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Coping with Complexity in Command and Control

Topic 4: Collaboration, Shared Awareness, and Decision Making

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ABSTRACT

Combat presents a complex system that requires effective management to ensure successful completion of missions. Management of own forces and other assets in the pursuit of mission objectives is performed by the Command and Control (C2) system. The trend of modern combat is to move away from conventional warfare, increasing the occurrence of "messy" and "wicked" problems. Modern C2 systems require new frameworks and designs to cope with the increase in complexity experienced in warfare. Despite the trend to automate analysis and decision making, humans are still better equipped for providing creative solutions to unforeseen occurrences. Development of C2 systems must focus on assisting the human to enhance his cognitive capabilities and experience. Complexity should not be avoided, rather embraced for its richness in reaching creative solutions. Possible approaches are advances in the field of Cognitive Work Analysis (CWA) for designing displays and Human Machine Interfaces (HMI) and utilising Snowden's Cynefin framework. The objective of these two approaches is to make sense of the available information to support effective decision making in a complex environment. The aim of this paper is to describe an approach, focussed on the complexity aspects, to developing C2 systems.

1 Introduction

Effective Command and Control (C2) is key to the success of military and other related operations. It is utilised for the processes of identification of objectives, determining intent and planning of actions right through to the monitoring of the situation and making decisions about changes in plans. All this is required to ensure a successful completion of a mission.

Modern technology continuously expands the ability to gather and communicate data about the combat environment, forcing the C2 system to cope with increasing complexity. As the trend of modern combat is to move away from conventional warfare, the importance of accurate sense making is steadily increasing. To simply display all the available information without tools to assist in sense making is not beneficial. Endsley [1] found that the problem with sense making and decision making is no longer the lack of information, but rather to find the right information when it is required.

Despite the advances in machine learning (including reinforcement learning and other non-supervised approaches) humans are still a crucial part of the analysis and decision making process. Humans are still better equipped for providing creative solutions to unforeseen occurrences, as noted by Parasuraman [2]. Computers can be used to wade through data and turn it into usable information that can be presented in a manner that enables humans with cognitive capabilities to make the crucial decisions. The focus should be on assisting the human with his cognitive capabilities and experience when developing C2 Concepts. Complexity should not be avoided, nor should one attempt to reduce it (in a classical manner), but instead complexity should be embraced for its richness when striving for creative solutions to "messy" or "wicked" problems.

Two such approaches are Snowden's Cynefin framework [3] and advances in the field of Cognitive Work Analysis (CWA) by Vicente [4] for designing displays and Human Machine Interfaces (HMI). The objective of these two approaches is to make sense of the available information to support effective decision making in a complex environment. Applying them to C2 models, such as the OODA loop from Boyd [5] and derivatives thereof, is a possible starting point for developing C2 systems and related interfaces for modern combat.

This paper will investigate the factors that contribute to the complexity of modern C2 and it will propose a framework for developing C2 support systems. The focus will be squarely on complexity and human cognitive and social aspects as well as the development of suitable ecological HMIs. The HMI integrates the human operator to the rest of the C2 system for Situation Awareness, sense making and decision support. The output of this paper is a development framework for C2 systems that is capable of assisting commanders in coping with complexity in the execution of a military mission.

It is also foreseen that the framework that is established will be used during the development of conceptual models that can be used to scope experiments for use in simulated military exercises. Once the models are properly qualified and verified, real world exercises will be required to effectively validate the proposed concepts.

2 Command and Control

2.1 Background

The US DoD [6] defines military C2 as the exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. It consists of planning, directing, coordinating, and controlling of forces and operations towards the accomplishment of the mission.

Alberts [7] summarises C2 as problem solving within a military context to provide focus and convergence of effort. Commanders are required to assess the environment, decide on a course of action and lead those under their command. The purpose of C2 is to bring all available information and all available assets to bear on an objective. It requires a vision of the results to be achieved, an understanding of higher level intentions, concepts, missions, priorities and the allocation of resources, an ability to assess people and risks and involves a continual process of re-evaluating a situation. Command and Control can be related to a knowledge system. It converts data into information to build knowledge where the information can be applied. Knowledge can be synonymous with Situation Awareness.

2.2 A Command and Control Model

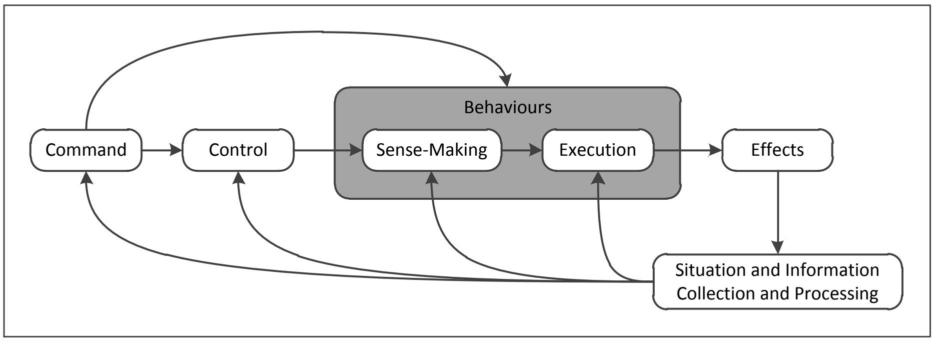

Figure 1: Model for Command and Control (adapted from [7])

Alberts [7] provides a basic model for C2, as seen in Figure 1, which will form the basis for further discussions. In short, the main elements of C2 are:

a) Command. Establish and communicate the initial set of conditions for the mission and include the continual assessment of the situation for possible changes in the intent. Command flows out of an assessment of the “problem” and the operational environment in the form of a decision on the most suitable high level solution.

b) Control. Determine whether current or planned efforts are still in line with the commander’s intent or the high level solution. The control function then has to make the required adjustments, while keeping in line with the Command Intent.

c) Behaviours. Behaviour includes the following:

   i) Sense-making. Sense-Making is the heart of the C2 process. It takes the perception of available information through cognitive and social activities and processes to support the making of decisions. Tacit knowledge and previous experience is combined with real-time information to identify, analyse and understand what is happening and predict what is going to happen. The aim is to make sense of the complex environment to guide the making and adjustment of plans.

   ii) Execution. Plans and orders guide the execution of an operation. The effects of C2 are determined by the action chosen, when and under which conditions it is executed, the quality of execution and interactions with other possible related actions in the environment.

d) Effects. Effects are the visible outcomes of actions. They consist not only of the effects of own actions on the adversary, other parties or the environment, but also the effect of the environment and other entities on own forces in the execution of their orders.

e) Situation Information and Processing. The C2 process and other sense making related actions require information about the environment and interaction of the present forces. The information required for sense making is gathered and transmitted to the role-players in the C2 system.

