19th ICCRTS

C2 Agility: Lessons Learned from Research and Operations

Understanding and Evaluating Command & Control Effectiveness by Measuring Battlespace Awareness

Primary Topic

Topic 4: Experimentation, Metrics, and Analysis

Alternate Topics

Topic 5: Modeling and Simulation

Topic 2: Organizational Approaches, Collaboration, Social Media/Networking

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Abstract

Establishing and maintaining effective Command & Control (C2) is essential to mission success. Over time, C2 has evolved due to changes in technology, doctrine, and threats. While C2 may be necessary, it is not sufficient to guarantee mission success, which depends on many factors. This research investigates a time-valued information entropy-based method used to quantify battlespace awareness. The goal of this research is to determine how this existing information entropy-based method can be extended to aid C2 decision makers in understanding and evaluating military C2 effectiveness independent of mission success, particularly for complex military System-of-Systems network architectures. The end result is a set of analyses that can be incorporated into traditional Modeling & Simulation techniques to evaluate and classify C2 system performance under varying factors and conditions. These changes can include differences in the following: C2 systems and approaches, enemy action, information sharing and decision making, planning, intelligence collection and data gathering, platform and sensor performance, etc. From this, a more quantitative estimate of desired C2 attributes such as agility, robustness, and responsiveness can be achieved. Collectively, this set of analyses is referred to as TABS or Tracking Awareness in the Battlespace during Simulation.

Introduction

According to the Department of Defense (DoD), C2 can be defined as "The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission" [1]. Ref. [2] provides a more detailed breakdown of the essential C2 functions that must be executed:

- Establishing Intent
- Determining roles, responsibilities, and relationships
- Establishing rules and constraints
- Monitoring and assessing the situation in progress
- Inspiring, motivating, and engendering trust
- Training and education
- Provisioning (Resource Allocation)

Each of these functions can be further decomposed, if necessary into even more activities, functions, or tasks specific to any organization. The salient point that must be recognized, however, is that establishing and maintaining effective Command & Control (C2) by warfighters is essential to mission success.

While the purpose of C2 remains unchanged over time, C2 itself has evolved due to changes in many factors. These include advances in technology, changes in doctrine, and changes in the threat environment [2]. For example, today's military depends on progressively complex information technology to conduct joint operations against increasingly asymmetric forces. The end result is a dynamic operating environment with changing force capabilities. These types of challenges affect how well C2 is being performed over any length of time.

The importance of C2 in achieving military objectives along with the dynamic operating environment underscores the pressing need to evaluate how well C2 is being performed. Yet the official DoD definition previously introduced provides only one way to assess C2 quality. While it is easy to test for the presence of a properly designated commander, the DoD definition is not adequate in determining the quality of C2 exercised. This is because the DoD definition equates C2 quality to mission accomplishment [2]. The use of mission success alone as a measure of C2 effectiveness is problematic; while C2 may be necessary, it is not sufficient to guarantee mission success, which depends on many factors. As Ref. [2] states, the availability of appropriate means and the capabilities and behaviors of adversaries must be taken into account as well. Ref. [2] also goes on to state that C2 quality "should be directly measured by examining how well the functions of C2 have been performed."

Warfighters have been able to articulate and define desirable C2 attributes [3], but have fallen short in proposing clear methods to translate these attributes into metrics. For example, Ref. [4] outlines a list of 12 C2 attributes from a Joint Capability perspective:

1. Interoperability
2. Understanding
3. Timeliness
4. Accessibility
5. Simplicity
6. Completeness
7. Agility
8. Accuracy
9. Relevance
10. Robustness
11. Operational Trust
12. Security

Many of these C2 attributes are emergent properties of the C2 system as a whole, and can only be evaluated by taking into account both the systems involved and the C2 approach used, i.e. by evaluating the C2 architecture. Therefore, the need arises to develop a framework in which changes in factors that affect each of these 12 attributes can be measured to determine the impact on C2. This will provide a positive step in the direction of translating these attributes into actual metrics that can be used to evaluate C2 effectiveness.

The challenge of sufficiently measuring C2 effectiveness not only affects current operations, but has an impact on the composition and operations of future forces as well. Without an adequate measure of C2 effectiveness, it becomes exceedingly difficult to fully justify that the acquisition of future C2 systems or that investments in upgrades to existing systems will provide the most cost-effective benefit for the warfighter [5]. It also makes it difficult to determine what the best combination of materiel, training, and doctrine should be to achieve desired military objectives. Ref. [5] also makes note that the problem of analyzing warfare in the modern age is due to "an inability to quantify battlespace awareness, its mapping, or the capabilities to gather awareness."

Thus, the goal of this research is to develop a method of characterizing C2 performance and effectiveness that is independent of mission success. The proposed method is developed using a Systems Engineering approach, which allows for the application of system architecting principles. Within this context, the architecture provides a means of defining the manner in which the contributing, constituent systems work together. The architecture itself can be further described as a shared, persistent technical framework that governs the structure of components within the overall system, their relationships and dependencies, and the principles and guidelines governing their design evolution over time. The architecture includes not only systems and their functions, but data flow and communications protocols, key system functions, as well as end-to-end functionality. The architecture is used to address possible changes in functionality, performance, or interfaces [6, 7, 8]. For this particular application to C2, the C2 architecture is then viewed as a combination of C2 systems and a C2 approach. The C2 approach, as discussed in Ref. [2] defines the allocation of decision rights, patterns of interactions among the actors and the distribution of information and awareness in and between competing forces [2].

This research investigates a time-valued information entropy-based method used to quantify the amount of awareness possessed by both friendly and enemy units of their surroundings during the course of a simulation. It will be shown that this time-valued measure of awareness serves as a suitable measure of C2 performance during the simulation. The goal of this research then is to determine how this existing information entropy-based method can be extended to aid C2 decision makers in understanding and evaluating military C2 effectiveness independent of mission success, particularly for complex military System-of-Systems network architectures. The end result is a set of analyses that can be incorporated into traditional Modeling & Simulation techniques to evaluate and classify C2 system performance under varying factors and conditions. These changes can include differences in the following: C2 systems and approaches, enemy action, information sharing and decision making, planning, intelligence collection and data gathering, platform and sensor performance, etc. From this, a more quantitative estimate of desired C2 attributes such as agility, robustness, and responsiveness can be achieved. Collectively, this previously unpublished set of analyses is referred to as TABS or Tracking Awareness in the Battlespace during Simulation.

