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# Agility, Automation, and Autonomy[1]

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## Introduction

Success in military, civil-military, and other complex endeavors depends on the ability of command and control[2] arrangements and approaches to effectively employ automation, manage autonomy, and achieve requisite levels of agility. A failure to accomplish any one of these three essential interdependent objectives could, under certain circumstances, adversely affect an entity's ability to effectively and efficiently accomplish C2 functions, and employ an appropriate approach to C2. This, in turn, could affect the ability to manifest C2 Agility.

The need for agility, and for C2 Agility in particular, has been well articulated. A growing body of evidence supports the importance of enhancing the agility of organizations faced with dynamic situations characterized by complexity and uncertainty. The increasing likelihood that military organizations will be operating in highly contested cyber environments only increases the importance of C2 Agility.

The automation of a variety of C2-related tasks also has been prevalent for some time. Yet, there has not been a clear recognition of what this increased automation means in terms of the constraints it places on commanders and C2 systems. These constraints may be, under certain circumstances, impediments to agility and therefore to mission accomplishment.

The emergence of autonomous systems is a more recent development. From a C2 perspective, as is the case with automation, the design and operation of 'autonomous' systems involve delegations of decision rights; however, the impacts and consequences of these delegations are not well understood.

### Purpose and Organization

This paper, focused on Agility, Automation, and Autonomy, addresses the problems of a wide variety of decision makers throughout military organizations, from commanders at all levels, to policy makers and those involved in systems design and acquisition. The lens through which Agility, Automation, and Autonomy is viewed in this paper is the critical military function of Command and Control. The problem of interest is the identification of the most appropriate approaches to command and control given the mission and circumstances. Finding solutions will

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[1] This research was sponsored by the DOD Command and Control Research Program (DOD CCRP).

[2] The term command and control is normally associated with military organizations even when they are supporting civil authorities. C2, as the term is used here, refers to the functions needed to dynamically govern and/or manage forces and includes providing intent; setting expectations, priorities, and constraints; and allocating responsibilities, tasks, decisions, information access, and resources.

require an understanding of the relationships between and among Agility, Automation, and Autonomy.

The objective of this paper is to suggest the need for explicit consideration of the decision rights, now and in the future, that will be delegated to non-human entities, virtual and physical, that enable kinetic and non-kinetic effects.

This paper is organized into four main sections. Given the diversity of the intended audience, the first two sections of this paper are devoted to restating key elements of the C2 research literature, namely C2 Agility Theory and the Composite Network Model, to make the paper more immediately accessible. The third section briefly discusses both the nature of autonomy as it relates to battlefield entities and supporting systems, and the automated capabilities that are or could be integrated into platforms and networks. The paper concludes with a section that suggests a way forward.

## Scope and Key Terms

This paper's consideration of C2 Agility, Automation, and Autonomy is in the context of endeavors that require the contributions and efforts of a number of disparate organizations to achieve a desired result.[3] These organizations are, in reality, socio-technical systems that are supported by a variety of platforms, systems, and networks, each of which has or will have some level of intelligence built in.

While it is straightforward to examine the relationship of specific instantiations of automation and autonomous systems to mission success on a case-by-case basis, the relationship between the capabilities provided by automation and autonomy and the resulting level of agility is more involved.

The key terms used in this paper are widely used, and have come to mean different things to different communities. Some of these definitions are accompanied by descriptions or specifications that allow us to observe and measure key attributes of the concepts involved. These measures will need to be reviewed and possibly modified to be applicable in the C2 context.

Given that readers are likely to bring a variety of meanings for these terms, the following preliminary descriptive definitions are provided to promote a shared understanding of these concepts. These definitions will be replaced later in this paper with ones that adopt a "C2 perspective" and provide metrics for their key attributes.

> Agility is the capability of an entity to remain successful in the face of expected and unexpected changes in circumstances that impose constraints and create a variety of stresses

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[3] The consideration of agility, automation, and autonomy and the related tradeoffs are equally applicable to individual organizations, platforms, systems, and networks. When the unit of analysis is not at the endeavor level, the success metric employed (e.g., system performance) should be related to a measure(s) of endeavor success.

that, if not adequately avoided, handled, or mitigated, would otherwise adversely affect the entity's ability to accomplish its mission(s).

C2 Agility is the capability to adopt and execute an appropriate approach to C2 when operating in the different regions of the entity's Endeavor Space, the universe of possible futures.

Automation is the employment of automatic decision making with a corresponding reduction in human cognitive involvement.

Autonomy is the exercise of the freedom to operate without external control or influence.

## C2 Agility Theory Overview

This overview of C2 Agility Theory is designed to: 1) provide the terminology and conceptual framework that will be used to explore the relationships between and among automation, autonomy, and agility; 2) explicitly incorporate the variables and relationships necessary to represent the C2 of Defensive Cyber; and 3) highlight a number of C2 Agility-related hypotheses that can help us to better understand these relationships. After briefly reviewing the conceptual origins of C2 Agility Theory, the basic concepts and tenets of the theory shall be presented and discussed.

### Origins of C2 Agility Theory

The need for and a way to think about what makes approaches to C2 different from C2 Agility has its origins in the conceptual developments that led to the articulation of Network Centric Warfare (NCW), now widely referred to as Network Enabled Capability. NCW proponents advocated a radically different approach to command and control, enabled by emerging technologies – one that was designed to leverage the power of information sharing to create and leverage shared awareness.

Two seminal publications laid out the future of military operations. The first was an article published in the U.S. Naval Institute Proceedings that proclaimed a "new era in warfare" characterized by a "shift in focus from the platform to the network" and "a shift from viewing actors as independent to viewing them as part of a continuously adapting ecosystem."[4] The second, a book published by the DOD Command and Control Research Program,[5] described the NCW concept in detail, addressing some of the myths then in circulation. It explained how NCW embodies the characteristics of the Information Age, identified challenges in transforming this concept into a real operational capability, and suggested a way forward.

Both publications cited the U.S. Navy's Cooperative Engagement Capability (CEC) as an example to demonstrate that NCW was not just a theory that might come to pass in the distant

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[4] Cebrowski, Arthur K. and Garskta, John. J., "Network-Centric Warfare: Its Origins and its Future," U.S. Naval Institute Proceedings, 1998.

[5] Alberts, David S., Garstka, J. J., and Stein, Fred P., *Network Centric Warfare: Developing and Leverage Information Superiority*, CCRP 1999, ISBN 1-57906-019-6. http://dodccrp.org/files/Alberts_NCW.pdf

future, but was, in fact, beginning to emerge as an operational capability with greatly increased combat power. The CEC is a network of sensors and shooters that share data; possess embedded intelligence; and is able to, at the entity level, merge various inputs to create shared awareness that, for the first time, allowed shooters to engage beyond their line of sight. CEC capabilities, as described in 1995[6], stated that CEC "engagements can be coordinated, whether conventional or cooperative, via real-time knowledge of the detailed status of every missile engagement within the CEC network. Moreover, a coordination doctrine may be activated by the designated NCU for automated engagement recommendations at each unit based on force-level engagement calculations."