As seen in the model, C2 is an iterative and cyclic process that requires continuous updates of decisions in order to adapt to a changing situation. Brehmer [8] highlighted the effect of delays in every step of the C2 process. By the time the orders for action are sent, the information and even the planned solution may already be out of date. This makes it even more difficult to implement an effective solution to the perceived problem. According to the work of Sterman [9], the process of decision making within an environment with inherent risks and delays result in a complex dynamic system which requires a structured approach with modelling and management.

Brehmer [10] also noted that despite being a human activity, C2 is executed within a system, that consist of equipment and people (commanders and subordinates) organised to execute a task as well as the methods applied. It is a socio-technical system, and all elements (organisation, methods, and the supporting systems) should be considered in unison when analysing C2.

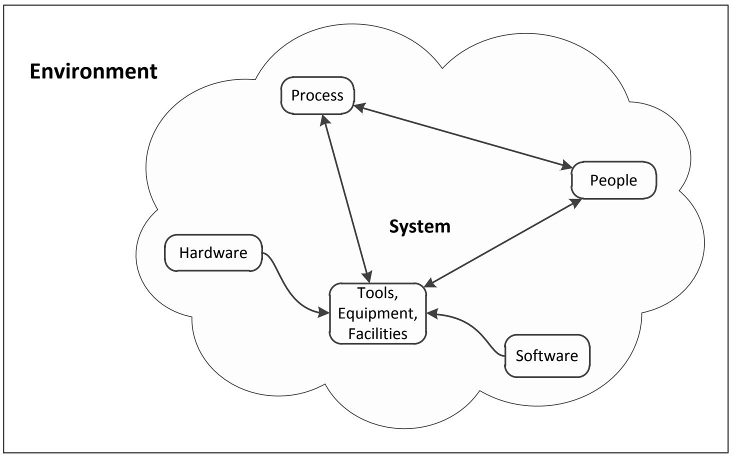

Figure 2: A socio-technical system

The output of the C2 system is not a guaranteed successful outcome of an operation, but a necessary requirement for the successful operation. It produces orders and the success of the operation is dependent on many other factors such as actual action of own resources as well as the actions and reactions of the enemy.

2.3 OODA Loop

One of the most widely used Industrial Age C2 models is the “Observe-Orientate-Decide-Act” (OODA) loop as defined by Boyd [5]. He noted that it is the objective to operate inside the enemy’s OODA loop, and forcing him to react to your actions, instead of the other way round. The aim is to be faster than the enemy and attack him where he does not expect it. Despite being widely accepted and used, the OODA loop is flawed and criticised. Grant’s [11] analysis identified that it is reactive, and does not incorporate the commander’s intent, planning or exit criteria. Furthermore, the OODA loop does not address the inherent delays in the C2 and execution system.

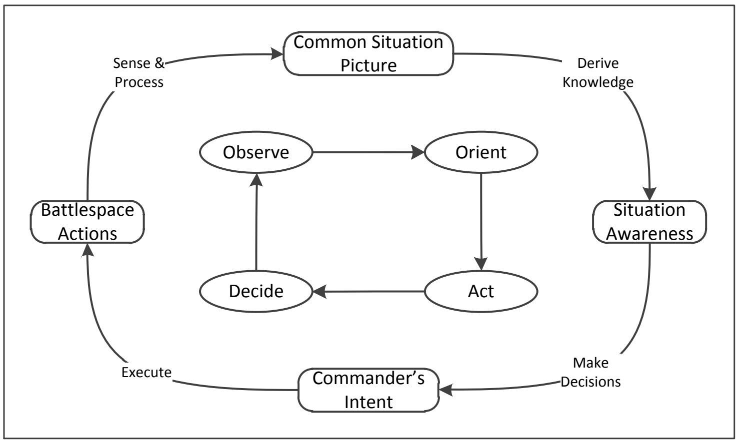

Figure 3: Modified OODA Loop

On its own, the OODA loop is supposed to be a model for winning and losing, not specifically for implementing C2. OODA still has the ability to absorb the latest terminology such as Situation Awareness and Sense-making. As the OODA Loop is a high level and general concept, it can be applied to almost any environment. Different wordings and concepts can be absorbed as shown by Oosthuizen [12] in Figure 3. The OODA loop still remains the basic model throughout the world to guide the development and implementation of C2 doctrine.

2.4 Dynamic OODA Loop

Brehmer [13] expanded the OODA loop with Cybernetic C2 model inputs and manoeuvre warfare concepts to form the Dynamic OODA (DOODA) loop, as provided in Figure 4. It includes the elements of the mission and command concept or intent. There also exists an exit condition when the mission objectives have been achieved. An effective C2 system must be able to continuously maintain control in the process of achieving the objective or commander's intent. This is achieved through collecting data, making sense of it and performing planning.

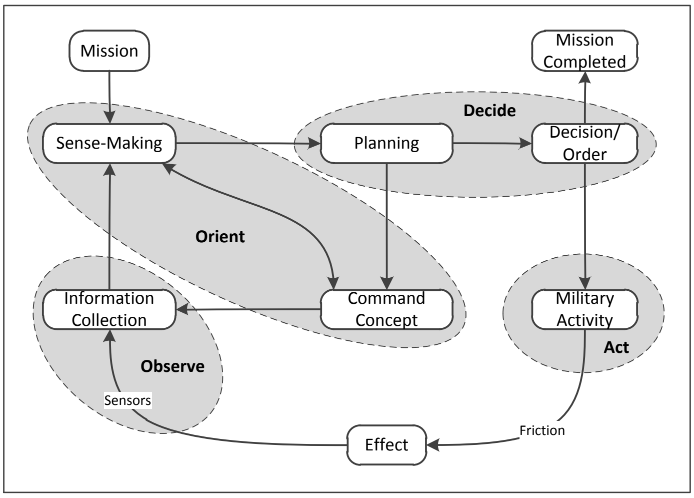

Figure 4: Dynamic OODA Loop

2.5 Situation Awareness

Situation Awareness is defined by Endsley [1] as "the perception of elements in the environment within a volume of time and space, comprehension of their meaning and projection of their status into the near future". This is echoed by Vicente [4], in that Situation Awareness is a prerequisite for decision making. Within C2 a common Situation Awareness is required for effective decision making. Building and keeping effective Situation Awareness is difficult and requires great effort to update information in a rapid changing environment.