Addressing the problem in this manner allows for the later creation of a suitable modeling and simulation (M&S) environment upon which a virtual experimentation framework for evaluating

C2 effectiveness can be developed. TABS will prove to be a key requirement and enabler for developing such a future framework.

Uncertainty & Time in the Battlespace

Ref. [9] provides a useful perspective on C2 that states "Command and control is inherently an iterative decision making process, as feedback from the battlespace is incorporated into plans and corrective actions." Consequently, we must be able to come to understand the context in which certain decisions and actions are taking place, if we are to understand the overall effectiveness of different C2 architectures or the impact of different factors such as technology, interoperability, operational trust, etc. Perhaps the two most important factors that affect any decision making process are uncertainty and time, and these prove to be the two fundamental factors that define the C2 environment in every military operation [10].

Uncertainty has many different definitions and connotations. In this case, uncertainty can be defined as the difference between what is actually known and what is desired to be known about any given situation [10]. Further complicating the matter is that information and derived knowledge obtained from the battlespace is both limited and perishable. The enemy is usually constantly taking new actions to change the current situation, the rapid tempo of modern operations limits the amount of information that can be gathered and processed before having to make another decision, and if taken to the extreme the pursuit of additional information can lead to operational paralysis. Thus, as Ref. [10] states, "The key to achieving command and control will always come down to finding a way to cope with the effects of uncertainty and time."

Coping with these effects means achieving and maintaining an acute awareness of the battlespace and current situation in order to gain knowledge and understanding of the operational area's environment, factors, and conditions. Thus, Battlespace Awareness (BA) is defined as "The ability to understand dispositions and intentions as well as the characteristics and conditions of the operational environment that bear on national and military decision making by leveraging all sources of information to include Intelligence, Surveillance, Reconnaissance, Meteorological, and Oceanographic" [4]. This includes knowing the status of friendly and adversary forces, as well as neutrals and noncombatants in addition to the weather and terrain. Figure 1 provides an example decomposition of the relevant battlespace objects and features that forces would need to be aware of during an operation.

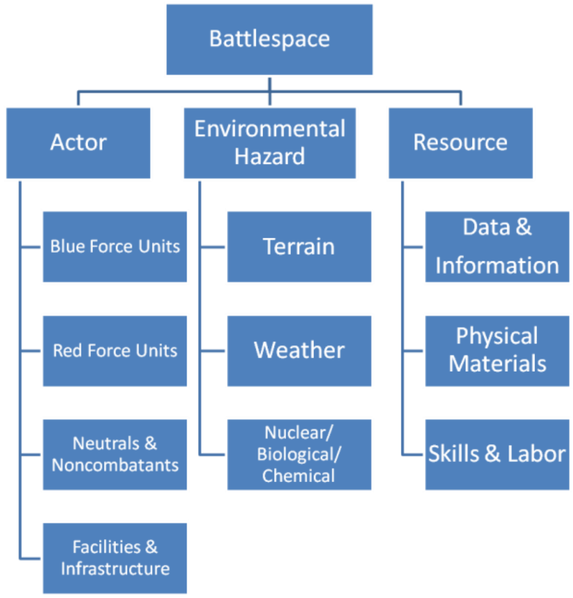


Figure 1: Example Battlespace Decomposition

High levels of awareness lead to comprehensive and accurate assessments, aids in successfully applying combat power, and helps protect the force and/or complete the mission [1]. In this way, establishing and maintaining BA is crucial to mission success and is a defining trait of an effective C2 architecture. A related term is Situation Awareness (SA), which can be described as being able to perceive and comprehend the current status of one's environment, and then project what the future state of the environment might look like [11]. While this term proves useful as well, SA usually implies some human-in-the loop testing. This research seeks to address C2 M&S during the conceptual design phase, typically characterized by limited system information but where architectural tradeoffs have the most impact on cost, schedule, and performance [12, 13]. Also, to reduce the complexity of the effort, there is a desire to avoid complex cognitive models of human understanding and reasoning, especially when applied under battlefield conditions. For these reasons, the term BA will be utilized more often.

Measuring Uncertainty

The aim of C2 then, is to deal with the uncertainties inherent in warfare during the course of an engagement in a manner that promotes mission success. Since awareness, whether described as BA or SA, is a crucial aspect of effective C2 it follows that measuring awareness in terms of uncertainty and time may help in better understanding and evaluating C2 architectures. A literature search uncovered previous efforts that described and developed methodologies [5, 14) for quantifying BA in such terms by applying the techniques developed in the field of Information Theory [15]. Specifically, Shannon's Information Entropy is applied to quantify awareness to capture not just what is known about the battlespace, but also precisely how well it is known [5].

Entropy is a fundamental property that can be described as a measure of a system's disorder or unpredictability. Shannon applied the concept of Entropy to the uncertainty associated with a random variable, making it possible to quantify the expected value of the information contained in a message [15]. The greater the amount of measured entropy, the greater the uncertainty; this means there is a small amount of informational value contained with the message or signal.

Ref. [15] provides an example using the simple toss of a coin as the basis of the signal passed over the communication channel. Only two outcomes are expected and can be passed along as information from the source to the receiver, either heads or tails. Therefore, the measured entropy H(X) represents the expected surprise that results from the coin flip. Mathematically, this can be expressed using the following equation:

$$H(X) = -\sum_{i=1}^{n} p(x_i)\log_b p(x_i); \{x_i : i = 1,\dots,n\} \tag{1}$$

Continuous distributions can also be used, resulting in a differential form of Equation 1. Since there are only two possible outcomes n = 2. If a logarithmic base of b = 2 is chosen, then the value of H(X) is expressed in bits. Thus, a message containing the results of the coin toss only requires at most 1 bit to encode the message, where X = 1 represents a result of heads and X = 0 represents a result of tails, for example. The following graph can be created using Equation 1.