The logic that underpins NCW and Network Centric or Enabled C2 is expressed in the following set of NCW Tenets, as articulated in the NCW Report to the Congress:[7]

- A robustly networked force improves information sharing.
- Information sharing enhances the quality of information and shared situational awareness.
- Shared situational awareness enables collaboration and self-synchronization, and enhances sustainability and speed of command.
- These, in turn, dramatically increase mission effectiveness.

These tenets are a set of linked hypotheses that express a value chain (see Figure 1[8]) that relate the existence of a robustly networked force. Advances in communications and information technologies enable widespread sharing of information and unconstrained potential interactions. These, in turn, lead to improved quality of information, enhanced situation understanding, and the development of shared understanding that, if exploited by self-synchronization, results in dramatic improvements in mission effectiveness.

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[6] The Cooperative Engagement Capability, *Johns Hopkins APL Technical Digest*, Volume 16, number 4 (1995) http://www.jhuapl.edu/techdigest/td/td1604/APLteam.pdf.

[7] This report was provided to the Congress in July of 2001. It can be found at: http://www.dodccrp.org/files/ncw_report/report/ncw_cover.html.

[8] The version of the NCW Value Chain depicted in Figure 1 appears on page 27 of the NATO C2 Maturity Model. This document can be found at: http://www.dodccrp.org/files/N2C2M2_web_optimized.pdf.

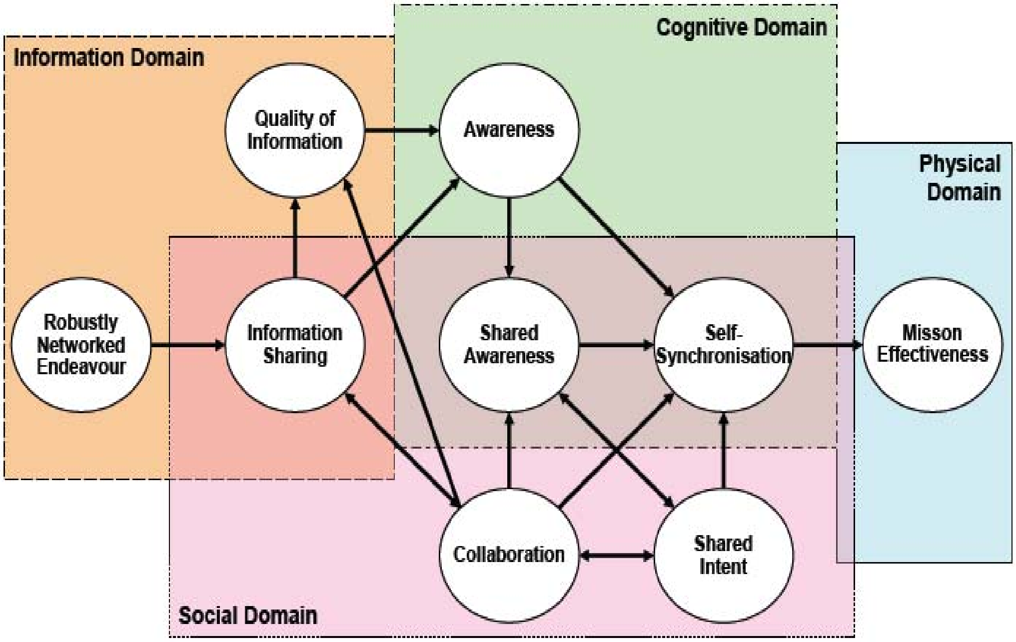

Figure 1: Network Centric Value Chain

The realization of NCW was predicated on the co-evolution of C2 with communications and information technologies. In other words, the benefits of NCW could not be realized without the development and adoption of new C2 Approaches that were designed to take advantage of shared awareness. This set up a contrast between "Traditional C2" and what later became known as "Edge C2." The development of the C2 Approach Space provided a means of visualizing this contrast with respect to the three dimensions depicted in Figure 2.[9] The nominal locations of both Traditional or Classic C2 and Edge C2 are shown in this figure.

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[9] This depiction of the C2 Approach Space was taken from the NATO SAS-050 Final Report (page 6) that can be found at: http://www.dodccrp.org/files/SAS-050%20Final%20Report.pdf.

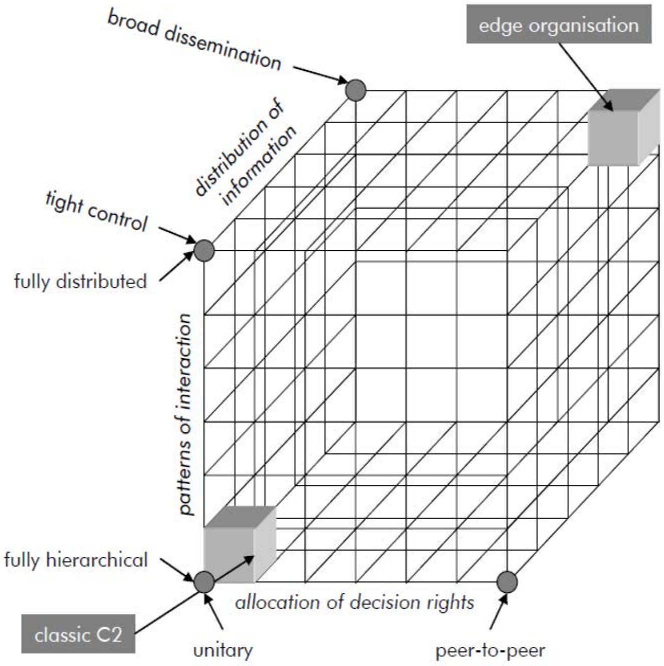

Figure 2: C2 Approach Space

While comparing and contrasting these two corners of the C2 Approach Space is useful, the C2 Approach Space actually provided a means of identifying, at least conceptually, the option space for C2, an option space that contains many more options that deserve study and consideration. NATO Research Group SAS-065 members identified a set of C2 Approaches that were "network enabled" to varying degrees and located them along the diagonal of the C2 Approach Space as depicted in Figure 3.[10] NATO SAS-065's frame of reference was a coalition or collective. Therefore, the dimensions of the cube were relabeled. However, given that militaries themselves are composed of various kinds of units, each with somewhat different capabilities and degrees of freedom to operate, this formulation remains applicable.

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[10] This figure was taken from page 66 of the NATO C2 Maturity Model and can be found at: http://www.dodccrp.org/files/N2C2M2_web_optimized.pdf.

