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Network Foundation for Command and Control (C2) Systems: Literature Review

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ABSTRACT We review the command and control (C2) literature to develop a comprehensive understanding of C2 systems and identify network evaluation methods. C2 is the recursive process of sharing the intent of decision-makers across organizations, turning intent into action, monitoring success, and adjusting goals to meet changing needs. Although substantial C2 research exists, the literature remains isolated by application context, and advances are rarely integrated. Our review identifies research in military, emergency response, civilian infrastructure, and management literature that inform the analysis of C2 systems. We organize C2 research with theory from Network Centric Warfare and complex systems to integrate knowledge across broad disciplines and applications. The review organizes studies across four interrelated domains (i.e., physical, information, social, and cognitive), presents system design and evaluation constraints across subsystems, and offers practical considerations for advancing C2 theory. The review also catalogues network evaluation methods used to study C2 agility, i.e., the ability to successfully effect, cope with, and/or exploit changes in circumstances. Together, this paper supports the organizing, integration, and advancement of knowledge for the influential, yet broad research subject of C2.

INDEX TERMS Agility, command and control, multilayer networks, network science, system architecture.

I. INTRODUCTION

Command and control (C2) systems are important, pervasive systems in modern society. C2 is understood as the process taken by teams and organizations to complete a shared goal [1], [2], and C2 systems are sociotechnical collections of human interactions, social norms, and built technologies that enable this process [2], [3]. Historical understandings of C2 refer to the strict, bureaucratic, and hierarchical structures of military organizations where individual roles are clear and mission expectations are non-negotiable [4], [5]. Contemporary notions of C2, in contrast, refer to any organizational structure that connects people to perform shared goals, and emphasizes processes that enable decision-making and information-sharing rather than the social context in which they occur [4], [6]. This broad view on C2 includes military hierarchies alongside public utilities and civil infrastructure managers [7], loosely connected non-governmental organizations during emergency response [8], and even virtual organizations formed on the internet that lack rules for establishing leadership, allocating workloads, or monitoring business activities [9]. Definitions of a leader, the act of sharing intent, and completing a task or mission depend upon the organizational structure in which C2 is being performed. C2 organizations are often geographically separated in such a way that requires information and communication technology (ICT) to share skills and knowledge, yet still have long-term interests and shared goals that maintain interaction among participants [9]. Linking the historical and contemporary, essentially any collaborative group of people using ICT to achieve a shared goal can be characterized by a form of C2.

The purpose of C2 research is to be *descriptive* for which social and technological relationships will succeed in performing shared goals and *prescriptive* for how to design better C2 systems. Descriptive research reveals underlying factors that enable successful completion of missions, often measured as the speed an organization can complete a task, the diversity of different tasks an organization can complete, the amount of shared information among organizational members, or a combination of all three [10]. Some descriptive research is also explanatory of sociotechnical phenomena and uncovers drivers and causal forces that dictate why some human or technological arrangements are more effective than others [11], [12]. Prescriptive research then builds on these results to rearrange existing social relationships and/or introduce disruptive technologies to improve existing C2 processes. Together, C2 research endeavors have broad impact on social systems of decision hierarchy, interpersonal interactions, knowledge sharing, training, and skills and technological systems that enable data collection and resource use to act upon changing situation context.

Despite the potential for C2 research to improve the design of real-world sociotechnical systems, the broad literature remains disorganized and isolated in publication. Only few seminal works offer an integrated understanding of C2 theory (see [4], [8]), and none organize applied studies to show how C2 is understood and evaluated across contexts. This allows almost any new study involving a shared goal, ICT systems, software development, or a social network to claim it advances C2 theory. This lack of organization produces a disconnected body of knowledge and creates confusion for newcomers as some C2 related topics like 'social networks' encompass thousands (if not millions) of research records. This also results in a lack of standard practices across experts that limits advances in C2. One consequence is that the majority of research remains descriptive rather than prescriptive in experimental design, modeling, and analysis. New studies slow the development of prescriptive studies by relying on novel methods for analysis rather than common frameworks. The few studies that do prescribe ways to improve system-level C2 processes are completed in a piecemeal fashion that is not re-integrated into a comprehensive theory. C2 literature is marred by a disconnected landscape of research that inhibits the possibility of advancing research to an applied practice.

The purpose of this work is to review and organize the C2 literature in a manner that makes it more understandable and more usable. C2 literature needs integration of existing knowledge to guide the design of systems that successfully adapt to changing circumstances. This work has two specific goals: (1) organize and integrate the disconnected C2 body of knowledge, and (2) offer guidance to support more informed descriptive and prescriptive research. We achieve these goals via a comprehensive literature review that organizes research with well-established C2 theory and network evaluation methods. The paper concludes with a network science perspective on C2 literature that presents design and modeling constraints considered in past C2 research and five considerations for future C2 research.