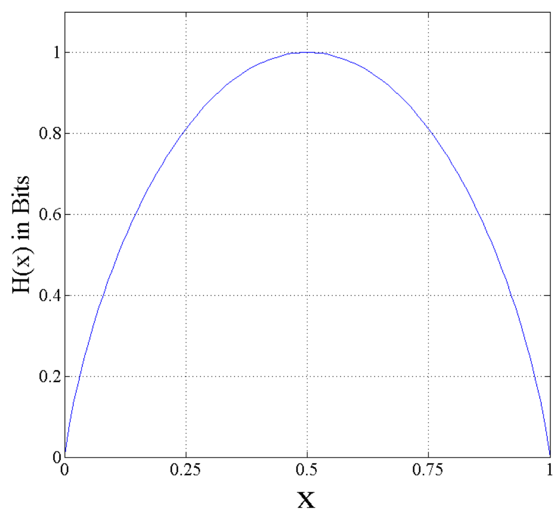


Figure 2: Coin Toss Entropy Plot

Because of the discrete nature of the variables involved, $x_i = 1/n$ gives the maximum entropy for a discrete distribution of n outcomes. Consequently, the maximum entropy of 1 bit occurs at x = ½. This corresponds to the maximum uncertainty of the result of the coin toss. If for example, the coin is altered so that it always comes up heads or tails, the amount of uncertainty and thus entropy is zero. Intermediate values of H(x) can be interpreted as an unfair coin that is artificially biased towards either heads or tails.

Applying Information Entropy to the Battlespace

Ref. [5] identifies and develops a methodology for applying Shannon's Information Entropy to mathematically quantify awareness in a military C2 environment. This is then used to create an awareness curve that shows the awareness of the C2 system throughout the process of attacking a ground target from the air. This awareness curve is a plot of entropy vs. time. The higher the entropy value calculated at a given point in time, the lower the awareness and vice versa. The information warfare entropy model presented in Ref. [5] serves as a basis for constructing a C2 signature curve that will aid in determining the effectiveness of various C2 architectures. First, a formal process must be described that extends the model presented in Ref. [5] for use with many dispersed, collaborating systems interacting within a battlespace that contains many relevant features that impact uncertainty. This process is described as the following:

1. Discretize the battle space into relevant objects/features such as the location, ID and type of friendly/enemy forces, environmental and hazardous features, and resources such as data & information. These can be referred to as *state properties* of the battle space. See Figures 1 and 3.
2. Model each state property as a discrete probability distribution. Probability estimations can then be derived from the performance of system functions (sensing, assessing, etc.) corresponding to related mission tasks. See Table 2.
3. Use Information Entropy to determine the amount of maximum uncertainty, U, based on the maximum number of possible outcomes. See Equation (2).
4. Use Information Entropy to determine the amount of uncertainty, H(x), represented by the probability distribution. See Equation (3).
5. Transform H(x) to a measure of awareness, A. See Equation (4). This way, total awareness of the battle space for a particular agent means having complete certainty of the state property for each battle space object/feature within the battle space.
6. Incorporate the BA calculations into a warfare simulation.
7. Analyze the resulting C2 signature plot of Awareness versus time to determine the effectiveness of various C2 architectures.

$$S_i^A(t) = \begin{bmatrix} \text{Location} \\ \text{Threat ID} \\ \text{Type} \\ \text{Operational Level} \end{bmatrix} \qquad S_i^H(t) = \begin{bmatrix} \text{Location} \\ \text{Type} \\ \text{Hazard Level} \end{bmatrix} \qquad S_i^R(t) = \begin{bmatrix} \text{Sender} \\ \text{Receiver} \\ \text{Type} \end{bmatrix}$$

Figure 3: Example Actor, Environmental Hazard, and Resource State Properties

Table 1: Example Non-Location State Property Values

State Property	Example Values
Actor Threat ID	Red, Blue, Neutral/Noncombatant
Actor Type	Aircraft, Tank, Facilities/Infrastructure
Actor Operational Level	Fully Operational, Disabled, Destroyed/Neutralized
Hazard Type	Terrain, Weather, Nuclear/Biological/Chemical
Hazard Level	Low, Medium, High
Resource Sender	Specific Actor within the Battlespace
Resource Receiver	Specific Actor within the Battlespace
Resource Type	Data Link, Jet Fuel, Senior Watch Personnel, etc.

Table 1 provides an example of the values that can be assigned to the non-location based state properties. Meanwhile, Table 2 provides an example awareness measurement for the Threat ID state property of an un-identified unit, where three cases are shown. The first is where there is max uncertainty, as the unidentified unit is estimated to be an enemy (Red), friendly (Blue), or Neutral unit with equal probability. The opposite extreme (Case 3) is where the unit is quickly and easily identified, leading to an awareness value of 1. Case 2 demonstrates a calculation where the uncertainty distribution is skewed between Cases 1 & 3, resulting in an intermediate value. The corresponding equations are as follows:

Table 2: Entropy calculations for quantifying Threat ID awareness

	Threat ID Probability Distribution			Awareness Calculations		
	Red Unit x1	Blue Unit x2	Neutral x3	U (bits) log base = 2	H(X) (bits) log base = 2	A(t)
Case 1 (Max Uncertainty)	1/3	1/3	1/3	1.585	1.585	0
Case 2 (Intermediate)	1/4	3/4	0	1.585	0.8113	0.4881
Case 3 (Max Certainty)	1	0	0	1.585	0	1

$$U = H(X)_{\max} = \log_b(n_o) \qquad \begin{aligned} n_o &= \text{maximum number of possible outcomes} \\ n &= \text{number of non-zero possible outcomes} \end{aligned} \tag{2}$$

$$H(X) = -\sum_{i=1}^{n} p(x_i)\log_b p(x_i); \{x_i : i = 1,\ldots,n\} \tag{3}$$

$$0 \le A(t) = 1 - \frac{H(X)}{U} \le 1 \tag{4}$$

Quantifying the uncertainty due to location within the battlespace requires also taking into account both the area and resolution of sensing capabilities as well the speed and direction of objects as they move within the battlespace. Different sensors have different resolutions to which they can accurately pinpoint a target, and this effect must be taken into account in the entropy calculations [5]. This can be seen in Equation (5), where Equation (3) has been modified to incorporate the effects of different sensor resolutions.