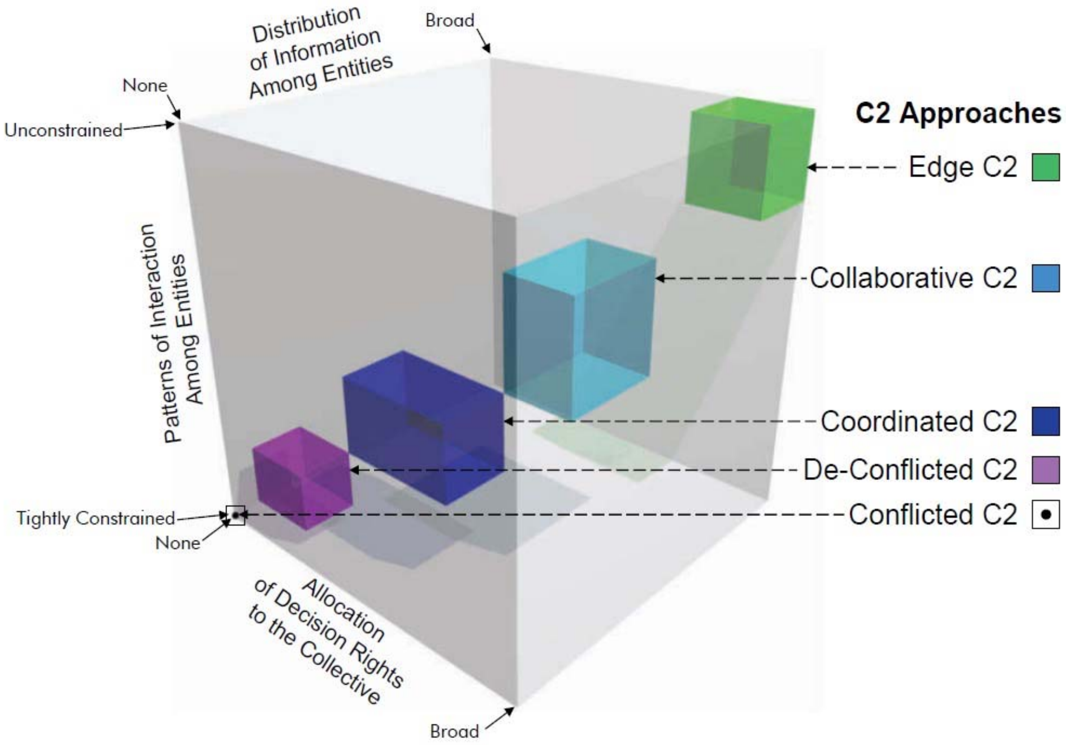

Figure 3: C2 Approaches and the C2 Approach Space

Using the description that accompanied these mappings, researchers conducted both case studies and experiments that were designed to see if network-enabled approaches were more likely to succeed than were traditional approaches to C2 in a variety of missions and circumstances. Among the findings and conclusions of SAS-065 were: 1) different C2 Approaches had, in real-world situations, been adopted not only from mission to mission but in the different phases of a given mission, and 2) more network-enabled C2 approaches were more agile, meaning that they were effective over a wider range of missions and circumstances. In other words, network-enabled C2 gave an entity a competitive advantage over an adversary that did not or could not adopt network-enabled C2.

Another conclusion reached by SAS-065 was that levels of C2 Maturity were related to agility; that is, the more mature an entity's C2 capability was, the more agile it would be. SAS-065 levels of maturity are depicted in Figure 4.[11] As an entity moves up the C2 maturity ladder, each successive level includes a more network-enabled approach to C2, while retaining the ability to appropriately employ less network-enabled approaches to C2. Thus, there are two possible sources of the increased agility asserted by SAS-065. The first is the ability to adopt a more

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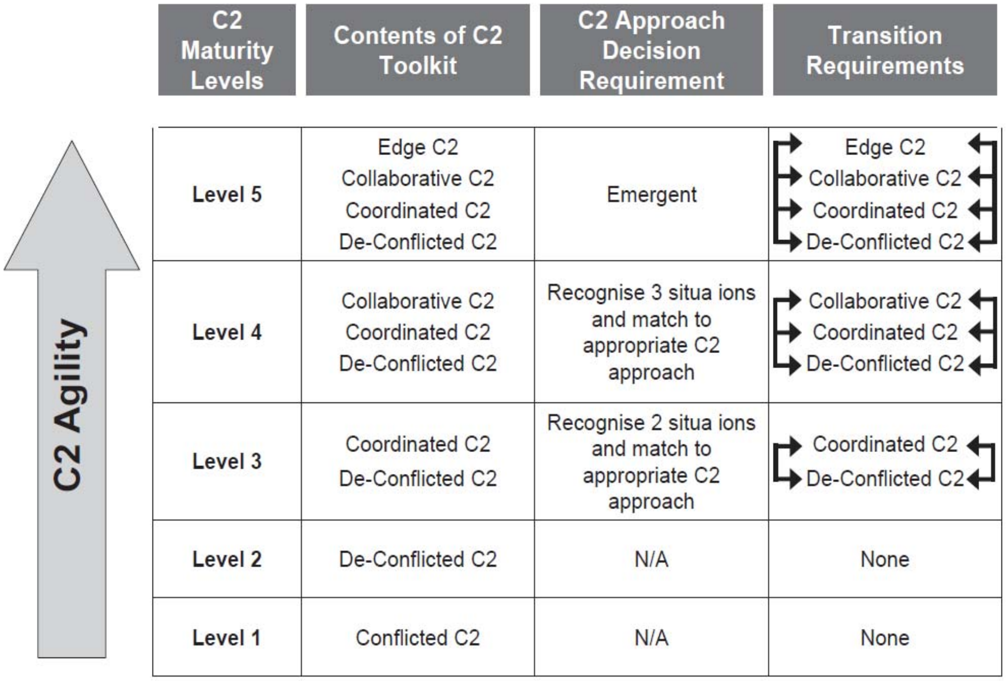
[11] This figure is also taken from the NATO C2 Maturity Model referenced earlier.

networked-enabled approach to C2. The second is the ability of entities to choose from a bigger set of C2 options.



| C2 Maturity Levels | Contents of C2 Toolkit | C2 Approach Decision Requirement | Transition Requirements |
|---|---|---|---|
| **Level 5** | Edge C2<br>Collaborative C2<br>Coordinated C2<br>De-Conflicted C2 | Emergent | Edge C2<br>Collaborative C2<br>Coordinated C2<br>De-Conflicted C2 |
| **Level 4** | Collaborative C2<br>Coordinated C2<br>De-Conflicted C2 | Recognise 3 situations and match to appropriate C2 approach | Collaborative C2<br>Coordinated C2<br>De-Conflicted C2 |
| **Level 3** | Coordinated C2<br>De-Conflicted C2 | Recognise 2 situations and match to appropriate C2 approach | Coordinated C2<br>De-Conflicted C2 |
| **Level 2** | De-Conflicted C2 | N/A | None |
| **Level 1** | Conflicted C2 | N/A | None |

Figure 4: C2 Maturity Levels and C2 Agility

Figure 4 also specifies the transition requirements associated with a given maturity level. Whether an entity has two C2 Approaches to choose from (Maturity Level 3) or more (Maturity Levels 4 and 5), entities, if they are to manifest C2 Agility, the entity must be able to:

1) adopt the most appropriate C2 Approach (from the toolkit);
2) monitor the situation and recognize when the current C2 Approach is no longer the most appropriate; and,
3) adapt the current approach or transition to a new, more appropriate C2 Approach as the situation dictates.

Accomplishing these steps requires a level of understanding of how the characteristics of missions and circumstances map to the C2 Approach Space, an ability to monitor the entity's position in this space, and the ability to transition from one C2 Approach to another.