Endsley [14] developed a model for Situation Awareness, as seen in Figure 5, and proclaimed that true Situation Awareness only exists in the mind of the operator. The HMI of the Situation Awareness system is the interface to the human cognitive "framework". The presentation of information must be in line with natural cognitive patterns and processes for direct perception. An information bombardment is not the solution; a careful analysis is required to determine what is actually required for effective decision making. A Situation Awareness system must support the processing and display of large volumes of data to support understanding of the situation along the following guideline:

a) Operators require direct presentation of a high level Situation Awareness instead of lower level data still requiring interpretation.
b) Information displays must be goal orientated by co-locating information required for a specific goal.
c) Always provide a situation overview to support global Situation Awareness.
d) Critical cues for situations where shifting of goals and priorities are required must receive prominence on the display.
e) Remove unrelated and extraneous information from the Situation Awareness display.
f) Data rich environments must be supported by providing the capability for parallel processing and multi-modal displays.
g) System complexity must be addressed in the Situation Awareness displays.
h) The level of confidence in the information must be indicated.
i) Include warning tones or alarms into the display to highlight changes in important aspects on the Situation Awareness.

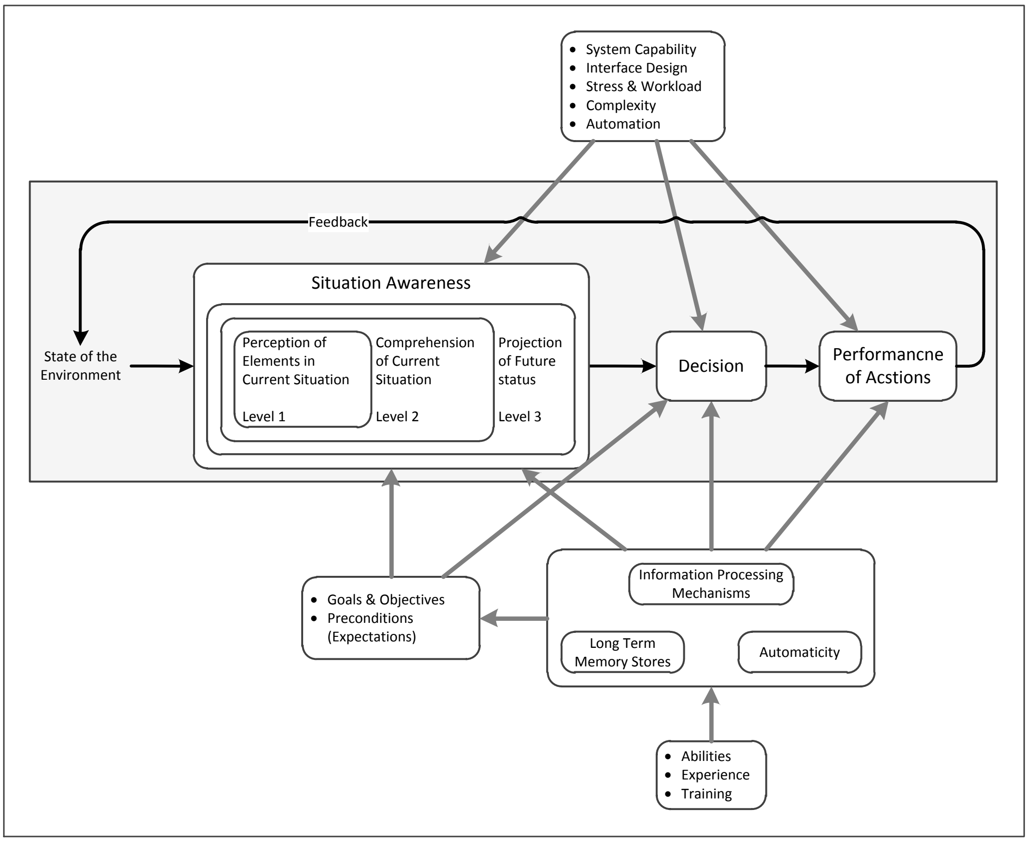

Figure 5: Endsley's Situation Awareness Model [1]

Endsley [1] compares difficulty of converting data into information with “beauty” as it lies in the eye of the beholder. An understanding is required of how the users of the information will process and utilise it for decision making. This may even include being sensitive to cultural perceptions.

Expertise is one of the main contributors to successful Situation Awareness. However, not all operators of systems are experts and experience may come too late. As the environment and available data or information gets more complex, the interaction between the Situation Awareness support system and the operator requires careful consideration.

2.6 Decision Support / Sense Making

As discussed before, C2 is about making decisions on how to adapt to a changing environment in order to achieve a set of goals. Nteun [15] summarised sense making as central to decision making in support of C2. It includes aspects of human cognition such as reasoning, pattern recognition, comparing of facts and differentiation between information that makes sense or not. Bennet [35] defines decisions as guesses about the future. With the increase in complexity, the decision makers must utilise their intuition and judgement. However it should be possible to develop a strategy to guide problem solving through a serious of leading decisions and actions. These include, amongst others, boundary management, absorption, simplification, sense and respond, amplification and seeding. Humans must be able to use their cognitive abilities and past experience.

Brehmer [8] proposes that one way to investigate C2 is to make a split between planning (command) and execution (control). The “Command” of C2 is concerned with the planning of an advantageous encounter with the adversary. As it is almost impossible to predict the behaviour of the adversary, “Control” is required to steer the outcome of the conflict into a favourable direction. From the time of Moltke [16] this has been known, resulting in the famous dictum: “No plan survives contact with the enemy.” Thereafter, it depends on the responsiveness and opportunism of the commander and his forces.