$$H(X)=\left[-\sum_{i=1}^{n} p(x_i)\log_b p(x_i)\right]+\log_b(A_R);\{x_i : i=1,...,n\} \tag{5}$$

In order to use Equation (5), the battlespace is divided up into smaller areas or grids, where the minimum size of a grid cannot have a value of less than 1 in order to avoid problems with negative logarithmic values. For example, an area of operations that measures 3,600 km^2 (slightly less than the area of the state of Rhode Island) can be subdivided into 100 cells, each measuring 6km by 6km. In this case, 1 m^2 is selected as the smallest resolution. The maximum entropy, U, for the area of operations can then be determined using the following equations:

$$U=H(X)_{\max}=\log_b(n_o)+\log_b(A_{Total}) \tag{6}$$

$$U=H(X)_{\max}=\log_2(100)+\log_2(3{,}600E6\,\mathrm{m}^2)=38.39 \tag{7}$$

The probability of locating an object within a cell can be assigned to individual cells. Based on those probabilities and the given sensor resolution location-based awareness values can then be obtained. An example is given in Table 3 using the area of operations previously described:

Table 3: Example Location-Based Awareness Calculations

Quantifying Location Awareness	U bits	H(X) bits	A(t)
Case 1: Undetected in Wide Search Area (A_R = 180 km^2); 5 Cells each with location probability = 1/5	38.39	29.74	0.23
Case 2: Undetected in Narrower Search Area (A_R = 72 km^2); 2 Cells with location probabilities of 1/3 and 2/3	38.39	27.02	0.30
Case 3a: Positive Detection (A_R = 10 m^2); 1 Cell with location probability of 1	38.39	3.32	0.91
Case 3b: Positive Detection (A_R = 1 m^2); 1 Cell with location probability of 1	38.39	0	1

The first and second cases described in Table 3 are for undetected objects whose locations have been narrowed down to a certain number of cells or grids within the area of operations. For these cases, the resolution, A_R, is set equal to the total area of the number of cells. The third case describes a situation where the object has been detected within a single cell, and highlights the impact of sensor resolution. The sensor in case 3a has a much larger resolution than the sensor in 3b, resulting in a lower awareness value.

The second effect that must be accounted for is the changing speed and location of objects in the battlespace. As an object's location changes, this increases the number of cells that must be assigned a non-zero probability, resulting in increased entropy and decreased awareness. Accounting for this requires the use of a diffusion model that will accurately depict the growth of the area of uncertainty of an object's location if it is not constantly tracked over time.

Creating Command & Control Signatures

This process can be repeated for each state property so that a picture emerges of the level of awareness for each battlespace actor. This picture is not a static snapshot, but updates as the actors interact with one another and their environment. A matrix of awareness values for each force can be created that represents the awareness at a given time each actor possesses regarding each battlespace object or relevant feature. These awareness values can then be summed and normalized to values between zero and one to create an awareness value for the overall force. For example, if each member of the blue force has complete knowledge of every other object within the battlespace including other blue force actors, red force actors, hazards, and resources then the blue force as a whole would have a total awareness value equal to one. This allows for the plotting and analysis of not only an entire force, but individual units within each force as well, if desired. This has many important benefits. For example, one may analyze whether the level of evenness/unevenness of the distribution of awareness across units is an important factor under certain conditions. Also, this can help determine if the awareness level of a particular unit(s) seem to contribute more or less to overall mission success and the underlying cause for this. This can help identify weak links and key nodes within the C2 system architecture or help determine more efficient ways to distribute information among key actors.

Similar to Ref. [5] where entropy was plotted against time, a C2 signature plot can be created that depicts awareness versus time. For example, Ref. [15] utilizes some of the analyses that comprise TABS to compare the effectiveness of different combinations of C2 decision and information sharing network architectures. In this problem formulation, a team of Blue search agents are tasked with conducting an effective search of enemy Red agents that are actively trying to evade detection. An example C2 signature plot created from this M&S environment, as well as the corresponding Blue search and Red evasion efficiencies are shown in Figure 4.

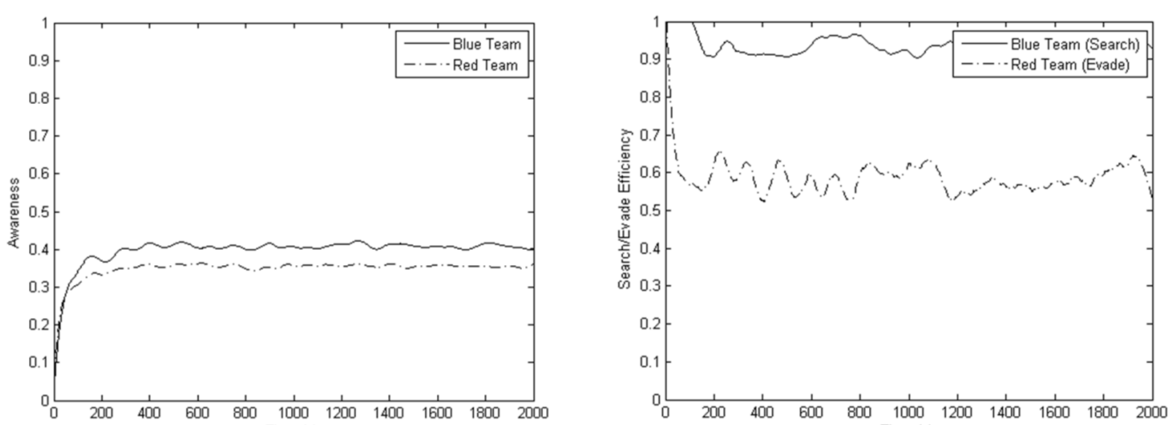


Figure 4: Example C2 Signature Plot and Search/Evade Efficiencies for Blue vs. Red Forces

From Figure 4, it is clear to see that though the Blue Force begins the engagement with zero knowledge of the battlespace, the Blue Force is quickly able to establish and maintain information superiority.