A follow-on NATO Research Group, SAS-085, built on these efforts, developing quantitative metrics for each of the dimensions of the C2 Approach Space and formally testing a series of C2 Agility-related hypotheses, including the SAS-065 finding that suggested that entities that have achieved higher levels of C2 Maturity are more agile. SAS-085 found evidence to support the following hypotheses[12]:

- Each of the C2 Approaches depicted in Figure 3 map to distinct regions of the C2 Approach Space.
- No one approach to C2 is always the most appropriate.
- More network-enabled approaches to C2 are more agile.
- Having more C2 options increases agility.

The last two of these empirically-based findings suggests that the agility SAS-065 attributed to C2 Maturity can be a result of the ability to adopt a more network enabled C2 Approach and/or having more C2 Approach options from which to choose. However, SAS-085 found that the increased agility observed was predominantly a result of being able to adopt a more network-enabled approach, rather than a C2 tool kit with more tools. In fact, SAS-085 experiments found that a C2 toolkit with two well-chosen options proved to be almost as good as one with three or more options. If practical considerations, such as the difficulties in being able to transition between and among a greater variety of options, were included, a strategically selected two-tool toolkit may be preferable.

A closer look at the relationship between more network-enabled C2 approaches and agility found a plausible explanation for why these approaches were more agile. Empirical evidence was found to support the hypothesis that more network-enabled approaches to C2 are better able to maintain their positions in the C2 Approach Space when subjected to various stresses. This finding is important because it highlights the importance of monitoring a set of measures, in as close to real time as practical, that tell us the entity's location in the C2 Approach Space.

Without the "C2 Approach Awareness" that this monitoring enables, case studies and anecdotal evidence suggest that commanders and staff usually believe that their adopted approach to C2 is functioning as it is designed and intended to, when the approach that is actually being employed is a different C2 Approach. Assuming that the C2 Approach selected for the endeavor was appropriate, a significant movement in the C2 Approach Space could translate into a change from one C2 Approach to another, i.e., from one that would have been an appropriate approach to one that is not.

The difference in the actual position in the C2 Approach Space (intended vs. actual) could be a result of the C2 approach not being executed properly by key individuals, or it could be a result of constraints being imposed on the behaviors and capabilities of supporting systems to function as required by a given C2 Approach.

Cyber is a major source of constraints on system behaviors. Cyberattacks and/or cyber defenses constrain capabilities and performance. Thus, when operating in a cyber-contested environment, the need for both effective C2 of Cyberspace Operations and the ability to monitor an entity's position in the C2 Approach Space is paramount. Cyber defenses, for a variety of reasons, need

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[12] In sum, SAS-085 tested 12 hypotheses, thus these results only represent a part of their conclusions.

to be automated to some extent and possess a level of autonomy. Cyber capabilities have a first-order impact on C2, and therefore must be considered explicitly in the selection of an approach to C2.

## Composite Network Model

A specific C2 Approach is a point in a three-dimensional space where the dimensions are inter-dependent. Each of the dimensions of this space can be thought of as a network. The decision rights dimension can be thought of as a set of decision nodes, each of which has certain decision rights and each of which has some authority relationship with every other node. The interactions dimension can be thought of as a collection of links, including the links between and among the decision nodes and the links between these decision nodes and sources of information. The information network nodes consist of sensors and processing centers. There are links between and among these information network nodes, as well as links to decision nodes. In addition, to enable transactions to occur between and among the nodes in accordance with the relationships that exist, a communications network is required. This collection of interdependent networks is referred to as a Composite Network.

While C2 Agility Theory provides the objective function and the set of controllable variables of interest in the form of the C2 Approach Space, a model or set of models that represent a Composite Network provides the context required by an OR Problem Formulation. These network models are needed to provide the relationships between and among all of the variables of interest. In the Network Science community, a network that consists of a single type of node, in this case a network of decision makers or the communications network, is referred to as a single-genre network. Thus, Composite Networks are multi-genre networks.

Figure 5, taken from an Army Research Laboratory technical report on Network Experimentation,[13] depicts a high-level model of a single-genre network with its inputs and outputs. Network Design is determined, in part, by the adoption of a specific approach to C2. The output of the dynamic network model is a network performance map that will be explained later in this section.

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[13] ARL-TR-7451 Network Science Experimentation Vision, Figure 10, September 2015

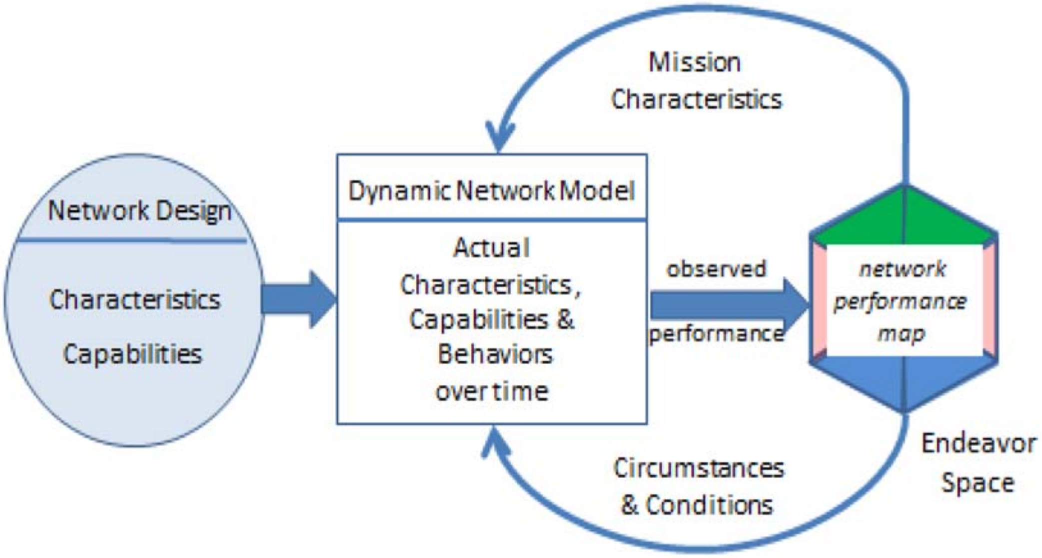

Figure 5: C2 Maturity Levels and C2 Agility

Given the complex interrelationships and interdependencies between and among the decision maker, information, and communications networks that give rise to the network of interactions, considering these individual genre networks in isolation is problematic. Experience has shown that intended C2 approaches (a desired location in the C2 Approach Space) can be prevented from being achieved in reality. This phenomenon can only be studied, understood, and accommodated by understanding and operating in the context of Composite Networks.

Figure 6, Composite Network Model Overview[14], shows the interrelationships between and among the C2/Cognitive/Social, Information, and Communications Networks and the interactions between and among them that enable one to observe and adjust one's location in the C2 Approach Space to achieve the desired results.

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[14] ARL-TR-7451, Figure 12.