A. NETWORK CENTRIC WARFARE AS GUIDING THEORY

The military doctrine of Network Centric Warfare (NCW; c.f. Network Enabled Capability (NEC) [8]) offers a basis for organizing advances in C2 research. C2 research is guided by few overarching theories that break down the structure and function of sociotechnical systems for analysis and design. NCW is one of the most widely cited C2 theories that emphasizes the relationship between successful C2 processes and networked system structure. NCW doctrine was developed by the US Department of Defense (DoD) Command and Control Research Program (CCRP) [4], [13], [14] for harnessing rapid, ubiquitous, ''Information Age'' technologies to improve C2 activities. NCW is centered on 21st century technological advancements like the internet, wireless networking, sensors, and satellites that brought a shift in society by making ''information'' a strategic asset [10]. Information in this context refers to high volume, velocity, and variety data [15] that enables automated and distributed systems to work together and now underlies most aspects of daily life. While society writ-large quickly adopted Information Age technologies, this transition was difficult in military organizations that have long-standing social hierarchies and strict information assurance and security requirements. NCW started in the late 1990s as a critique on the lack of adoption of Information Age technologies in military C2 processes alongside a shift in perspective from treating military units as independent platforms to networked systems [16]. The resulting doctrine developed by the CCRP provides a comprehensive theoretical overview of C2 systems, processes, and needs, while also identifying characteristics of successful C2 systems. Organizing C2 research with respect to NCW doctrine provides a useful way to understand the current state of knowledge and offers a basis for making recommendations for future work.

In particular, NCW doctrine establishes that successful C2 systems are *agile* to adapt to changing mission needs, such that reviewing how current research advances NCW theory may reveal how to design agile systems. Agility is defined in NCW literature as, ''the ability to successfully effect, cope with, and/or exploit changes in circumstances'' [10], which corresponds to similar definitions found in manufacturing [17], management [18], and infrastructure [19] contexts. Agility is comprised of both passive and active components such as responsiveness, flexibility, and resilience among others [10] that influence how exploiting a situation may occur. Agility is studied in NCW via three dimensions that define the *C2 approach space*: (1) allocation of decision rights to the collective, (2) patterns of interaction, and (3) distribution of information [8]. NCW doctrine asserts that these three organizational dimensions can predict a system's agility, where C2 systems range from ''Conflicted C2'' with the least agility due to constrained decision rights, patterns of interaction, and distribution of information to ''Edge C2'' with the highest agility due to unconstrained decision rights, patterns of interaction, and distribution of information. NCW prescriptive recommendations focus on shifting existing systems from Conflicted C2 to Edge C2 by adopting novel policies and technologies that decentralize decision rights, increase the frequency of interactions, and increase the richness of information sharing. An important output of this review is identifying studies that describe and prescribe ways to achieve agile systems and Edge C2.

B. MULTILAYER NETWORK SCIENCE AS A GUIDING FRAMEWORK

Advancing NCW doctrine requires finding the right balance between generic systems analysis methods that apply to a breadth of C2 sub-systems and operational specificity to capture C2 context and dynamic processes that dictate agility. Considering this need, we also review the C2 literature to identify network models and analysis methods that are generic enough to capture a breadth of contexts across descriptive research, but specific enough to prescribe context-specific network designs.

Network science is a popular way to model C2 sub-systems and offers a basis for comparing evaluation methods across C2 research. A network is a system model comprised of nodes representing constituent parts and links representing nodal interactions. Network science methods are useful for studying the structure and function of C2 sub-systems by ranking nodes and links, where social and technological networks use the same methods to represent different constructs and dependencies [20]. For example, a social network of people linked by who-knows-whom can quickly reveal critical actors and relationships that support information flow and decision-making. This is evaluated at the component scale by ranking individuals via simple measures like the number of links a person has [21] and at the system scale by classifying network topology [22]. Studies also show relationships between system structure with network stability [23] and C2 processes like agility and resilience [24]. Thus, network science models and analysis methods provide a consistent basis for comparing technical advances in the C2 literature, even when considering disparate models and application contests.

Recent advances in multilayer network science provide additional justification for using networks to compare evaluation methods found in the C2 literature. While research on a single C2 sub-system like ICT is important, advancing C2 theory requires new knowledge at the intersection of human and technological sub-systems. Growth in network science literature has brought with it the extension of methods for individual networks to the integrated analysis of multiple networks together. As network models provide a basis for comparing evaluation methods among disconnected sub-systems, multilayer network analysis [25]–[27] provides a consistent way to compare interactions among interdependent sub-systems. Examples of multilayer network studies that inform C2 theory include coupled cyber-physical networks [28], sociotechnical networks [20], and cyber-physical-social networks [29]. The breadth of these studies emphasizes that multilayer network science provides a flexible way to organize literature across disparate application contexts. Moreover, comparing C2 literature through the lens of network models and analysis can set a baseline for the current state of C2 knowledge within and across sub-systems.

This review links NCW doctrine and multilayer network science to identify which studies advance C2 agility. While the primary goal of this work is to organize the field, a secondary goal of this work is to identify how well network science serves C2 research. The generic nature of network science methods is both advantageous and problematic for C2 theory, because network analysis of diverse human and technological systems is possible even when detailed understanding of either is lacking. Research that is overly specific to a single application context is not necessarily helpful for advancing C2 research. However, multilayer networks that reveal interactions across sub-systems often lack consideration of the physical principles or operational specifications of C2 systems making them inappropriate for real-world use. In more extreme cases, network science studies can even be counterproductive to C2 research when narrow applications ignore the breadth of sociotechnical interactions or results produced with unrealistic models lack operational detail [30]–[32]. Identifying how network science is applied in C2 literature can help overcome these issues to further both NCW doctrine and network evaluation methods.

