel, strong portfolio management framework of JADC2 Acquisition Programs (to manage, optimize, integrate, and fund JADC2 related projects and acquisition programs); and *opportunity 5*: need for Model Based Systems Engineering (MBSE) for JADC2 as an SoS in domains of materiel, non-materiel, policies, authorities, organizational constructs, and operational procedures.

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References

Advanced battle management system (978-0-309-68621-1). (2022). https://nap.nationalacademies.org/catalog/26525/advanced-battle-management-system-needs-progress-challenges-and-opportunities-facing

Alberts, D. S., & Hayes, R. E. (2003). *Power to the edge*. http://edocs.nps.edu/dodpubs/org/CCRP/Alberts_Power.pdf

Alberts, D. S., & Hayes, R. E. (2006). *Understanding command and control*. https://apps.dtic.mil/sti/citations/ADA457162

Alkire, B., Lingel, S., Baxter, C., Carson, C. M., Chen, C., Gordon, D., Hanser, L. M., Menthe, L., & Romano, D. M. (2018). *Command and control of joint air operations in the Pacific: Methods for comparing and contrasting alternative concepts* (9780833098085). https://www.rand.org/pubs/research_reports/RR1865.html

Bass, B. K., Bartels, D. K., Escalante, S. A., Fenton, D. R., & Rathgeb, K. J. (2014). *Overcoming joint interoperability challenges*. National Defense University Press. https://ndupress.ndu.edu/JFQ/Joint-Force-Quarterly-74/Article/577545/overcoming-joint-interoperability-challenges/

Birch, P., Reeves, R., & Dewees, B. (2020). *Building the command and control of the future from the bottom up*. Metamorphic Media. https://warontherocks.com/2020/01/building-the-command-and-control-of-the-future-from-the-bottom-up/

Borel, É. (1927). Sur les systèmes de formes linéaires à déterminant symétrique gauche et la théorie générale du jeu. *Comptes rendus de l'Académie des Sciences*, *184*, 52–53.

Builder, C. H., Bankes, S. C., & Nordin, R. (1999). *Command concepts: A theory derived from the practice of command and control*. RAND. https://www.rand.org/pubs/monograph_reports/MR775.html

Chullen, C., & Nilchiani, R. (2021). Infusion complexity: Understanding the need to measure infusion success of advanced technologies into complex systems. *2021 IEEE International Systems Conference (SysCon)*.

Congressional Research Service. (2021a). *Defense primer: What is command and control?* https://crsreports.congress.gov

Congressional Research Service. (2021b). *Joint all-domain command and control: Background and issues for Congress*. https://crsreports.congress.gov

Congressional Research Service. (2022). *Joint all-domain command and control (JADC2)*. https://crsreports.congress.gov

Doctrine for the Armed Forces of the United States. (2013). A. F. o. t. U. States.

DoD. (2022). *Summary of the joint all-domain command & control (JADC2) strategy.*

Feickert, A. (2022). *U.S. special operations forces (SOF): Background and issues for Congress* (RS21048). https://crsreports.congress.gov/product/details?prodcode=RS21048

Friedman, B. H. (2019). *Bad idea: Management jointness in DoD*. Center for Strategic and International Studies. https://defense360.csis.org/bad-idea-management-jointness-in-dod/

Hansanyi, J. (1967). Games with incomplete information played by Bayesian players, I: Basic model. *Management Sci*, *14*(3), 159–182.

Hoehn, J. R. (2022). *Joint all-domain command and control: Background and issues for Congress*. https://crsreports.congress.gov/product/details?prodcode=R46725

JNT-501S introduction to joint operations: Curriculum. (2019). https://fairchild-mil.libguides.com/Introduction_To_Joint_Operations

Joint doctrine publication 5 command and control. (2012).

Jointness - A selected bibliography. (1993). https://apps.dtic.mil/sti/pdfs/ADA272189.pdf

Kirtland, M. A. (n.d.). https://www.airuniversity.af.edu/Portals/10/ASPJ/journals/Chronicles/joint.pdf

Kreisher, O. (2001). The quest for jointness. *Air Force Magazine*. https://www.airforcemag.com/article/0901joint/

Lawlor, M. (2007). *Military jointness grows up*. AFCEA International. https://www.afcea.org/content/military-jointness-grows

McInnis, K. J. (2021). *Defense primer: Commanding U.S. military operations*. https://crsreports.congress.gov/product/details?prodcode=IF10542

Michael, K., Siman-Tov, D., & Yoeli, O. (2017). Jointness in intelligence organizations: Theory put into practice. *Cyber, Intelligence, and Security*, *1*(1). https://www.inss.org.il/wp-content/uploads/2017/03/Jointness-in-Intelligence-OrganizationsTheory-Put-into-Practice.pdf

Nardulli, B. R., Cliff, R., Bensahel, N., Rostker, B. D., Pirnie, B. R., Gordon, J., IV, Orletsky, D. T., Hosek, S. D., Peltz, E., & Halliday, J., e. a. (2003). *The U.S. Army and the new national security strategy*. RAND. https://www.rand.org/pubs/monograph_reports/MR1657.html

Nilchiani, R. R. (2022). *Joint all-domain command and control (JADC2) technical challenges and research opportunities* [Report]. https://document.acqirc.org/publication_documents/reports/1670425668.JADC2_REPORT.pdf

Nilchiani, R. R., & Pugliese, A. (2017). *A systems complexity-based assessment of risk in acquisition and development programs*.

O'Rourke, R. (2021). *U.S. role in the world: Background and issues for Congress* (R44891). https://crsreports.congress.gov/product/details?prodcode=R44891

Priebe, M., Ligor, D. C., McClintock, B., Spirtas, M., Schwindt, K., Lee, C., Rhoades, A. L., Eaton, D., Hodgson, Q. E., & Rooney, B. (2020). *Multiple dilemmas for the joint force: Joint all-domain command and control*. https://www.rand.org/pubs/research_briefs/RBA381-1.html

Pugliese, A., Enos, J., & Nilchiani, R. (2018). *Acquisition and development programs through the lens of system complexity*.

Rapoport, A. (2012). *Game theory as a theory of conflict resolution* (Vol. 2). Springer Science & Business Media.

Spirtas, M. (2018). *Toward one understanding of multiple domains*. RAND. https://www.rand.org/blog/2018/05/toward-one-understanding-of-multiple-domains.html

Theohary, C. A. (2021). *Defense primer: Cyberspace operations* (IF10537). https://crsreports.congress.gov/product/details?prodcode=IF10537

Transforming the joint force: A warfighting concept for great power competition. (2003). Defense Media Activity - WEB.mil. https://www.pacom.mil/Media/Speeches-Testimony/Article/2101115/transforming-the-joint-force-a-warfighting-concept-for-great-power-competition/

Woolf, A. F. (2021). *Defense primer: Command and control of nuclear forces* (IF10521). https://crsreports.congress.gov/product/details?prodcode=IF10521

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