Alberts [7] notes that an important aspect is to detect when decisions need to be made as well as be able to make the decisions. One way is to have alternative plans available to be implemented if the situation requires it to save on decision and implementation time. Decisions are to be made in a changing environment while the impact of the decisions also changes the environment. Brehmer [8] describes this as Dynamic Decision Making, which requires the following:

a) A Series of Decisions. Dynamic tasks cannot be resolved by a single decision. To successfully complete the plan, a desired conclusion is required.

b) The Decisions are Interdependent. The series of decisions are implemented through limited resources. The same resource may be required to perform more than one task, and often this cannot be done simultaneously.

c) The Problem Keeps Changing Because of Own Actions/Decisions as well as Autonomously. The adversary is not only responsive but makes plans of his own. This issue is complicated through a number of delays in the process.

d) The Decisions have to be Made in Real Time. To be effective, decisions cannot be delayed until all information is available of the optimum conditions. Interactions and change have to be addressed in-time.

Leedom [17] surmises sense-making of a situation as the integration of all the different interpretations of the role-players in the sense making process. The different interpretations are from the different beliefs in terms of their cultural context, perspectives and previous experiences. Sense-making tends to be a dynamic, continuous and negotiated understanding of the environment and is distributed between multiple participants. Information is the total property of the communication between two actors. According to Shannon [18], information entropy defines information contents as relative to the total context of the message. The result is a complexity in the different interpretations and sense making of data and information. Therefore, sense making is dependent on how the information will be contextualised and interpreted.

It is clear that a C2 system must support the operator by presenting the information he requires for sense making. As we are in the digital age, this will mainly be in the form of a suitable HMI. The method of presentation must be aligned with his mental models and what he expect to see about the progress of the mission and the environment to support natural cognitive processes for decision making. This includes making the operator aware of what is not known within the scenario.

3 Complexity

According to the Merrian-Webster dictionary, the word “Complex” is defined as “a whole made up of complicated or interrelated parts”. Alberts [7] traces the definition back to the Latin word “Plexus” meaning braided or entwined. Therefore, “Complexus” means braided or entwined together. Pagels [19] notes that complexity as a concept has been with us for a long time, but it only since the development of computer systems and cybernetics that it has reached prominence.

Complexity in systems has dramatically increased over time as technology allows for more and more information to be exchanged between elements of systems. A Complex System consists of a number of interconnected nonlinear elements that causes unpredictable behaviours. As a result a Complex System cannot readily be decomposed into independent and manageable elements for analysis. This is differentiated from the word complicated, meaning that the system contains many, yet linear and predictable elements. A list of combined characteristics for complex systems as being applicable to Decision Support in C2 is (derived from [20] [21] [22] [23] [24]):

a) Complex Systems are large manmade systems to provide multiple functions to multiple users in multiple organisations over a large geographical area. They may have many autonomous and individual agents that are the building blocks. The components can operate independently as individual systems and even have different life cycles.

b) Complex Systems display emergent behaviour at a macro-level as a result of the actions of and interaction between individual agents as well as with a dynamic environment. The structure of Complex Systems cannot easily be deduced from the structure of the individual agents. The interactions among the parts are non-linear and may dominate the overall structure and behaviour.

c) The behaviour of the system may be non-deterministic despite an apparent order and may even exhibit chaotic behaviour under certain conditions as a result of nonlinear dynamics.

d) Complex systems are difficult to design and build. They exhibit complex behaviour, both internal and external. They have unexpected and unpredicted internal interactions where changes in one element will influence the behaviour of others.

e) Complex systems are seldom developed as a whole; they tend to be formed through a process of integration an evolution. The different elements may be in different stages of a system life cycle and developed using different standards. Complex systems adapt to their environment and other elements as they evolve, in return increasing the complexity even more. Over time they display increasing specialisation and capability.

f) Complex systems have a significant human and social dimension that contributes to complex behaviour and the evolution of the system as a whole.

g) Knowledge and control is distributed in the complex system and also exist at different operational layers of elements or subsystems.

h) The Complex System has a micro- and macroscopic memory. What happened in the past is to a degree responsible for the current behaviour.

The implication of complexity is that it is impossible to build a model that accurately and fully describes the Complex System, according to Cilliers [24], as it has to be as large and as complex as the actual system. The model has to include each and every interaction between the system elements. As a result it is all but impossible to predict the behaviour of a system accurately. Also, being an open system, the boundaries are hard to define and the “ports and hooks” through which it interacts with the world are exceedingly difficult to identify completely. However, modelling still has its place as it helps us to understand the system better, but the context, application, limitations and assumptions of the model have to be well understood.

White [25] explains that cross-boundary interactions between humans and machines characterise the modern world. The non-deterministic behaviour of people must be captured in the description of the total system. The success of the overall system will depend not only on the managing authority, but also on the cooperation of others. Fowlkes [26] agrees in the sense that the contributors to system complexity include the dynamic and context-dependant nature of cognitive work and the dynamic nature of socio-technical work settings. Systems where humans tend to play a role have a tendency to be complex. In development the focus must be on supporting the human with the available technology. The way that humans think and operate must be brought into context of the physical system design.

Richardson [27] points out that the value of complexity science and thinking is not so much in the model created to represent a system, but rather the value of the modelling process and the supporting culture. Sterman [9] continues that despite making absolute sense of a complex system being close to impossible, a suitable mental model to absorb and interpret information is important. Skills for assimilating the available information and making decisions in uncertainty needs to be developed. This can be enhanced through simulations, which are based on mental models of the environment under consideration to understand the effect of certain influences and factors. The simulations are to be supported through scientific reasoning and enhancement of social interaction within groups operating within the complex environment.