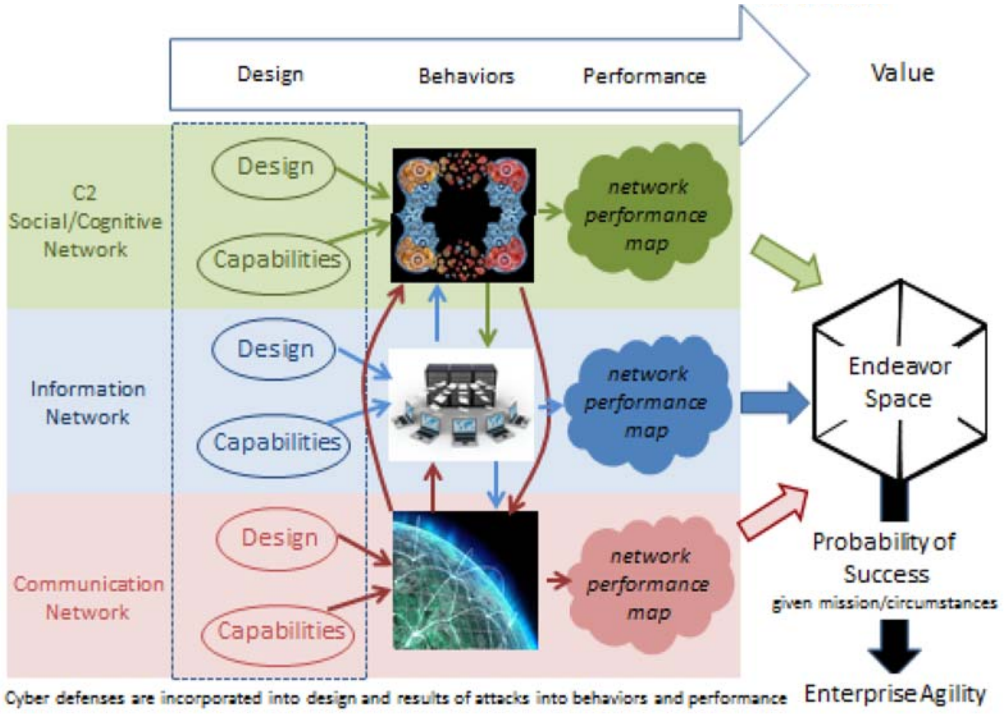

Figure 6: Composite Network Model Overview

### C2 Agility Theory and Composite Networks

Managing Composite Networks in an effort to achieve desired results begins with an integrated design of the C2/Social, Information, and Communications networks. Properly designed and managed Composite Networks can enable us to position ourselves appropriately in the C2 Approach Space. An appropriate C2 Approach, one that is determined by the nature of the mission and circumstances, is more likely to lead to better mission outcomes, particularly in light of changing circumstances.

Figure 7 depicts the concept of an integrated design. For the C2/Cognitive Networks, design amounts to a selection of a C2 Approach and an accompanying set of processes that identify the interactions that should take place.

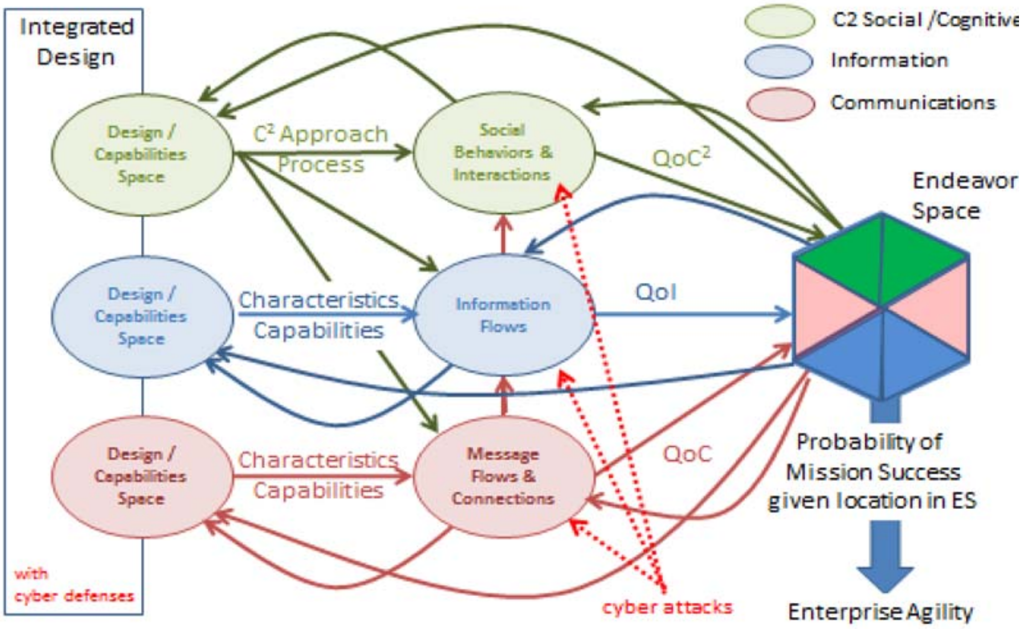

Figure 7: Composite Network Value Chain

The design of information and communication networks needs to be supportive of the C2 Approach and processes. This will encourage and facilitate the behaviors and interactions necessary to support the mission. Each type of network has a quality metric associated with it. For the C2 Network, the measure of quality is the appropriateness of the adopted C2 Approach, measured by the distance between the location of the actual approach in the C2 Approach Space, as determined by behaviors, and the location of the most appropriate approach, determined by C2 Agility Theory. For information and communications networks, the measures are Quality of Information and Quality of Communications, as defined in the NATO NEC C2 Conceptual Reference Model.[15]

The performance map, (see Figure 8[16]), depicted in previous figures, represents the projected outputs of the Composite Network Model. These outputs are mapped onto a three dimensional Endeavor Space. Mission Requirements specifies mission-related measures of effectiveness and

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[15] NATO NEC C2 Reference Model can be found at https://static1.squarespace.com/static/53bad224e4b013a11d687e40/t/551c054ae4b071275ffebfde/1427899722015/SAS-050+Final+Report.pdf

[16] The performance map is an instantiation of an Endeavor Space. This figure also appears in ARL-TR-7451. CAMPX refers to a campaign of experimentation – a series of linked experiments that collectively explore a particular endeavor space.

a minimum or desired level for these variables for each mission or class of missions. Mission Difficulty is a characterization of the nature of a mission. Circumstances and Conditions specify the values of parameters that represent the environment in which a mission took place. The performance map is translated into a value metric by the objective function provided by C2 Agility Theory. From an enterprise perspective, the C2 Agility metric is the fraction of the Endeavor Space where an entity can operate successfully (meet minimum effectiveness and timeliness requirements) over a defined range of circumstances and conditions.