II. METHODS

We review the C2 research literature to organize and integrate diverse studies. First, we collect research articles and reports across C2 disciplines including NCW doctrine, complex systems science, and theories of interdependent systems. Each of these topics on their own has thousands of associated research articles, however few studies cover all topics and integrate them into a comprehensive framework. To limit our review to the smaller subset of studies and frameworks that overview these topics, we used the following methods. First, we used the software ***Harzing's Publish or Perish 5*** [33] to retrieve and analyze C2, network science, and complex systems publications on Google Scholar [34]. We use Google Scholar as our preferred repository because a significant amount of literature on C2 is found in military reports and books that are not indexed in other academic search engines like ISI Web of Knowledge or Sciencedirect. We conducted three Google Scholar searches to collect articles with the exact phrase "command and control" and any of the words "centric, enabled, operations, OR capability" in the title or abstract. Each search was further specified to contain all of the words "multilayer AND agility" (412 records) and "sociotechnical AND agility" (739 records). Non-English records, records published before 1997, records with 0 citations, patents, and citations with no document were removed. Remaining records were combined to produce a raw data set of 588 records.

We define four sub-sets of records to refine the list from 588 to 97 records for more focused review. Google Scholar searches were compared to see which documents were duplicated across searches conducted. No single study was found by all three searches, and only 23 documents were found by more than one. These 23 records formed one sub-set of review articles, because they are a short list of studies that cover the greatest extent of C2 agility related topics. In addition, we formed three additional subsets for records with specific words in their title: command or control (32 records), C2 (10 records), and network (48 records). The four sub-sets were combined and further refined by removing records in topic areas unrelated NCW doctrine or the structure of C2 systems, including: network studies not involving NCW domains, post-modern social theory, video games, education, and health. The final combined list of 97 records represents the most relevant sources across peer-review articles, military reports, conference papers, and theses available on Google Scholar.

We review the 97 records based on theory from NCW doctrine and complex systems. We draw upon NCW doctrine to define the social and technological sub-systems that comprise C2 networks. NCW doctrine defines four *domains of warfare* that dictate C2 agility, where each domain can be represented by network models. Alberts and Hayes [4] and Atkinson and Moffat [35] provide the first descriptions of C2 domains by linking complex systems science to the structure and implementation of military policies. The authors describe C2 as an interacting set of layers, including the physical world, the information exchange that occurs over physical systems, the interpretation of data by people, and a shared understanding generated by this process. Thus, a simple task like sending an email involves networks of technologies that the individual has access to (e.g., computer), software and digital services required to deliver an email, values and beliefs of the individuals writing and reading the email, and actions taken due to this exchange. Based on this definition, C2 systems are comprised of at least four interacting sub-systems representing physical, information, social, and cognitive systems. These descriptions were formalized into four broad domains by the NATO research task group SAS-065 [8] as:

- Physical Domain: sensors, facilities, and equipment;
- Information Domain: creation, manipulation, and storage of data;
- Social Domain: human organization and interactions; and,
- Cognitive Domain: mental models, preconceptions, biases, and values.

We also use complex systems theory that defines the *architecture* of each NCW domain to specify how to analyze C2 networks. Current C2 theory falls short of defining network primitives used to construct a C2 network model (i.e., nodes and links). Instead, we draw upon complex systems theory of *system architecture* to establish the constraints that dictate model structure and function. In particular, Alderson and Doyle [31] define four design constraints that capture the breadth of system architectures found in physical, cyber, social, and cognitive domains, including:

- Component constraints: physical laws and requirements that dictate the capability of network nodes;
- Protocols: rules for the configuration and interaction of system components;
- System-level constraints: higher-level functional purpose of a single network layer including objectives and design criteria the system is meant to serve, e.g., maximizing radar signal; and,
- Emergent constraints: the laws that dictate physical limitations of real systems often expressed as needs and interactions across systems.

Together, this review organizes the research literature to identify the state-of-the-art with respect to NCW doctrine and complex systems science. Specifically, we assess the sample of 97 records from the literature based on the NCW domains of warfare they discuss and the systems architecture constraints they consider. Through this process we integrate perspectives across disparate research studies into a multilayer network framework. We also identify the network science measures used in literature that can act as a starting point for assessing C2 agility in future research.

III. RESULTS

Our review synthesizes technical considerations for each NCW domain from existing literature and how to translate them into networks. C2 literature span all NCW domains, with each work studying subsets of domains summarized in Table 1 and discussed throughout this section. We overview guidance from each domain and combination of domains with respect to technical considerations in system analysis and design. Moreover, we identify existing network science models and measures that may guide multilayer C2 network analysis.

TABLE 1. C2 Literature organized by NCW domains of warfare.

Phys.	Info	Social	Cog.	Qty.	References
■				1	[37]
	■			3	[36], [38], [39]
		■		7	[40]–[46]
			■	11	[47]–[57]
■	■			10	[58]–[67]
■		■		1	[68]
■			■	4	[69]–[72]
	■	■		7	[73]–[79]
	■		■	2	[80], [81]
		■	■	21	[1], [2], [78], [82]–[99]
■	■	■		4	[100]–[103]
■	■		■	5	[104]–[108]
■		■	■	5	[109]–[113]
	■	■	■	9	[114]–[122]
■	■	■	■	7	[5], [123]–[129]

A. SINGLE DOMAIN STUDIES

Few studies exist solely in either physical or information domains because researchers tend to study both domains simultaneously. Studies included in this review identify component-level constraints by focusing on technology development, including the design of networked systems, service-oriented architectures, and human factors involved in military training. For example, Mohamed and Pillulta [36] discuss software systems architecture, access, and service federation in the context of including knowledge management as a service within existing network service oriented architectures. Despite the detail provided in this work, greater clarity and definition of network architectures is available in multi-domain studies.