The C2 signature plot can be used to analyze C2 architecture performance during a combat simulation, and represents a way to evaluate C2 effectiveness independent of mission success; High awareness values may not always correlate to mission success due to other factors that may need to be addressed. Since the C2 signature plot is a visual means of expressing C2 effectiveness, it can also be used to develop a classification scheme of different C2 architecture performance, as seen in Figure 5.

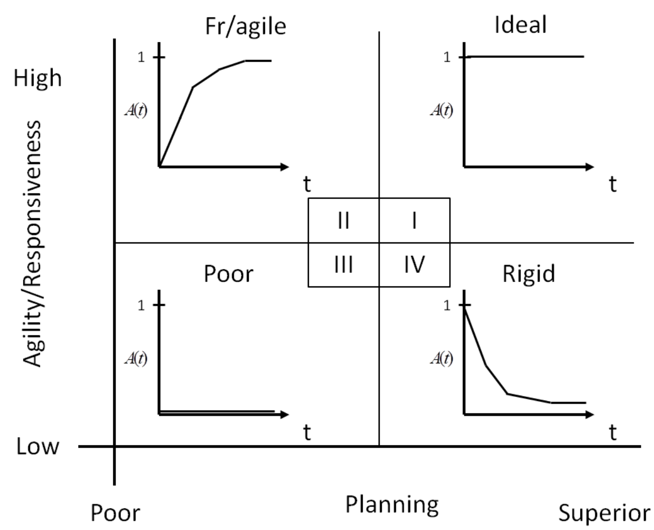


Figure 5: C2 Signature Classification

The classification scheme takes into account the level of awareness achieved through planning, intelligence, and data gathering. Poor planning results in lower initial awareness values while superior preparation results in higher initial awareness values. C2 agility is defined by Alberts as the capability to successfully cope with changes in circumstances [3]. In terms of signature classification, this translates to being able to achieve and maintain high levels of awareness over the course of an operation.

Thus, four distinct regions can be identified in Figure 5 that aid in classifying different behaviors of C2 architectures. Region I represents the ideal case where perfect awareness exists throughout. Region II can be classified as “Fr/agile”, a term that indicates that though the C2 system effectively ramped up to achieve a high level of awareness during the engagement, there was poor initial planning. This could lead to unfavorable outcomes under different circumstances [17]. Region III is characterized by both poor planning and poor C2 performance, so that low values of awareness occur throughout the engagement. Finally, Region IV is indicative of a rigid C2 architecture that cannot maintain high values of awareness as the engagement continues on. It should be noted that it is possible for multiple classifications to be present over the course of highly complex engagements.

The creation and classification of C2 signatures yields many important benefits. C2 signature analysis, combined with a rigorous experimentation plan can help identify and address key factors that have the most impact on C2 effectiveness and overall mission success. This can then be linked to specific C2 systems or approaches that need to be changed to deliver the most effective results. Or the impact of certain battlespace conditions can be isolated that have the most impact on C2 performance. An analyst can also explore if there is an average awareness threshold that must be maintained and under what circumstances this must occur. This could help in achieving C2 system agility and robustness. Likewise, an analyst can determine which key factors to exploit to minimize the awareness of an opposing force.

Actual vs. Perceived Awareness

Using entropy as a basis to measure BA and thus C2 effectiveness provides a flexible framework that is able to capture many non-linear effects present in real warfare that serve to introduce further uncertainty. Measuring entropy gives a sense of "expected surprise" since the measurement of entropy is based on one's own beliefs that are then translated into a probability distribution. Actual battlespace conditions may vary significantly, however. As a first example, the effects of misleading, false, or incorrectly processed data and information can be introduced into the M&S and captured in the entropy calculations. Figure 6 is comprised of two different examples that can illustrate how it becomes possible to measure unexpected surprise, or Δ. Each blue grid of 9 cells represents a state space. In this example the state space is a location state space that defines the probability distribution of where a Blue Force actor believes a Red Force actor to be located.

I)

Blue Force belief:
$$\begin{array}{|c|c|c|}\hline 0 & 0 & \frac{1}{3} \\ \hline 0 & 0 & \frac{1}{3} \\ \hline 0 & 0 & \frac{1}{3} \\ \hline \end{array}$$

Vs.

Actual:
$$\begin{array}{|c|c|c|}\hline 0 & 0 & 0 \\ \hline 0 & 0 & 0 \\ \hline 1 & 0 & 0 \\ \hline \end{array}$$

Δ for Event in SW Cell:

$$\Delta = 1 - 0 = 1$$

II)

Blue Force belief:
$$\begin{array}{|c|c|c|}\hline \frac{1}{9} & \frac{1}{9} & \frac{1}{9} \\ \hline \frac{1}{9} & \frac{1}{9} & \frac{1}{9} \\ \hline \frac{1}{9} & \frac{1}{9} & \frac{1}{9} \\ \hline \end{array}$$

Vs.

Actual:
$$\begin{array}{|c|c|c|}\hline 0 & 0 & 0 \\ \hline 0 & 0 & 0 \\ \hline 1 & 0 & 0 \\ \hline \end{array}$$

Greater overall uncertainty, but less unexpected surprise

$$\Delta = 1 - \frac{1}{9} = \frac{8}{9} = 0.89$$

Figure 6: Calculating Unexpected Surprise

In Case I, the Blue Force actor believes the Red Force actor is somewhere in the eastern most part of the grid when in fact the Red Force actor is located in the southwest corner cell. At this point in time, if the Blue Force actor were to encounter the Red Force actor in the southwest corner, the amount of unexpected surprise, Δ, can be measured as the difference in probabilities assigned to the southwest cell in each grid for Case I. This yields a maximum Δ of 1. For Case II, the Blue Force actor is completely uncertain as to where the Red Force actor is located. Thus, a lower Δ value of 0.89 is calculated. Figure 7 shows how this concept can be extended to a visual display termed a "Surprise Mapping."