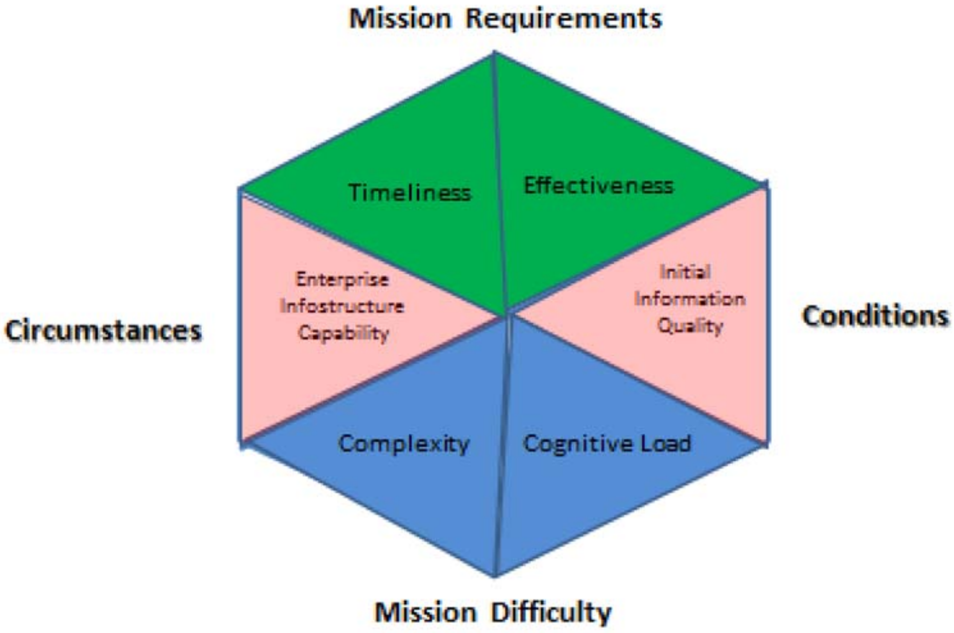

Figure 8: Endeavor Space

## Battlefield[17] Autonomy and Automation

Entities, both real and virtual, operating “on the battlefield” can be delegated specific decision rights and accesses that can be mapped to specific levels of autonomy. These entities range from commanders and subordinates to software agents and a variety of platforms, including robots. In the case of humans, autonomy is already a property of the nodes that form C2/Social/Cognitive networks, as these nodes represent individuals and organizations that are capable of independent

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[17] The term battlefield is used here to refer to military organizations and endeavors, whether or not they involve kinetic operations.

action. It makes sense to extend this formulation to non-human nodes that also are capable of some degree of autonomy.

The nature of the autonomy that entities have can be characterized by both the nature of the decisions delegated to them and the presence and nature of an override capability. This override capability can be employed to change their degree of autonomy dynamically. C2 Doctrine, based on C2 Agility Theory, calls for explicit decisions regarding the degree of autonomy that various entities should possess as part of their C2 Design process and the subsequent adoption of a specific C2 Approach. In the case of entities outside the chain of command (coalition partners, both military and civilian), these decision rights need to be negotiated or self-synchronized. When it comes to non-human entities with a physical presence operating on the battlefield, the current general practice is for direct human control in some form.

Virtual entities, such as embedded software or software agents that live and function in our information and communications networks, generally are not considered from a C2 Approach perspective in the same way that physical entities are. However, the nodes on information and communications networks can feature embedded software agents that can be thought of in the same way; that is, as having both a specific degree of autonomy and a specified override capability. As a point of reference, historically this software (having been pre-programmed to follow specific rules or perform specific functions) has been thought of as possessing a limited degree of autonomy without a dynamic override capability. It is now time for this perception to be critically examined to determine if the autonomy it possesses in practice needs to be better and more widely understood, and if and when it needs to be changed.

In the future, these agents are likely to possess enhanced automated cognition and be capable of "responsibly"[18] exercising greater autonomy. To exercise the autonomy they are given responsibly, these agents also need to possess an appropriate level of cognitive capability and have appropriate accesses to information and communications.

Communications, in whatever form it takes, enables the links between and among these entities and others. Their establishment and utilization are governed by C2 processes and constrained by accesses. They are enabled by communications capabilities. As a point of reference, humans in the chain of command can be given various degrees of autonomy and these permissions can be dynamically changed, provided appropriate communications are present.

### Definitions of Autonomy and Automation

This preliminary definition of the term Automation centered on the employment of "automatic" decision making and a reduction of human cognitive involvement. The nature of the reduction in human cognitive involvement to which it refers needs to be put in context. This cognitive reduction condition refers to the specific decisions that are automated, and does not address the fact that human cognitive involvement will be, in many cases, shifted to other decisions that are required to accomplish a given task or mission, even if this is limited to the exercise of an override. In fact, one of the most significant benefits of automation is that human cognitive

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[18] Responsibly, as it is used here, refers to the actions of both the human delegator and the agent.

capacity can be put to more productive use. Hence, automation not only impacts the decisions that are automated, but also other decisions that can, as a result, receive increased human attention.

The preliminary definition of autonomy centers on freedom from external control or influence. Note that the concept of autonomy is applicable to humans, agents embedded in systems, and robots (a system with a physical presence and a degree of autonomy). Reduced autonomy can be thought of as the imposition of external constraints on behavior. In the case of systems (non-human actors), autonomy cannot be completely separated from automation, since the former depends on the latter. Automation is necessary for systems to be capable of exercising autonomy; thus, increasing levels of automation enable increased autonomy.

In the case of humans, it is simply about "degrees of freedom" or "freedom of action." Humans can be conditioned (programmed) by upbringing, education, and training, and influenced by the culture in which they exist. Thus, humans are never completely free from external influences, even if these influences are no longer proximate. While the influences that shape human behavior need to be understood to adequately assess the fitness of C2 Approaches, it is beyond the scope of this paper.

The enabling relationship between automation and autonomy suggests that the decision processes that determine the degree of autonomy to be given to systems and mixed human/system organizations begin with a determination of the cognitive equivalent of the software embedded in the systems of interest.[19]

### Levels or Degrees of Autonomy and Automation

There have been a number of proposed characterizations of degrees or levels of autonomy and automation. These scales, in some fashion, allocate tasks or responsibility between and among a non-human entity (system or computer) and one or more humans. Some characterize their scale as an autonomy scale, while others speak about levels of automation. It is meaningless to talk about levels of autonomy without addressing automation capabilities or vice versa. Thus, these taxonomies, at least implicitly, say something about both. To reflect this, I will use the term Autonomy-Automation Scale to replace what others have referred to either as levels of degrees of autonomy scales or as level of automation scales.

All of the scales include bounding levels, one level at which all of the functions considered are performed by humans, and another at which all of the functions are performed by the non-human entity. In-between levels represent de-confliction, cooperation, or collaboration between and among members of a mixed human/non-human team.

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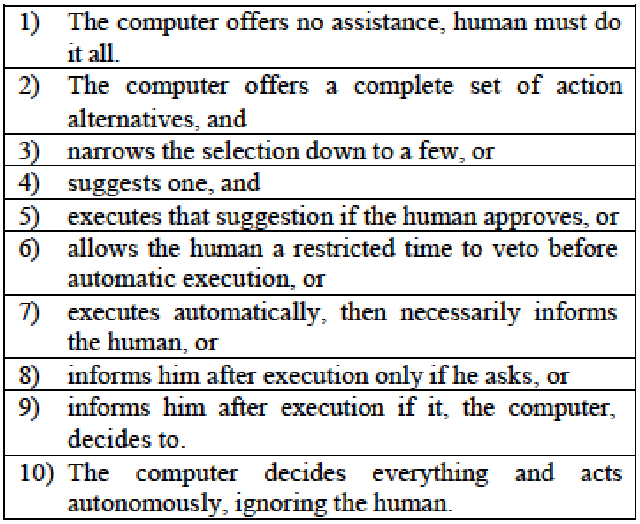
[19] The National Highway Traffic Safety Administration recently adopted the Society of Automotive Engineers' levels for automated driving systems, ranging from complete driver control to full autonomy.