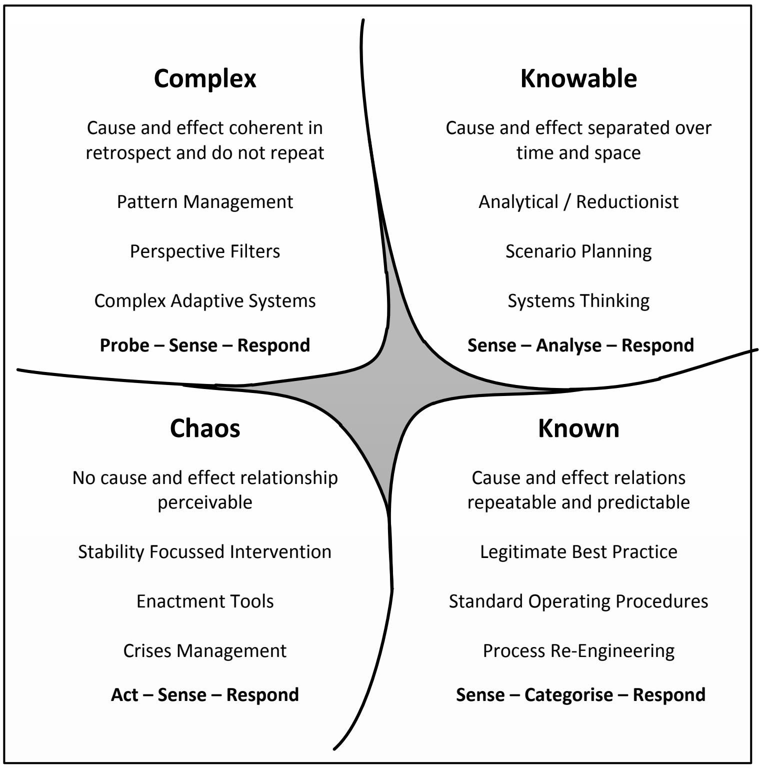

Figure 6: Cynefin Framework

Kurtz and Snowden [3] propose the use of their Cynefin framework in Figure 6 as a device for making sense in complex environments. It provides the decision maker with powerful constructs that are useful for making sense in complex situations. Knowledge of the location on the framework as well as the transitions over the boundaries is useful in learning about the requirements for coping with complexity.

For example, if one knows that the problem or situation can be cast in the “Knowable” part of the framework, one can work towards specific types of solutions, where a question may have a finite set of well-constructed answers. One could device a set of policies to deal with outcomes and exceptions in the organisational context. In the “Known” domain, we can employ simple rules to link situations with actions, as a specific situation warrants a singular action, or set of actions. In short, in that domain one can use rules and regulations in an organisational context to ensure proper operation. Snowden always points out that the domain of “Chaos” is the interesting one: here it is best to act sooner rather than later so as to be able to survive. The “Complex” domain requires one to ask first and to look for patterns to try and understand. However, as the patterns may not be easy to link causally, the development of the appropriate response remains open to be influenced by context and the environment. An example is how to decide what level of nuclear shelter to supply to communities.

Another interesting aspect of this framework is the movement across the boundary regions. When things break down in the “Known” domain, it often causes chaotic situations; the system goes from very stable into unstable and unpredictable. In the original work Snowden points out that the “boundary” there is in fact a discontinuity. This is in contrast to the other areas where the transition signifies more contextualised understanding, going clockwise. If a stable political system, which derives its stability from strong and enforced laws, gets under social pressure, it often crosses over from a system where the outcomes of actions are known, to a system where the turmoil of a revolution makes it impossible to know what will happen next.

4 Command and Control as a Complex System

Cil [29] noted that many authors, from Sun Tzu through Clausewitz to the modern day agree that primary nature of combat is complex and even a Complex Adaptive System. Complexity is also associated with uncertainty caused by the asymmetry of modern warfare. Ilachinsky [28] has described land warfare as a complex adaptive system along the same typical definitions for complex systems as discussed above. Therefore, according to Hallberg [30], C2 systems are an excellent example of complex systems. They must be capable of support in solving of complex problems during military operations. These systems are composed of personnel, organisational structures, work procedures and technical equipment. Vicente [4] provides a list for attributes for complex systems, which are related to C2 systems:

a) <u>Large Problem Space</u>. Many different forces face the commanders and decision makers in a military C2 system. They may vary from terrain (obstacles and weather), adversaries (resources and objective), own forces (capabilities and constraints), environment (political and cultural), information sources (delayed and incomplete).

b) <u>Social</u>. Individuals and/or teams will interact with each other within a C2 system, each with their own ideas, motives and objectives. This required clear communication to distribute information, orders and reports required for coordination of efforts.

c) <u>Heterogeneous Perspectives</u>. Participants may come from different social or cultural backgrounds, which may cause conflicting perspectives, views and sets of disciplines. All the different value structures must be catered for within the Decision Support System (DSS).

d) <u>Distributed</u>. Military operations often take place over large geographical areas. Decision makers in the home country are far removed from the war zone. They do not always have a full comprehension of the actual conditions and factors on the ground. This places importance on the communication system to support effective alignment of efforts.

e) <u>Dynamic</u>. C2 systems are dynamic due to the control part of the DSS that must adapt plans and actions to the requirements of the changing environment. As noted before, there may be long time constants and orders take time to be implemented and even longer time for feedback on progress or success to reach the originator. Any bit of information to be used in a C2 system has an age coupled to it, as decisions often have to be made on inaccurate and out of date information.

f) <u>Hazard</u>. The main hazard within a military conflict is getting killed. One tends to react differently when scared, hungry, thirsty and dirty within the operational environment as opposed to a safe and comfortable office environment removed from the dangers.

g) <u>Coupling</u>. Interaction between different elements or subsystems within a C2 system makes prediction of outcomes of an action difficult. Actions in one area of the system may be unintended and unexpected effect in a different part.

h) Automation. Automation still requires workers to handle abnormal situations. As this normally happens infrequently, it puts stress on workers to try and solve problems with a complex nature efficiently.

i) Uncertainty. The data available for situation assessment may be incomplete and have a high level of uncertainty in complex environments. Therefore the true state of the work environment may not be known.

j) Mediated Interaction. Computerised display and presentation systems are used as an interface for workers to analyse accumulated information. The ability of workers to solve complex problems are greatly affected by the ability of the interfaces to provide stimuli associated with natural cognitive thinking patterns.

k) Disturbances. It is common within combat scenarios for commanders to deal with unanticipated events. This requires improvisation to adapt to unforeseen contingencies in order to ensure a successful completion of a mission.