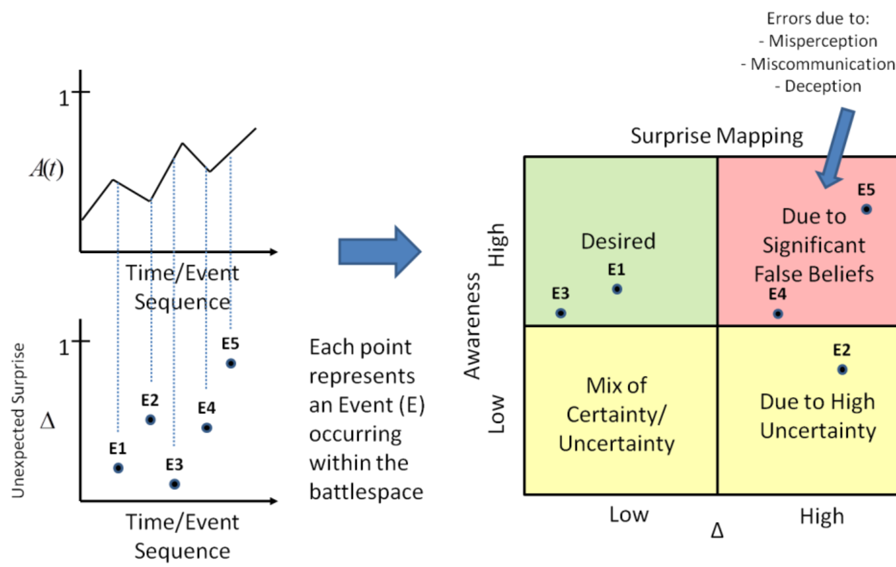


Figure 7: Surprise Mapping

Modeling Shared Awareness & Trust

Information and thus awareness may be shared across the battlespace by participating actors. In reality, between two actors, this shared information may confirm or conflict with previously held beliefs. This effect may be captured using an entropy-based framework to measure awareness. Quantifying this aspect, however, may require the use of Bayesian-based methods to help combine probabilities. Also, since operational trust was identified as a desired C2 attribute, this effect may be included in the modeling as well.

Bayes' theorem provides a method to show how new information can be properly used to update or revise an existing set of probabilities. Revised probabilities are based on posterior probabilities, $P(A_i)$, that are updated based on a conditional event B. Bayes' theorem is expressed in Equation (8) [18].

$$P(A_i \mid B) = \frac{P(A_i)P(B \mid A_i)}{\sum_{j=1}^{n} P(A_j)P(B \mid A_j)} \tag{8}$$

Figures 8 and 9 provide examples of how Bayes' theorem can be possibly applied to include the effects of shared awareness in the cases of confirming and conflicting information.

$$\begin{bmatrix} 0.7 & 0.1 \\ 0.1 & 0.1 \end{bmatrix} + \begin{bmatrix} 0.6 & 0.1 \\ 0.1 & 0.2 \end{bmatrix} = \begin{bmatrix} 0.87 & 0.03 \\ 0.03 & 0.07 \end{bmatrix}$$

Entropy $\downarrow$
Awareness $\uparrow$

Step 1: Determine Bias %	Step 2: Determine Multipliers (M)	Step 3: Apply Multipliers to Prior Probabilities	Step 4: Calculate Revised Probabilities
$\frac{0.6-0.25}{0.75}=0.47$	$0.5+\frac{0.47}{2}=0.73$	$0.7\times0.73=0.51$	$\frac{0.51}{0.59}=0.87$
$\frac{0.1-0.25}{0.25}=-0.60$	$0.5+\frac{-0.6}{2}=0.20$	$0.1\times0.20=0.02$	$\frac{0.02}{0.59}=0.03$
$\frac{0.1-0.25}{0.25}=-0.60$	$0.5+\frac{-0.6}{2}=0.20$	$0.1\times0.20=0.02$	$\frac{0.02}{0.59}=0.03$
$\frac{0.2-0.25}{0.25}=-0.20$	$0.5+\frac{-0.2}{2}=0.40$	$0.1\times0.40=0.04$	$\frac{0.04}{0.59}=0.07$
		$\sum=0.59$	

Figure 8: Shared Awareness for Confirming Information with Full Trust

$$\begin{bmatrix} 0.7 & 0.1 \\ 0.1 & 0.1 \end{bmatrix} + \begin{bmatrix} 0.2 & 0.55 \\ 0 & 0.25 \end{bmatrix} = \begin{bmatrix} 0.37 & 0.37 \\ 0 & 0.26 \end{bmatrix}$$

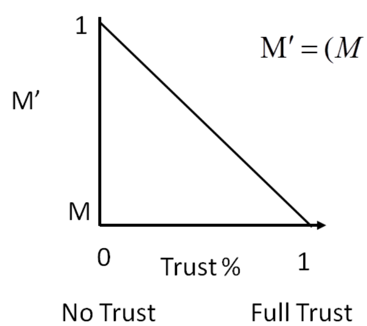
Entropy $\uparrow$
Awareness $\downarrow$