For autonomy and automation to be integrated into the C2 Agility and C2 approach constructs, two other issues need to be addressed. The first is the nature and patterns of interaction between and among the human and non-human entities that comprise the socio-technical organization and the connectivity that this requires. The second is the accesses to information required to support the implied sense-making aspects of the assigned task(s), which, in some cases, also requires connectivity.

Figure 9[20] addresses the allocation of tasks and the existence of an override function, but does not address the need for access to information or the need for communications. The difficulty of decisions is implied. For example, providing a list of alternatives is generally less demanding then selecting the most appropriate course of action. In this taxonomy, the tasks considered are characterized as either decisions or actions. Depending upon the decision-action and the circumstances, making a decision may be more difficult (cognitively or computationally) than acting on it. However, taking action may involve the existence of capabilities that are required for execution. These are not explicitly identified in Figure 9.



| | |
|---|---|
| 1) | The computer offers no assistance, human must do it all. |
| 2) | The computer offers a complete set of action alternatives, and |
| 3) | narrows the selection down to a few, or |
| 4) | suggests one, and |
| 5) | executes that suggestion if the human approves, or |
| 6) | allows the human a restricted time to veto before automatic execution, or |
| 7) | executes automatically, then necessarily informs the human, or |
| 8) | informs him after execution only if he asks, or |
| 9) | informs him after execution if it, the computer, decides to. |
| 10) | The computer decides everything and acts autonomously, ignoring the human. |

Figure 9: Scale of Degrees of Automation

The 10-level Scale of Degrees of Automation, depicted in Figure 9, focuses on the generic functions of decision making and acting. While the allocation of responsibility for these is at the heart of an approach to C2, to have practical application, an autonomy-automation scale needs to differentiate between the kinds of decisions and functions that are allocated between and among humans and non-human decision-capable entities, the required interactions between and among the entities involved, and accesses to and processing of information required for the decision(s)

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[20] Parasuraman, R., Sheridan, T. B., and Wickens, C. D. “A Model for Types and Levels of Human Interaction with Automation,” in Proceedings of IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans, Vol. 30, No. 3, 2000.

involved. In other words, to be applicable to C2, an autonomy-automation scale needs to be organized in a way that makes it possible to project the levels onto the C2 Approach Space.

### C2-Oriented Automation-Autonomy Scale

For many individuals, C2 is associated with Boyd's functional model of C2, the OODA loop. Engineers at NASA explicitly and systematically used Boyd's OODA loop construct to define an eight-level autonomy scale and develop a functional assessment tool to help them decide how to design a human spaceflight vehicle.[21] Figure 10 presents their allocation of functionality for each of the four C2/sense-making functions – observe, orient, decide, and act – in the context of their spaceflight vehicle.

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[21] Proud, Ryan W, Hat, Jeremy J, Mrozinski, Richard B, Methods for Determining the Level of Autonomy to Design into a Human Spaceflight Vehicle: A Function Specific Approach: NASA 2003. This document can be found at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100017272.pdf

| Level | Observe | Orient | Decide | Act |
|---|---|---|---|---|
| 8 | The computer gathers, filters, and prioritizes data without displaying any information to the human. | The computer predicts, interprets, and integrates data into a result which is not displayed to the human. | The computer performs ranking tasks. The computer performs final ranking, but does not display results to the human. | Computer executes automatically and does not allow any human interaction. |
| 7 | The computer gathers, filters, and prioritizes data without displaying any information to the human. Though, a "program functioning" flag is displayed. | The computer anlayzes, predicts, interprets, and integrates data into a result which is only displayed to the human if result fits programmed context (context dependant summaries). | The computer performs ranking tasks. The computer performs final ranking and displays a reduced set of ranked options without displaying "why" decisions were made to the human. | Computer executes automatically and only informs the human if required by context. It allows for override ability after execution. Human is shadow for contingencies. |
| 6 | The computer gathers, filters, and prioritizes information displayed to the human. | The computer overlays predictions with analysis and interprets the data. The human is shown all results. | The computer performs ranking tasks and displays a reduced set of ranked options while displaying "why" decisions were made to the human. | Computer executes automatically, informs the human, and allows for override ability after execution. Human is shadow for contingencies. |
| 5 | The computer is responsible for gathering the information for the human, but it only displays non-prioritized, filtered information. | The computer overlays predictions with analysis and interprets the data. The human shadows the interpretation for contingencies. | The computer performs ranking tasks. All results, including "why" decisions were made, are displayed to the human. | Computer allows the human a context-dependant restricted time to veto before execution. Human shadows for contingencies. |
| 4 | The computer is responsible for gathering the information for the human and for displaying all information, but it highlights the non-prioritized, relevant information for the user. | The computer analyzes the data and makes predictions, though the human is responsible for interpretation of the data. | Both human and computer perform ranking tasks, the results from the computer are considered prime. | Computer allows the human a pre-programmed restricted time to veto before execution. Human shadows for contingencies. |
| 3 | The computer is responsible for gathering and displaying unfiltered, unprioritized information for the human. The human still is the prime monitor for all information. | Computer is the prime source of analysis and predictions, with human shadow for contingencies. The human is responsible for interpretation of the data. | Both human and computer perform ranking tasks, the results from the human are considered prime. | Computer executes decision after human approval. Human shadows for contingencies. |
| 2 | Human is the prime source for gathering and monitoring all data, with computer shadow for emergencies. | Human is the prime source of analysis and predictions, with computer shadow for contingencies. The human is responsible for interpretation of the data. | The human performs all ranking tasks, but the computer can be used as a tool for assistance. | Human is the prime source of execution, with computer shadow for contingencies. |
| 1 | Human is the only source for gathering and monitoring (defined as filtering, prioritizing and understanding) all data. | Human is responsible for analyzing all data, making predictions, and interpretation of the data. | The computer does not assist in or perform ranking tasks. Human must do it all. | Human alone can execute decision. |

Figure 10: NASA Level of Autonomy Assessment Scale

The OODA tasks explicitly identified by the NASA scale are as follows:

- Observe: gather, filter, prioritize, display
- Orient: predict, interpret, integrate
- Decide: rank options, display reasoning
- Act: act unconditionally and inform, act with explicit approval, act if no veto, provide backup

### Autonomy and an Override Capability

Various levels of autonomy are associated explicitly or implicitly with a preemptive veto or an after-the-fact override capability, as identified in Figures 9 and 10. To exercise this override capability, the situation needs to be monitored and this, in turn, requires access to information. This requirement has been a topic of discussion in the automation literature dating back decades. Bainbridge[22] provides an excellent discussion of the nature of the responsibilities humans need to take on as processes are automated, and dispels the myth that automating a process frees humans from the need to stay engaged and that, when a process is automated, humans are needed to handle a variety of situations. That, in turn, requires monitoring with an intention to take over selected functions under some circumstances. This human-machine collaboration requires appropriate training and practice if the automation effort is to succeed.