Work in the social domain addresses political and legal phenomena that shape C2 network structures by providing component-level constraints of physical and information systems and system-level constraints on social networks. In general, these studies and reports discuss international policies regarding national security [40]–[42]. With respect to the structure of C2 systems, these works bring attention to the role the US DoD must play in societal change around ICT. For example, Kadtke and Wells III [40] suggest that the US DoD is reluctant to be involved in public trends in cyber-space, yet is so affected by ICT technology that the department needs better management of cyber assets and the act of cyberwar. This is echoed by Krekel et al. 41], which argues that US infrastructure is vulnerable to malicious cyber-attacks because there is no policy to determine response options to large-scale cyber warfare, there are few US-based upstream manufacturers for physical infrastructure, and organizations housing sensitive data have inadequate information security defense mechanisms. Together, these studies reveal the tradeoff between increased use of ICT to ensure agility in C2 systems and the risks of online distributed systems in sensitive situations.

The cognitive domain focuses on how people make decisions in integrated, human-technology environments and offers guiding principles for social and cognitive network design. Dodd et al. [55] demonstrate that agile C2 systems include networked teams with different command structures, e.g., a team with a rigid command structure will have to interact with teams with a looser command structure to be agile. The way in which technology influences these command structures is captured in surveys on the benefits NCW has on C2 decision-making settings [48]. Specific measures of the potential benefits from NCW doctrine include shared situational awareness, improved decision-making, and interoperability with coordinating partners. Bowman et al. [51] reviewed literature and held an academic workshop to understand ''intense collaboration'' when facing emergency situations to propose a set of team, leadership, and technology factors that influence system agility.

One important analysis method from the cognitive domain that supports multilayer network studies is cognitive work analysis (CWA). CWA is a set of analysis tools used to model and measure how work gets done in teams and reveals information flow among teams, the relationship between completing tasks and mission success, and supports measures of C2 agility based on the time it takes to complete a mission. Oosthuizen and Pretorius [50] show how C2 activities and CWA methods relate by providing an overview of CWA and how to develop measures of system agility. CWA is helpful to map decision making and C2 networks in a number of different contexts, including military missions [53], [57] and hospital operating rooms [56]. CWA is particularly useful for mapping information flows by generating work-flows autonomously or recreating them as real people perform tasks [47], [52]. Combining CWA methods with C2 theory also enables new measures of multilayer agility in military teams by aggregating decisions taken at a mission command center, actions and timing in the field by warfighters, and comparing time to finish tasks against a standard. Together, CWA and related decision mapping offer a flexible way to establish network models in both social and cognitive domains and develop real-world measures of agility.

B. MULTI-DOMAIN STUDIES – 2 DOMAINS

The majority of C2 research considers two NCW domains and provides guidance for multilayer network modeling and analysis by discussing distinct architectural constraints in each domain. We group these works into sub-categories based on the system architectural constraints they address: techno-centric studies that consider physical and information domains, human-centric studies that consider social and cognitive domains, and sociotechnical studies that consider technological and human constraints.

Techno-centric studies reveal cyber and physical constraints on the design of C2 communication networks by integrating physical infrastructure systems with software services. Chan *et Al.* [61] provide the most extensive overview of component, protocol, and system-level constraints in cyber-physical C2 networks, including multiple communication modalities, channel types, technology generations, services, transfer rates, and protocol types. Other studies address specific types of network heterogeneity through cyber-physical technology development in radar [66], cognitive radio [62], [65], and network switching [58]–[60], [64]. These works also reveal how task definition and social hierarchy influences cyber-physical network structure, such as in Woods *et al.* [59] where embedding mission-defined networking requirements in the software stack dictates the interaction among wireless systems. Overall, the key emergent phenomena across physical and information domains is the processing, storage, and access of information assets, where it may be inappropriate to develop ICT and digital service networks separate from each other. Choice of underlying ICT network components and protocols can be overcome by digital services, however, increasing reliance on a diversity of software systems increases heterogeneity in underlying cyber-physical networks.

Human-centric studies link social and cognitive domains to study the relationship between a social network's structure and the cognitive decision-making and tasking activities that dictate human actions. Several human-centric studies provide generic taxonomies of the combined social-cognitive processes that influence C2 agility [1], [93], [98], including seven activities performed by people: receiving data, planning, rehearsing, communicating, requesting, monitoring, and reviewing. Cultural values also dictate social hierarchy and knowledge management, suggesting a need to assess the beliefs and values held by teams to model social-cognitive multilayer networks [83], [94]. Associated architectural constraints in integrated social-cognitive networks relate to the context-specific type of tasks being done by people within a single team [87] and across multiple teams [85], [88], [99]. Social network structure is particularly influential on the importance of different tasks, where core team members that complete a variety of important tasks have a hierarchical team structure, while peripheral team members that do less frequent, less important work lack hierarchy. This enables researchers to also identify critical actors within organizations based on a network structure [97], and suggests certain system vulnerabilities to loss of critical actors [96]. Thus, the success of a given cognitive task is dictated by the structure of the underlying social network, but the availability and completion of tasks must be distributed across many actors to avoid critical task failures. Like techno-centric studies that indicate a need to consider both physical and information domain networks together in model development, human-centric studies suggest a similar duality in social and cognitive domains.