Step 1: Determine Bias %	Step 2: Determine Multipliers (M)	Step 3: Apply Multipliers to Prior Probabilities	Step 4: Calculate Revised Probabilities
$\frac{0.2-0.25}{0.25}=-0.20$	$\left\lvert 0+\frac{-0.20}{2}\right\rvert=0.10$	$0.7\times0.10=0.07$	$\frac{0.07}{0.19}=0.37$
$\frac{0.55-0.25}{0.75}=0.40$	$0.5+\frac{0.40}{2}=0.70$	$0.1\times0.70=0.07$	$\frac{0.07}{0.19}=0.37$
$\frac{0-0.25}{0.25}=-1.0$	$0.5+\frac{-1.0}{2}=0$	$0.1\times0=0$	$\frac{0}{0.19}=0$
$\frac{0.25-0.25}{0.25}=0$	$0.5+\frac{0}{2}=0.5$	$0.1\times0.50=0.05$	$\frac{0.05}{0.19}=0.26$
		$\sum=0.19$	

Figure 9: Shared Awareness for Conflicting Information with Full Trust

Figure 8 shows the impact of confirmatory information when updating the state space for an actor. This causes entropy to decrease and awareness to increase. Figure 9 shows that when the incoming information conflicts with the prior held belief, the opposite effect is encountered where the amount of entropy increases while awareness decreases. Both cases assume the incoming information is fully trusted. It should also be noted that this operation is noncommutative. The prior held belief forms an important basis and impacts the final value of awareness.

Trust can be incorporated into the Bayesian calculation through the inclusion of a trust percentage. The value of the trust percentage between actors sharing specific information can be based on numerous factors if desired, such as prior history and experience, reliability, or some estimate of the relevancy of the information due to its perceived timeliness, accuracy, or correctness. Once the trust percentage is determined, the impact on shared awareness can be modeled by altering the multiplier (M) used in the Bayesian calculations. An example of how this can be applied is shown in Figure 10.



$$M' = (M-1)\times(\text{Trust\%})+1 \qquad \text{Revised Prob.} = \frac{(\text{Prior Prob.})\times M'}{\Sigma}$$

Full Trust: M' = M $$\text{Revised Prob.} = \frac{(\text{Prior Prob.})\times M}{\Sigma}$$

No Trust: M' = 1 $$\text{Revised Prob.} = \frac{\text{Prior Prob.}}{\Sigma}$$

Figure 10: Incorporating Trust into Shared Awareness Calculations

Now, the impact of trust can be seen on the Bayesian calculations for shared awareness, as seen in Figure 11. This is the case for confirming information with varying degrees of trust.

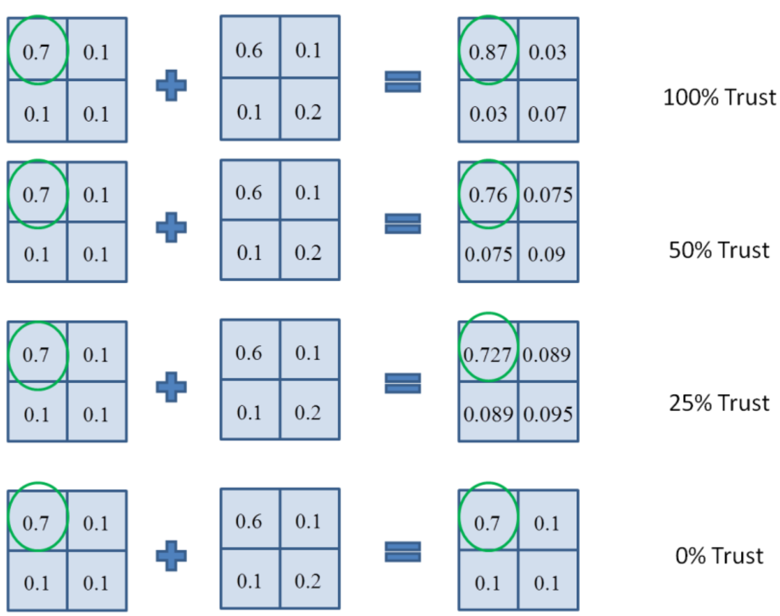


Figure 11: Shared Awareness for Confirming Information with Varying Trust

Figure 11 shows that when the information is not trusted at all, the prior probabilities of the original state space is maintained. As trust in the incoming information grows, greater awareness values are calculated. Other aggregation rules are possible, though, that can capture additional effects. For example, a pessimistic and untrusting actor that only accepts the highest entropy/lowest awareness set of values can be modeled. Or, the effects of an overly optimistic and trusting actor who consistently substitutes his/her own beliefs for the highest awareness values regardless can be modeled as well. These represent either/or (min/max) types of aggregations.

Network Centric Warfare Effects

The modern, post Cold War military of today can be characterized as placing greater emphasis on the use of Information Technology (IT) and Network Centric Warfare (NCW) principles to realized battle space dominance [9, 19]. As Ref. [9] states, "Network Centric Warfare is the best term developed to date to describe the way we will organize and fight in the Information Age." This is in contrast to platform-centric warfare, where each weapon or platform operates independently for the most part, and where a military must mass *force* in order to achieve combat effectiveness. On the other hand, during NCW *effects* are massed rather than force. This is accomplished through increased shared awareness and information superiority through collaboration. The potential drawbacks are the increased possibility for information overload and the increased complexity that arises due to the networking of individual platforms [20].

The network architecture helps determine the manner in which systems share and process information. Specification of the overall network architecture goes beyond simply defining which systems must collaborate, but also means specifying the degree of interoperability between systems, or the degree in which information or services are exchanged [1]. It is desired that information and services are exchanged in a timely, secure manner to ensure mission success. Using TABS, analyses can be conducted in which system and network parameters such as communications latency, bandwidth, information processing capability, network size, etc. can be varied and the impact on BA and mission success quantified. From these analyses, it can be determined where capability gaps exist and what combination of materiel, doctrine, tactics, procedures, etc. are the best to employ to fill those critical gaps.

Thus, the selection of an appropriate M&S platform when constructing the warfare simulation, coupled with the entropy-based awareness framework should allow network and collaborative effects such as data fusion, limited bandwidth, information overload, etc. to also be modeled. This will allow analysts and decision makers to quantify the potential benefits of NCW versus a traditional platform-centric approach, while also helping to mitigate the possible drawbacks from increased network complexity.