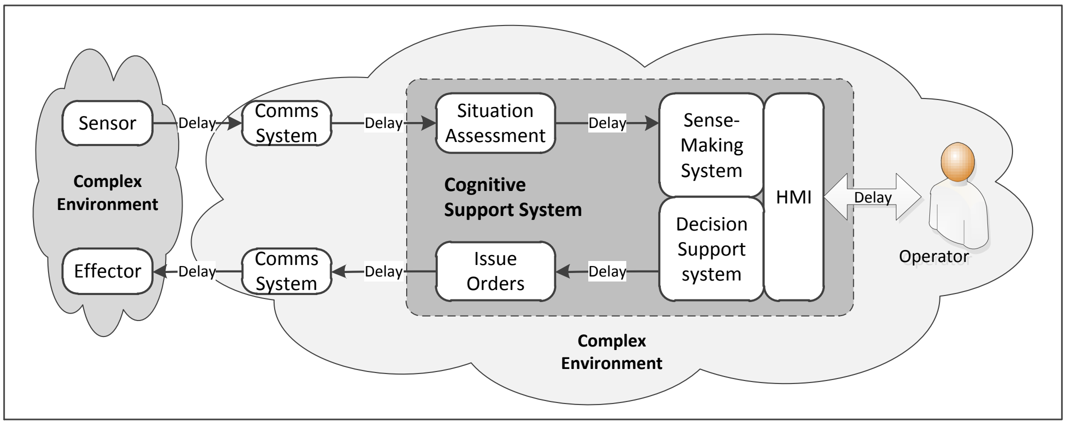

Figure 7: Complexity within C2

According to Bennet [31], C2 is required to make sense of complex situations and manage the risks during the execution of an operation. Consequently, in the operational environment, the C2 system is targeted through attacks on the personnel and communications infrastructure; this affects its reliability. As seen in Figure 7, an effective C2 system must have the capability to assimilate the available information while harnessing the cognitive and social capabilities of decision makers to control military operations. Development and improvement of modern communications technology ensures that more and more information is available, even too much at times. As a result, Decision-Support tools capable of working in the complex environment and that will help manage the rich data sets, are required.

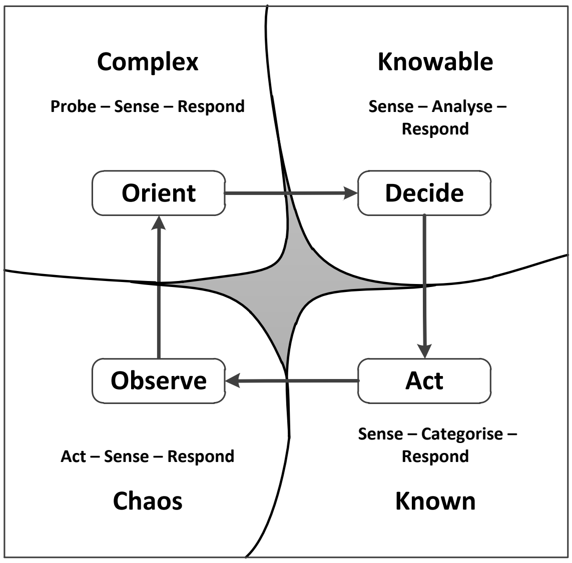

Figure 8: Cynefin and OODA

One way to consider the complexities of C2 is to map the OODA loop onto the Cynefin diagram, as seen in Figure 8. The implications for the different phases are as follows:

a) Observe. Data is gathered in within the chaos of modern combat. It is not always clear what the meaning or implication of the data is, but each element of data may have some form of value. At this stage the level of understanding is still very low.

b) Orient. Data analysis should take place to convert data into information in the Complex regime to try and make some sense of the chaos. Here patterns are observed and possible outcomes and causes identified. Experienced operators should be more capable at assessing information as they rely on skill and mental models to identify and assess patterns.

c) Decide. The information and the current and possible future states of the operation are compared to the mission objectives and the commander’s intent. Planning is performed on the information in order to make changes to ensure successful completion. The output of the planning process can be tested using simulations and enactment for refinement.

d) Act. The output of the planning process is a set of orders for execution by the assets under control of the commander. Within the “Known” regime a simple set of orders is executed according to exercised and trained doctrine. However, the actions taken within the environment may have many different direct and indirect outcomes, resulting again in actions being observed and data recorded in the “Chaos” regime.

Knowledge of where on the Cynefin diagram the C2 process is will assist in determining the actions and resources required for migration to more favourable regimes. As from the discussions above, the execution of orders will be preferred in the “Known” regime for lower risk of failure. Therefor the C2 process must facilitate the gathering of date in the “Chaos” regime, analysis to make sense in the “Complex” regime, planning in the “Knowable” regime resulting in execution in the “Known” regime. As a result of the complexity involved, transition from the “Chaos” through the “Complex” to the “Knowable” may not be possible in automated C2 systems. The human operator with his cognitive and social skills is crucial in this process, but he must be supported with C2 related equipment such as Situation Awareness Displays and DSS.

5 Cognitive System Engineering

According to Bonaceto [32] traditionally, the focus of System Engineering (SE) was on the technical aspects and automation of systems and not so much on the humans to meet the demands of the work domains. However, often system errors attributed to the operator were actually design flaws from early on in the development cycle. It has caused serious failures as seen by the downing of friendly aircraft by the Patriot missile system during the Iraq war in 2003. Investigations found that more operator involvement is required to overcome the limitations of the automated system. How the human will apply the system in the work domain has to be considered from the beginning. More automation in order to attempt to design human error out of the system will make it inflexible and unable to cope with complex or unforeseen conditions.

As discussed before, the human remains central to the operation of complex systems. Elm [33] noted that the increasingly complex work domain, such as C2, requires an effective DSS to help solve real world problems. Elm [33] and Vicente [4] list the following roles of a DSS:

a) It ensures the human decision maker is presented with “information” required instead of raw data.

b) It ensures ease of control by the human operator by being transparent to allow a total focus on the problem to be solved.

c) It complements the cognitive capability of the human mind to avoid thinking patterns that may induce errors (fixation).

d) As different humans have different natural problem solving strategies, capabilities and limitations, the DSS must support all of them.

e) It supports operators to cope with and adapt to unfamiliar events that the system designers could not anticipate.

f) It must ensure (through correct functionality) that intellectual tasks that require discretionary decision making are identified in time.

Ockerman [34] states that the objective of Cognitive Engineering is to develop an optimal interface to ensure effective interoperability between man and machine. This is crucial in today’s complex systems where humans use machines to assist in decision making. One of the elements of Cognitive SE is Cognitive Work Analysis (CWA). CWA is used to develop “cognitive affordances” to support decision making. They are devices that intuitively fit in with how human cognitive processes are performed. Bennett [31] agrees that the products of CWA define the required information content as well as the applicable context where it will be used. The aim is to enable informed decisions using the interfaces to the DSS to support the work domain. Operators need to perceive critical information on situational factors and to prevent reasoning about the factors (direct perception). Once a decision is made, the operators must be able to act directly on objects in the interface to execute control (direct manipulation).