Sociotechnical studies show that the choice of ICT technology to include in a physical or information network layer changes the structure and function of social and cognitive layers. Physical-social domain studies observe that the choice of physical communication infrastructure influences social hierarchy within military teams [86], [107]. The literature on physical-cognitive interactions show decision-making options and tasks in manufacturing [71], supply chain management [70], and electric power delivery [69], [72] differ because of available ICT. Finally, information-human interactions reveal systemic human factors that link the structure and values held by teams to the software and digital services they interact with [73]–[77], [80], [81]. Across all studies, there is a strong connection between the digital tool used (e.g., a video game), the cognitive task at hand (e.g., rules of the game), and the most agile team structure that results. Together, these works emphasize that the available ICT technologies, the origin and destination of communication traffic, and task needs influence both individual network layers and their emergent interactions across them. Moreover, given a team structure and decision-making context, the human factors embedded in digital services dictate who can complete certain tasks and make decisions.

C. MULTI-DOMAIN STUDIES – 3 OR 4 DOMAINS

The majority of 3 domain studies focus on frameworks and tools for coupled human-technological interactions that support multilayer network modeling and analysis. Two prominent examples are the *event analysis for systemic teamwork* (EAST) framework [115], [117], [127] and its related predecessor, *workload, error, situational awareness, timing, and teamwork* (WESTT) [118]. The purpose of EAST and WESTT is to model the sociotechnical relationships that dictate successful completion of work using networks, ranging from air traffic control [115] to military operations [117]. Few EAST and/or WESTT studies include physical systems (see [127]), and emphasize models of social organizational structure, cognitive task precedence, and the distribution of knowledge within teams dictated by human factors. Interactions between domains are defined by the structure and function of each individual network. Social networks dictate the hierarchy among individuals and the propagation of information among teams. Task networks dictate temporal aspects of decision-making, i.e., when different tasks and decisions must be made, which people are involved in each task, and who contributes information to perform different tasks. Knowledge networks relate individuals to each other and the tasks they need to perform.

In contrast, studies done in the *experimental laboratory for investigating collaboration, information-sharing and trust* (ELICIT) [76], [79], [99]–[102], [124], [125] combine models of physical domains with social and cognitive domains to develop network measures that relate infrastructure dynamics to data flow and information correctness. ELICIT methods provide a taxonomy of communication infrastructure and social/cognitive constructs and compare measures and dynamics in communication systems and human teams [100]–[102].

Two physical-information-cognitive studies embed decision-models within fully developed technology and service-oriented information systems using different rules and methods than ELICIT. Noel *et al.* [105] develop a detailed modeling framework for cyber-attacks on infrastructure systems that integrate cyber-physical models, mission goals, and cognitive models of attackers. The framework uses a suite of tools to analyze the potential impacts of cyber-attack on mission success and presents a case study on air force targeting activities. Feng *et al.* [106] provide a mathematical framework for optimizing the social structure of collaboration in C2 organizations around different tasks and technological platforms. Although the authors do not present a case study, the methods give a basis for measuring the impact of misinformation and losses.

Four studies cover all four domains. Three studies use EAST and ELICIT frameworks in unique ways, where other works propose novel frameworks for cyber-physical-social interactions. Salmon *et al.* [127] and Walker *et al.* [128] extend EAST and incorporate explicit modes of communication infrastructure within the distributed information-social-cognitive framework. Interestingly, these studies predate other EAST / WESTT studies in this review by several years, yet, these are the only works linking physical systems to social, task, and knowledge network models. A more recent, innovative study builds on social network theory of teams [120], links EAST and ELICIT together to contrast hierarchical and agile networks [124], and uses simple network measures to relate C2 system structure to NCW doctrine. The final work reviewed herein by Wong-Jiru [126] presents an integrated, four domain network science framework for measuring the awareness of commanding units in cyber-physical-social networks consisting of process, people, applications, systems, and physical network layers. The thesis proposes graph theory measures of mission effectiveness and conducts a case study of the 2006 joint expeditionary forces experiment.

D. NETWORK MODELS AND MEASURES – DESCRIPTIVE

Despite the significant emphasis on studying technological and social network structure across the literature, formal applications of network science in C2 research is still a nascent topic. As a result, few studies employ network science methods for analysis. Here we highlight research using network science and how it relates network measures to the C2 approach space and system agility. For example, few studies use descriptive measures for NCW doctrine that categorize communication network nodes, links, and structures, and relate them to the C2 approach space. Chan and Ivanic [101] provide the most comprehensive review and list of descriptive measures of communication systems, including latency, packet loss, and communication/data collection signal radius. These measures are embedded into ELICIT studies to create quantifiable distinctions between hierarchical and agile systems.