Some of the sources of information that non-human decision makers need may be external (non-organic); therefore, the non-human partner also may require significant communications capability. As the level of autonomy increases, one can reasonably expect that more variables will need to be monitored and more access to information and communications will be required. This adds complexity to the tasks that fall to the human team member.

| Degree of Autonomy | Override | Monitoring | Information & Networking |
|---|---|---|---|
| **Full Autonomy** | none | n/a | extensive access to information sources & communications |
| **Conditional** | conditional | focused | extensive access to information sources & communications |
| **Functional** | hands off exception only | limited continuous | appropriate access to information sources & communications |
| **Limited Functional +** | hands off | continuous | limited access to information sources & communications |
| **Limited Functional** | hands on | continuous | limited access to information sources & communications |
| **No Autonomy** | n/a | n/a | some organic sensors & communications |

Figure 11: Degrees of Autonomy and Associated Attributes

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[22] Bainbridge, L. (1983) Ironies of Automation. Automatic, 19(6), 775-779.

### From OODA to C2 Approach

All of the autonomy-automation scales consider one non-human entity and an unspecified number of human entities working as a team, with the allocation of decision rights and functions differing from level to level. However, the future “battlefield” will see a proliferation of non-human cognitive entities that will be delegated some decision rights. Thus, three kinds of teams will exist: human-only teams, mixed human-non-human teams, and teams composed of only non-human entities. The extent and nature of their collaborations will be shaped by the selection of a C2 Approach and the capabilities and cognitive equivalence of the embedded intelligence in our information and communications networks that support these teams.

Klein, et al.,[23] identify 10 challenges that need to be addressed to make non-human decision makers or agents effective team members alongside of their human counterparts. These include some that have yet to be adequately met by existing human-non human teams or the agents embedded in our networks, or built into the current generation of robots and UAVs. For example, their third challenge calls for humans and agents to be mutually predictable, while their second challenge states that “intelligent agents must be able to adequately model the other participants' intentions and actions vis-à-vis the joint activity's state and evolution.” Other challenges have and must continue to be met in order to prudently allocate decision rights to non-human entities. For example, their fourth challenge specifies that agents must be directable. This implies the need for near real-time monitoring and communications in order to re-direct agents as the mission and circumstances change.

From a C2 perspective, the near-term challenge will be to effectively incorporate non-human entities that cannot meet all or even a large number of these challenges into C2 arrangements. This is because decision rights have been routinely allocated to non-human entities, and the number and variety of these entities will grow dramatically in the near future.

### Autonomy and Cognitive Capability

A decision regarding the appropriate level of autonomy for battlefield entities, human or non-human, is an integral part of the determination of an appropriate C2 Approach. As the level of autonomy explicit or implicit in the delegation of decision rights increases, the number and nature of the decisions that need to be made by the software will increase, perhaps non-linearly. While the number of decisions that need to be made and the time available for making them are important considerations, the types of decisions that need to be made are of paramount interest, as they determine the cognitive equivalence required. Even very large numbers of decisions, provided they are simple ones, can be handled with relative ease. While a full discussion of the relationship between levels of autonomy and cognitive capabilities are beyond the scope of this paper, it is clear that a taxonomy of decision types is required, as is a classification of the types of conditions under which the decisions need to be made.

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[23] Kein, G., Wood, D. D., Bradshaw, J. M., Hoffman, R. R.,and Feltovich, P.J. (2004) Ten challenges for making automation a “team player” in joint human-agent activity. IEEE Intelligent Systems, 19(6), 91-95.

This taxonomy of decision types would need to make a distinction between simple decisions (ones that involve a choice between pre-defined alternatives) and complex decisions (where the alternatives need to be generated). As for the conditions that prevail, both the level of uncertainty and the need to analyze incoming information are prime considerations.

## Summary and a Way Ahead

The importance of properly formulating the problem cannot be overstated. The problem that this paper addresses is the determination of an appropriate C2 Approach for a socio-technical organization/system that consists of humans and intelligent agents, both virtual and real (physical), for a given mission and set of circumstances. C2 Agility Theory provides a basis for the objective function, while the Composite Network Model identifies many of the variables and relationships of interest, both controllable and uncontrollable. While previous works have certainly mentioned both autonomous systems and embedded automation, they have not been explicitly incorporated into the problem formulation.

This paper has taken a first step to integrate these important considerations, arguing that the delegation of the decision rights dimension of the C2 Approach Space applies not only to human battlefield entities, but also to embedded software agents and robotic platforms. It has also argued that the cognitive equivalent of the software needs to be understood and factored into the allocation of decision rights.

Much, however, remains to be done if we are to be able to develop an adequate understanding of the behaviors of our socio-technical composite battlefield networks and design and manage them under a variety of circumstances and stresses. A major research effort is needed to understand the cognitive equivalence requirements of different levels of autonomy. This, in turn, requires a decision taxonomy that makes sense for both human and non-human intelligence and could be embedded in robotic entities as well as in information and communications networks.

Cyberspace operations are emerging as a critical component of military operations, evidenced by recent conflicts and the standing up in the U.S. of USCYBERCOM in 200924. USCYBERCOM has significant scope, as it “plans, coordinates, integrates, synchronizes and conducts activities to: direct the operations and defense of specified Department of Defense information networks and; prepare to, and when directed, conduct full spectrum military cyberspace operations in order to enable actions in all domains, ensure US/Allied freedom of action in cyberspace and deny the same to our adversaries.”[25] The scope of this activity is considerable. In late 2016, all 133 of U.S. Cyber Command’s Cyber Mission Force teams achieved initial operating capability.[26] Cyberspace operations can not only enable C2 and operations in all domains, but can, under some circumstances, constrain one’s ability to operate in portions of the C2 Approach Space. Cyberspace operations, by their very nature, must possess some degree of autonomy, and the

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[24] http://www.stratcom.mil/Media/Factsheets/Factsheet-View/Article/960492/us-cyber-command-uscybercom/

[25] Ibid.

[26] https://www.defense.gov/News/Article/Article/984663/all-cyber-mission-force-teams-achieve-initial-operating-capability/

automation that enables the exercise of delegated decision rights requires some cognitive capability.

Thus, research and analysis is needed to understand: 1) the C2 of Cyberspace Operations and the regions of the C2 Approach Space that are appropriate to employ as a function of specific missions and circumstances; and 2) multi-domain C2, the harmonization of operations across multiple domains.

To explore these and other aspects of Agility, Autonomy, and Automation, further modeling and analysis is required. However, it is important that these research efforts be in the context of a campaign of experiments that can systematically explore the properties and performance characteristics of Composite Networks that contain intelligent agents, and the appropriateness of various approaches to C2 in particular, in the context of a highly contested cyber environment.

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14. ABSTRACT

Success in military, civil-military, and other complex endeavors depend upon the ability of command and control arrangements and approaches to effectively employ automation, manage autonomy, and achieve requisite levels of agility. A failure of C2 to accomplish any one of these three essential interdependent objectives can lead to adverse consequences and potential mission failure. This paper explores the nature of the C2-related interdependencies between and among agility, automation, and autonomy and provides the integrated conceptual framework that is necessary to systematically explore these relationships and their impact on C2 and on mission effectiveness.

15. SUBJECT TERMS

C2, C2 Agility, C2 approaches, C2 Approach space, Autonomous systems, composite networks, socio-technical organizations

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