Incorporating TABS into Modeling & Simulation

The next step towards investigating optimal C2 architectures is identifying an environment capable of modeling these architectures and simulating their effectiveness in various missions.

Over time, there have been many approaches to modeling and simulating warfare. Since warfare is extremely complex with interactions between numerous entities giving rise to often unpredictable and emergent behavior, agent-based modeling (ABM) approaches are often used. For example, ABM has been used to formulate and simulate mission plans [21], model terrorist networks [22] and land combat [23], and simulate fully autonomous hierarchical and adaptive control of tactical forces [24]. The appeal of any ABM approach is that it allows one to model and observe agent reactions to real-time battlespace information and conditions as they dynamically evolve. Discrete Event Simulation (DES) and System Dynamics are examples of other M&S methods that may be employed as well. Each has its benefits and limitations [25].

Regardless of the particular M&S method used, it is necessary to define a higher level process flow that will help facilitate the analyses enabled by TABS. These processes represent the actions actors within the battlespace must execute in order to gain awareness of the battlespace, the decisions and actions they execute during the simulation, and the feedback mechanisms that make C2 an iterative decision-making process. Figure 12 depicts the overall structure of the simulation and the sequential relationship of each process.

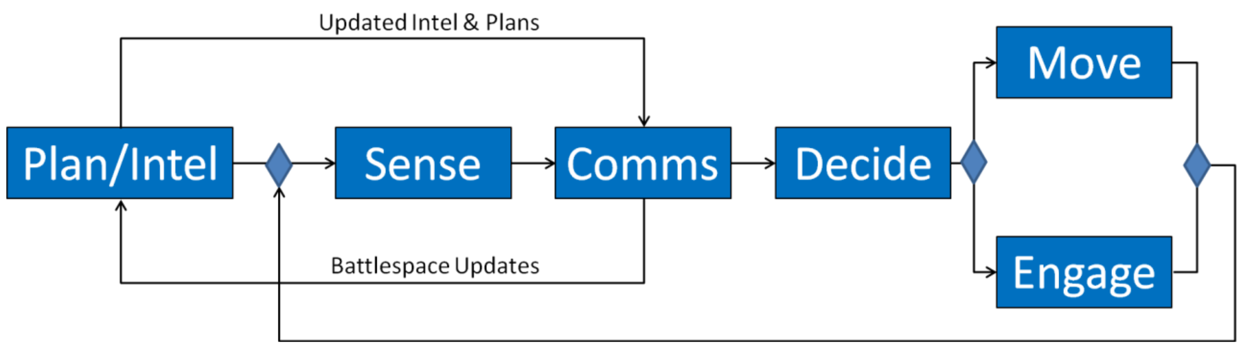


Figure 12: Example Simulation Process Flow

The Plan/Intel process is responsible for determining the initial awareness values for each actor within the battlespace. Feedback mechanisms can be included such that battlespace updates can be communicated to help update mission planning and feed that back to actors within the battlespace. The Sense process is where different sensor models are executed for corresponding actors to determine any changes in awareness. The Comms process handles the exchange of data and information in order to incorporate shared awareness. Network effects such as latency, bandwidth restrictions, and information overload can be modeled within this process as well. The Decide process is where actors make decisions based on their current battlespace awareness, to include what routes to take through the battlespace and what courses of action to take. Once a decision is made, the Move and Engage processes are responsible for executing those decisions and determining the changes that occur to objects within the battlespace. The process is then repeated until victory conditions and stopping criteria are met. These can be based on the number of units lost or a certain time limit being exceeded, as examples.

Conclusion

For a complex military SoS, especially there exists a wide array of architectural parameters that can vary that affects both C2 effectiveness and/or mission success. It is crucial that this analysis is conducted independent of measures used for mission success so that the effects of changes in C2 systems and approaches, data fusion and information sharing, platform and sensor effectiveness, etc. can be accurately determined. Until now, warfighters have been able to articulate and define desirable C2 attributes such as agility and timeliness, but have fallen short in proposing clear methods to translate these attributes into metrics. TABS provides an important first step in developing the types of M&S environments that better quantify the C2 attributes that are of greatest important to warfighters and decision makers. This is necessary in order to provide decision makers with the best information to architect and acquire robust, cost-effective systems to meet warfighter needs.

This research investigates the use of a time-valued information entropy-based method to quantify BA for both friendly and enemy units and forces. Through this research, a new set of analyses, collectively known as TABS is developed. TABS, or Tracking Awareness in the Battlespace during Simulation, extends the current methods of information entropy based BA measures so that the C2 performance and effectiveness of complex C2 SoS network architectures can be analyzed. TABS begins with a method of discretely defining the battlespace. This allows the application of information entropy based calculations to determine the changes in BA for different entities within the battlespace. Once this is accomplished, analyses corresponding to determining the level of unexpected surprise each actor or set of actors are subject to can be conducted. Next, the effects of shared awareness and trust can be mathematically modeled during the course of a simulation. Lastly, relevant network analyses can be conducted to determine the effect of changing architecture network approaches.

Overall, these analyses directly relate to measuring the real-world effects observed in complex SoS architectures with networked components. This research illustrates how existing measures can be extended towards a more comprehensive analysis of C2 performance and effectiveness. This includes looking at factors such as trustworthiness and surprise, interoperability, network bandwidth, and network latency. Such real world effects such as misinformation, incomplete or inaccurate information, enemy deception, or information that fails to be transmitted in a timely or secure manner can be scrutinized within the M&S environment.

The suite of information-entropy based analyses that make up TABS is designed to be implemented into traditional M&S techniques. This helps to create an environment where C2 system performance can be classified for varying factors and conditions. This classification is referred to as a C2 signature. A C2 signature is best explained as a graph depicting the level of battlespace awareness achieved and maintained over time. The C2 signature also allows for the evaluation of relevant C2 metrics such as robustness, agility, and responsiveness to changing conditions over the course of an operation. Ultimately, the creation of a C2 signature for a particular C2 architecture will provide decision makers a way to visually interpret C2 effectiveness and helps answer the question: "What does effective C2 look like?"

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