Social network analysis methods are used to describe the structure C2 interactions across teams. Several authors use known graph-theoretic methods to identify important people and decisions in networks. Walker *et al.* [115], [117], [128] use network centrality as a characteristic measure for ranking key agents in military command and air traffic control systems. This measure is a normalized combination of multiple network measures, but is primarily based on node degree, i.e., number of links attached to a given node. Joblin *et al.* [85] also use degree to characterize the social status of individuals within software development teams, but extend this notion to sub-categories of different types of developers, i.e., core developers to the project, peripheral developers who are only partially involved, absent developers who do almost nothing, and isolated developers who work on the project but are not well-connected to the team. Studies by Stanton *et al.* [120], [124] focus on assessing team structures with five fundamental sub-networks (chain, Y, wheel, star, and all connected), and measure performance for completing a collaborative strategy game where participants had to capture enemy pieces. This work builds upon Walker *et al.* [117] to characterize the C2 dimensions of each team using network theory, relating the measures of network centrality to individual decision-rights, network diameter to patterns of interaction, and network density to distribution of information. In addition to density and diameter measures, Huang *et al.* [46] describe a number of statistical tools to generate and estimate the degree distribution of a social network to relate nodal link values to overall network structure and team hierarchy. Towards a similar goal, Joblin *et al.* [85] also use network measures to characterize the hierarchy among software development teams by linking network degree distribution and network clustering (i.e., how well connected the neighbors of a node are relative to their total possible number of links) together. Nodes with high degree and low clustering are at the top of the network hierarchy, where nodes with low degree and high clustering are at the bottom of the team hierarchy. The combination of these measures describe changes within teams over time, with emphasis on how centralized and clustered core and periphery developers are for each software team. Wong-Jiru [126] further describes the implications of degree, clustering, density, and betweenness-based measures which characterize the ability for individuals to facilitate interactions across teams, reveal key social interactions for a number of tasks, and estimate the maximum throughput of actors in a social network. Taken together, the measures across studies provide useful metrics that advance C2 agility theory and relate node and network-level dynamics to system structure.

E. NETWORK MODELS AND MEASURES – PRESCRIPTIVE

Like descriptive network studies, few prescriptive C2 studies focus on network measures for technological systems, yet those that do tend to use the same standard measures. For example, the majority of techno-centric studies, e.g., Mihailescu *et al.* [58], Huang *et al.* [37], and Noel *et al.* [105], all use throughput as a characteristic measure of communication systems. Thus, the only aspects of physical and information systems captured by authors are the amount of data that can be sent over systems and the quality and speed that data is passed throughout the network.

Several prescriptive measures of social and cognitive networks defined by authors can guide the improvement of C2 agility and shared awareness. Prescriptive network measures found in the literature quantify the likelihood of mission success by developing network-based measures of actor awareness, information sharing efficiency, and team success. Measures of awareness estimate how much information sharing and knowledge is distributed among teams, such as in Tran *et al.* [110], [113] where authors measure battlespace awareness using Shannon's information entropy. Likewise, Stanton *et al.* [120], [124] measure shared awareness based on the frequency and type of interactions among team members for distributing data where the act of sharing, pushing, and pulling are captured in different network analysis methods. Walker *et al.* [116] extend this notion of shared awareness to include the subjective experience of team members via a measure of network cohesion. Similarly, Chan *et al.* [100] use a system-level measure of "correctness" that combines the output of multiple teams into a single measure. The authors decompose a task into collecting, "who, what, where, and when," information across multiple teams. The correctness score is the combination of the accuracy of these pieces of information at a given location within the social network. Increasing the likelihood of battlespace awareness, cohesion, and correctness may prescribe better awareness.

IV. NETWORK FOUDNATION FOR C2 RESEARCH

We organize C2 literature into a multilayer network framework to offer guidance for future C2 research (Fig 1 and Tables 2-6). Fig. 1 shows a generic representation

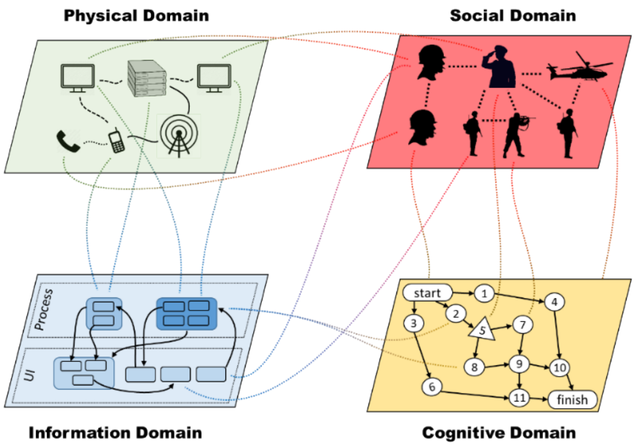

FIGURE 1. Multilayer network super structure of NCW domains and C2 literature. NCW domains are comprised of distinct sub-systems that interact to form a four-layer network superstructure. C2 literature informs the drivers, models, and measures that describe and prescribe inter- and intra-network structure and function (see Tables 2-6).

TABLE 2. C2 architecture for each NCW domain.

C2 Domain	Component-level Constraints	Protocols	System-level Constraints
Physical Domain: *Information & Communication Infrastructure*	- Manufacturer - Energy Use - Size - Security - Reliability - Cost	- Industry Standards - Routing (e.g., TCP / IP) - Security (e.g., key generation) - Data Federation	- Latency - Access - Geographic Location
Information Domain: *Digital Services*	- Programming Language - Latency - Accuracy - Security - Reliability - Cost	- Software Architecture - Access (e.g., User Interface) - Discovery - Service Federation	- Availability - Security - Storage - Resource Budget - Documentation
Social Domain: *Organizational Structure*	- Roles & Duties - Psychological Traits - Beliefs & Practices - Demographics	- Standards - Administration - Policies - Partnerships	- Laws & Regulations - Politics - Geographic Location - Cultural Norms
Cognitive Domain: *Mission & Goals*	- Manpower - Funds - Time - Energy - Skills Required - Safety	- Execution Order - Control Logic	- Shared Objectives - Commander Intent - Stakeholder Needs - Budget

Table II presents the breadth C2 domain architectures and subsystem considerations found in this review. Advances in C2 research depend on the analysis of component, protocol, and system-level constraints within NCW domains with respect to past studies on similar and interdependent systems.

of a potential multilayer network representing a C2 system. We organize domain-specific results from section III as the constraints and primitives that comprise these layers. As such, Tables 2-6 categorize the current state-of-the-art in C2 research for network evaluation, and these tables could be used for conceiving and executing future advances in the literature. Specifically, the network architectures of NCW domains is presented in Table 2, linked via emergent constraints in Table 3, and comprised of model primitives in Table 4. Tables 5 and 6 present a list of established descriptive and prescriptive measures to guide analysis of C2 agility.