According to Naikar [35] CWA is an approach capable of supporting the analysis, design and evaluation of complex sociotechnical systems and is steadily gaining momentum in this field. CWA provides a formative approach that focus on how work can be done. It affords workers ability to solve unanticipated events through creativity and innovativeness. The focus is on the constraints that may shape the execution of tasks. The constraints still allow for a variety of work patterns to solve unexpected problems and situations.

Ockerman [34] further highlights the importance of utilising experts throughout the process of developing DSS and associated interfaces as their operational experience and domain knowledge is used to identify cognitive processes and requirements as well as assisting in design evaluations. In future less experienced operators can benefit from this. Scenarios are used to assess the effects and goals of a cognitive in context. It can also be used during interviews to elicit knowledge from operational stakeholders.

Bennett [31] noted that an ecological interface is created with the translation of the output of the Cognitive SE analysis to into a specific interface design. The user must be able to read the relevant affordances, implying a direct perception. It must also enable the user to interact with the system using high capacity sensori-motor skills to execute actions for a capability of direct manipulation. The processing for data into information must be visible/available to the operator, not being a black box. The assumptions and approximations must be explicit.

Again, the application of the Cynefin framework is useful in relating Cognitive SE to the complexities within C2, as seen in Figure 9. Here the typical cognitive strategies are placed along with the OODA loop elements within the different regimes. The design of HMIs and other sense-making and DSS may differ when operating in the different regimes. In the “Complex” regime, a HMI may be required to support the detection of patterns or changes in the environment. Developing and optimising plans as well as predicting the possible effect needs to be supported in the “Knowable” regime. The distribution of orders and guiding the execution of doctrine are typical aspects of an HMI in the “Known” regime. Within a C2 system, the HMIs must be capable of functioning and supporting operators within all the regimes. By applying a CWA approach to the development of C2 systems, as well as assessing the complexity requirements within a Cynefin framework, will assist in addressing complex problems.

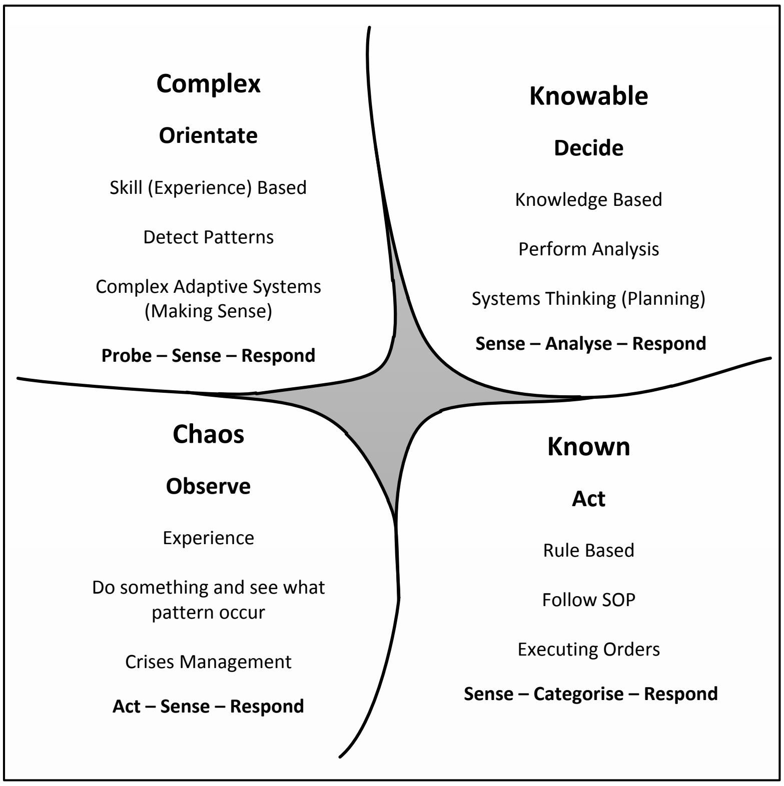

Figure 9: Cynefin Diagram Applied to C2 and CWA

6 Bringing it Together: Coping with Complexity in C2

From the prior discussions in this paper, it is clear that in modern combat C2 systems are required to support commanders (or other decision makers) to address increasingly complex and dynamic problems. The identified objective of the mission and the intent of the commander may require some serious changes of course. Even the “pre-set” objectives and original intent may require adjustment as the scenario and environment changes. The C2 system must be able to support operations to the best ability within each of the areas as determined by the context. It is now possible to propose a conceptual framework for C2 design using the elements discussed before.

The proposed starting point is to use CWA within the context of Cognitive SE. CWA offers a design approach for C2 systems, which take cognisance of the constraints, complexity, uncertainty and risk in the operational environment. Next, this process can be supported through application of the Cynefin framework to analyse scenarios and the environment to determine in which regime it resides. This includes formulation of mitigating strategies to move over the boundaries to more appropriate regimes for decision making and mission execution. In this respect Kurtz [3] notes that different operations, and even different phases of operations or different occurrences within operations, may result in finding the C2 system in different quadrants of the Cynefin framework. It will be unwise to force the strategies from any of the regimes onto all operating environments and scenarios. One should be flexible by assessing the environment, understand in which regime it lies and to use technology or processes to move to the most suitable operating regime.

Knowledge of which regime you are currently operating in is important as it will determine the tools used for Situation Awareness, Sense-making and Decision Support to generate a solution. Missing this will result in assumptions and insensitivity to valuable inputs to warn of possible hazard and failure. For example, Kurtz [3] warns that care must be taken not to enforce order onto a knowledge system - as important attributes (information and patterns) may be missed - to detect the development of a problem situation or relevant solution. You must be aware that environmental changes could move you suddenly into a new quadrant.

Cynefin is about sense making in different environments. We have made the case that it may be applicable also to Situation Awareness, the Sense Making and finally, Decision Support in C2. To this end the cognitive strategies used during CWA as well as the steps in the OODA loop are mapped onto the Cynefin framework in Figure 9. The C2 system can use different tools for sense making, decision support and execution for the different complexity regimes in the Cynefin framework. However, depending on the scenario the C2 cycle may start and end in different regimes of the Cynefin framework, as seen in Figure 10. The result is different interfaces and processes for different scenarios. This information can be added to the context analysis of the CWA to guide the development of cognitive support systems and interfaces.

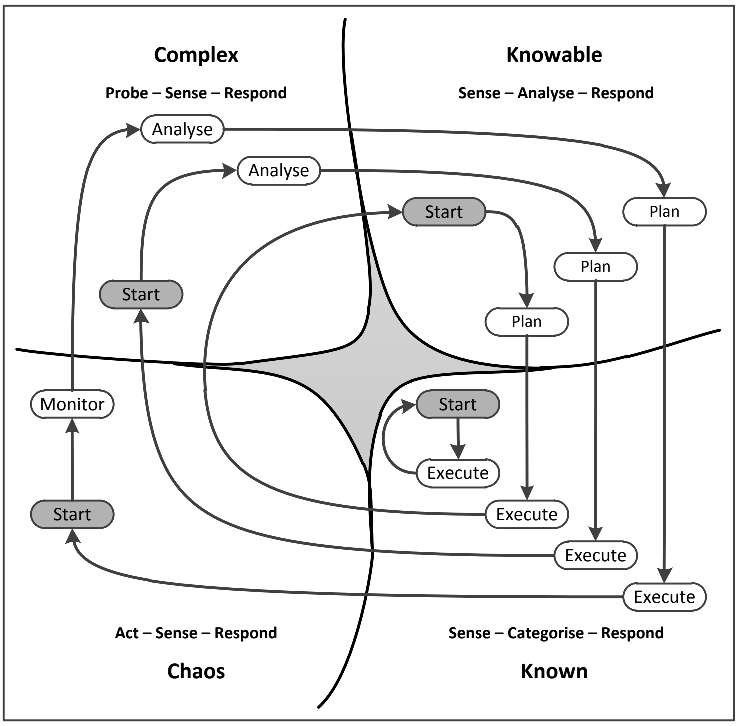

Figure 10: Cynefin and Complexity in C2

a) Known. This is applicable for scenarios where a one-to-one relationship exists between cause and effect and standard processes and procedures can be used during C2. The environment is stable with low risk in the outcome of action. This is usually the case with mundane day to day tasks and Standard Operating Procedures (SOP) is followed. The operators use a rule-based strategy to define actions to be undertaken from a predefined list. A high level of automation in the C2 system can be utilised. Orders can only be issued in the Known (Simple) Quadrant. The result is a list of orders or actions to be executed. If the impact of constraints and risks within the environment is low enough, this may be the suitable regime for operation.

b) Knowable. Scenarios where a deeper assessment and investigation is used to determine the current state of the system. Here a one-to-many relationship exists and linear analysis can be used for situation assessment and decision support. The information available can be assessed with a Knowledge Management-based approach to support sense-making and decision-making. Actions in this domain are similar to systems based thinking and related planning activities. The planning process can be used to mitigate risks and to develop alternative approaches for perceived possible changes in the environment. The solutions can be assessed through testing (simulation) in order to choose the best option.

c) Complex. C2 for tactical operations is more probable to be conducted in the Complex domain. There exist a many-to-many relationship for these complex interactions between causes and effects. The operator requires continuous situation awareness and should focus on detecting patterns for sense making. Social interaction as well as personal cognitive skills and experience are used in identifying patterns and formulation courses of action. In this domain less automation is applicable and the DSS should focus on converting data into useful information for the operator to use. The HMI also plays a major role in affording the operator direct perception and action. Sense-making is to be performed in the Complex Quadrant as there may exist many relationships, not all known, between the information elements. The process of building situation awareness occurs at the transition between the Complex and Complicated Quadrant.

d) Chaos. No real sense making is possible in this domain. The reality here is that the operator must act consistently and the actions must be ethical and within a certain moral framework. To achieve this, the DSS should focus on giving ethical hints and moral guidelines within cultural context to help the operator act within a comfortable mental model of right and wrong actions. A lot of work must be done here to understand the implications of this. However, if the actions are within the boundaries of morality and ethics, it is possible that enough positive feedback can be sensed to allow for a pattern to be established that will help the situation move to a more manageable domain. Training will play an increasingly important role here.

An analysis of the type and level of complexity of the mission and operating environment will determine the starting regime. The design of the C2 system must be able to support operating at the starting point. The C2 technology (Situation Awareness, Sense-Making and Decision Support) must support transition to the required regime for effective completion of the mission. In most cases it will be in the in the “Known” regime to support effective execution of orders.

As one of the factors contributing to success in operations and good decision making is experienced operators, the C2 must encapsulate the knowledge of experienced operators to boost those that are inexperienced. By knowing what operators would like to see and know, HMIs can be enhanced to assist novices. The Cynefin Framework can be applied during the knowledge elicitation phase of the CWA process. It will assist the interviewed SMEs to contextualise their knowledge relative to the level and type of complexity experienced. Using modern machine learning and computational intelligence techniques, this knowledge can be captured to be used as a starting point for intelligent software agents that can be used in modelling exercises.

7 Conclusion

The successful execution of a military operation in the complex environment of modern warfare is difficult. The system entrusted with this task is C2. For effective and resilient C2, the human operators and decision makers have to be considered and designed into this system as well as taking the constraints of the operating environment into consideration. Through cognitive capabilities and social interaction, humans are still more capable in solving unforeseen problems than automated systems.

C2 systems, in particular the required HMI and DSS, need to be designed by following an appropriate CSE approach. CWA has lately been utilised to this end. The design should assist operators in sense making and implementation of decisions. However, to ensure that the C2 system as defined through the CWA process is capable of dealing with the complexity associated modern warfare, the Cynefin framework can be utilised to define the attributes of the operational environment.

The Cynefin framework can be used throughout the knowledge elicitation phase to assist the SMEs in identifying the level and type of complexity experienced. This will help viewing the CWA inputs in context to guide the development of a C2 HMI and DDS systems that are resilient and capable of assisting the operators in addressing the complexities of modern warfare. HMIs and DSS optimised through the process of combining the Cynefin framework into the CWA process will enable C2 commanders and operators to successfully cope with the complexities experienced in the modern battlefield.

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