The C2 literature reviewed here focuses almost entirely on the human factors when teams use technology and digital services to facilitate distributed decision-making and action. We refine the broad definition of physical, information, social, and cognitive domains to more specifically refer

TABLE 3. Emergent constraints across C2 network layers.

Needs for... / Constraints for ...	Software & Digital Services	Social & Organizational Structure	Mission & Goals
Information & Communication Infrastructure	Resource Use (processing, storage, connectivity, etc.)	Communication Traffic	Communication Activities
Software & Digital Services		Service Access	Human Factors & Capabilities
Social & Organizational Structure			Skills & Knowledge

Table III presents emergent constraints across multilayer C2 systems revealed by 2-, 3-, and 4-domain studies. System architectures within a single domain influence the dynamics of other domains, such that emergent, cross-layer constraints dictate C2 agility. Advances in C2 research could benefit from an improved understanding of how emergent constraints influence the allocation of decision rights, patterns of interaction, and distribution of information.

TABLE 4. C2 network layer primitives.

C2 Domain	Nodes	Links	Dynamics
Physical Domain: *Information & Communication Infrastructure*	- Sensors - Routers - Access Points	- Cables / Fiber - Wireless Signals - Containment	- Network Traffic
Information Domain: *Digital Services*	- Functions - Packages	- Data Streams - Dependencies	- Service Provision - Service Use
Social Domain: *Organizational Structure*	- Individuals - Teams - Organizations	- Interactions - Knowledge	- Shared Awareness - Communication
Cognitive Domain: *Mission & Goals*	- Activities - Decisions	- Preconditions - Iterations	- Needs Assignment

Table IV presents network primitives considered across the C2 literature. Columns present the different constructs that comprise C2 network models, where the combination of nodes, links, and dynamics across rows defines a network layer. Advances in C2 research may reveal new primitives, structures, and multilayer analysis methods that combine network models together into a single study.

to networks of ICT infrastructure, digital services, organizational structure, and decision-making goals, respectively. Based on theory and models developed across the literature, this four-layer network framework is comprehensive to incorporate a breadth of studies across C2 research and provide guidance for prescriptive sociotechnical multilayer network design.

A. COMMAND AND CONTROL NETWORK ARCHITECTURES AND CONSTRAINTS

Each domain layer in Fig. 1 embeds context-specific information that dictates the structure and function of underlying systems. Each cell in Table 2 lists the types of technical information experts consider within reviewed articles when modeling physical, information, social, or cognitive systems. For example, physical domain includes connections among ICT hardware networks, the information domain by software architectures, service federation, calls, and pointers,

TABLE 5. Descriptive measures of C2 network agility.

Measure	References
Tech-centric	
Latency	[63], [100], [101], [110], [123]
Packet Loss	[100], [101], [126]
Signal Radius	[110]
Throughput	[58], [60], [62], [65], [112]
Human-centric - nodal	
Network Centrality	[115], [126], [128]
Node Degree	[46], [69], [97], [126]
Human-centric - system	
Team Structure / Network Hierarchy	[85], [120], [124]
B-L Centrality	[124]
Diameter	[124]
Density	[97], [98], [116], [117], [124], [126]
Degree Distribution	[46], [69], [85], [126]
Clustering Coefficient	[46], [85], [126]

TABLE 6. Prescriptive measures of C2 network agility

Measure	References
Awareness measures	
Battlespace Awareness	[110], [113]
Shared Awareness	[120], [124]
Cohesion	[116]
Success measures	
Efficiency / Mean Geodesic Path	[79], [110], [113], [126]
Sharing Frequency	[120], [124]
Correctness	[100], [101]
Approach space measures	
Geometric Hull	[124]

the social domain by teams and organizational structure and the policies and beliefs that are embedded within them, and the cognitive domain by task networks that show the dependencies between actions in a logical sequence.

Emergent constraints that dictate multilayer sub-system interactions are summarized in Table 3. Table 3 is organized where each row represents a C2 sub-system and each column represents emergent constraints discussed in the literature that arise from interactions across interacting sub-systems. For example, in the first cell, constraints that dictate the structure and function of a physical network layer (ICT) are set by resource needs in the information network layer (digital service stack). Likewise, digital service capabilities (e.g., throughput) are constrained by ICT design decisions in the physical layer. Emergent constraints between these two networks may lead to inter-layer links that are asymmetrical depending on which information network nodes dictate digital asset needs and which physical ICT network nodes dictate service throughput. Referring to Table 2, these asymmetrical links can be associated with any component-level and protocol constraints and may represent different resource needs (e.g., energy, cost, etc.). The same is true for each cell in Table 3, where consideration of interlayer needs and constraints offers a simple way to guide sociotechnical and social-cognitive model development.

B. COMMAND AND CONTROL NETWORK PRIMITIVES AND MEASURES

With results organized by domain, we summarize the primitives used for constructing and studying C2 systems as networks (Table 4). Table 4 builds on system architecture and constraints to develop representative network primitives that comprise each network layer in Fig. 1. Each cell lists model primitives included in network models across the literature, where the combination of nodes, links, and dynamics define a single domain layer. For example, the list of network primitives presented by Chan *et al.* [79], [100] for social and technological systems can be represented by a combination of architectural constraints from Table 3 and studied with associated network models. Chan *et al.* [100] lists communication and social network parameters that relate to technological and human dynamics such as buffer size in the communication systems relates to memory capacity of people in social systems. A network of the physical domain ICT systems embeds buffer size constraints within the network architecture. The resulting network model is constructed of primitives from Table 4 representing the physical communication system of sensors, routers, and access points with effective buffer sizes for data streams. Likewise, a social domain network considers the psychological traits of individuals like memory in its architecture, and its network model is the representation of the linkages among individuals and teams with given memory capacity. Information and cognitive domain models can be constructed accordingly.

Tables 5 and 6 present measures of C2 agility. Choice of descriptive measures depends on the specific network layer under consideration as studies focusing on technological and human networks require different context-specific measures. Associated descriptive research and future measure development may be able to focus on limited multilayer network models that ignore some NCW domains. On the other hand, all prescriptive network measures consider cross-domain interactions, and require complete multilayer network models. The three categories of measures also provide a basis for understanding different aspects of C2 systems, including awareness, mission success, and approach space measures.

C. CONSIDERATIONS FOR ADVANCING C2 SYSTEMS AND NETWORK EVALUATION

Fig. 1 and Tables 2-6 support NCW theory and C2 research by providing a standard basis to advance existing theory. The dimensions that influence C2 agility identified by NCW doctrine (i.e., allocation of decision rights, patterns of interaction, and distribution of information) are a result of the structure and function of integrated C2 systems. Thus, decisions on which constraints, primitives, and measures to use in C2 network analysis will dictate future advances in research. For both placing new studies within the existing literature and identifying new avenues for future research, we recommend experts pose five questions of C2 studies:

1) ***What NCW domains and constraints are considered?*** Physical, information, social, and cognitive domains each have specific, real-world design constraints that influence system analysis, and C2 research needs to reveal the tensions among these constraints. Recognizing which architectural constraints are under consideration can reveal requirements and potential bottlenecks in C2 modeling and analysis. Existing C2 literature already provides broad guidance for several domain architectures, where future research should frame results with respect to existing knowledge.
2) ***Are emergent, cross-domain constraints considered?*** C2 research provides an important perspective for studying sociotechnical systems and revealing emergent constraints across domains that influence network agility. Advances in the identification and modeling of emergent constraints across domains can support the construction of dependencies within multilayer networks. Existing C2 literature reveals few, key emergent constraints, where further advances in techno-centric, human-centric, and sociotechnical interactions is needed.
3) ***Which C2 model primitives are included in analysis?*** C2 systems are comprised of constructs that are poorly understood in an integrated context. While constraint-based research reveals the structure and function of NCW domains, additional research is needed to translate complicated interactions to simplified models. Existing C2 literature focuses on a limited number of nodes, links, and dynamics that comprise C2 networks. Further work is needed to establish a more extensive set of model primitives and relate their networked structure to C2 agility.
4) ***Which framework does the study rely on or relate to for multilayer analysis?*** Frameworks like EAST, WESTT, and ELICIT help standardize C2 research, yet each defines different multilayer interactions across C2 sub-systems. Identifying how new studies either fit within one of these existing frameworks or reveal their limitations is important for advancing the literature. This is particularly important for 3- and 4-domain studies, as the majority of associated C2 research use these frameworks.
5) ***What measures of approach space and agility are used in the study?*** Studies that use network evaluation tools to inform C2 agility are rarely related to NCW doctrine. Existing literature shows that descriptive measures of approach space and agility can be associated with common network science measures (e.g., degree, closeness, etc.) for individual layers and prescriptive measures are multidimensional and context-specific such as battlespace awareness or shared awareness. C2 research would benefit from more explicit explanation as to how network analysis connects system agility to approach space, and future studies should consider past measures to explain how new methods improve upon existing network studies.

V. DISCUSSION AND CONCLUSION

This review organizes the broad, interdisciplinary C2 research literature and develops a network science framework to advance future descriptive and prescriptive research. Existing C2 literature offers limited guidance for organizing the broad application contexts involved in system evaluation. Importantly, there is lack of integration of knowledge across descriptive and prescriptive studies limiting the analysis of sociotechnical processes like agility and integrating this knowledge into guiding theory.

We integrate system model architectures and constraints across a diversity of C2 research contexts – from military systems to weather stations, businesses, and electric power systems among others. Associated C2 systems include a combination of constructs across physical, information, social, and cognitive domains of warfare, which we further specify to be ICT infrastructure, digital services, social organization, and mission networks. This categorization reveals a variety of 1-, 2-, 3-, and 4-domain studies that are further described to combine methods and results. Each combination of domains offers guidance for future C2 studies, such that multilayer C2 network analysis is best supported by a combination of literature across domains, and associated measures of agility come from a variety of single and multi-domain studies. C2 research that formally uses network science methods is also discussed to identify useful measures for future studies.

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