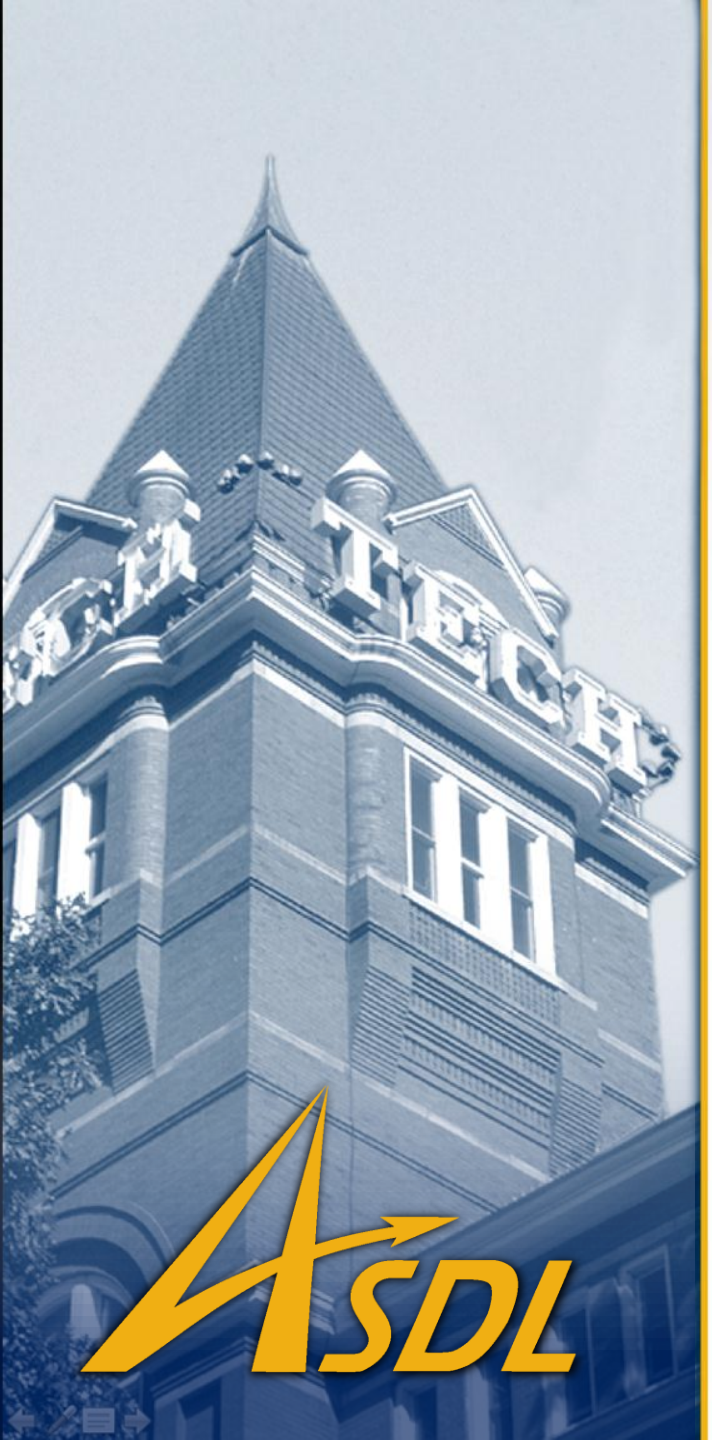

Understanding & Evaluating C2 Effectiveness by Measuring Battlespace Awareness

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19th ICCRTS
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Georgia Tech Aerospace Systems Design Laboratory

Overview

- Introduction
- Background & Motivation
- Problem Formulation
- Research Objective
- Technical Approach

The basic aim of this research is to answer the question "What does good C2 look like?" from a Modeling & Simulation standpoint for SoS architecting.

Introduction

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Allison Hill

International Programs & Fellowships Manager
Elena Garcia

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Senior Advisor: Robert Loewy

Director
Dimitri Mavris

Associate Director
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Front Office
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Finance Manager: Marisol Vega-Holthaus
Admin Assistant: Loretta Carroll
System Admin: Diego Remolina

Advanced System Engineering
Division Chief: Kelly Griendling

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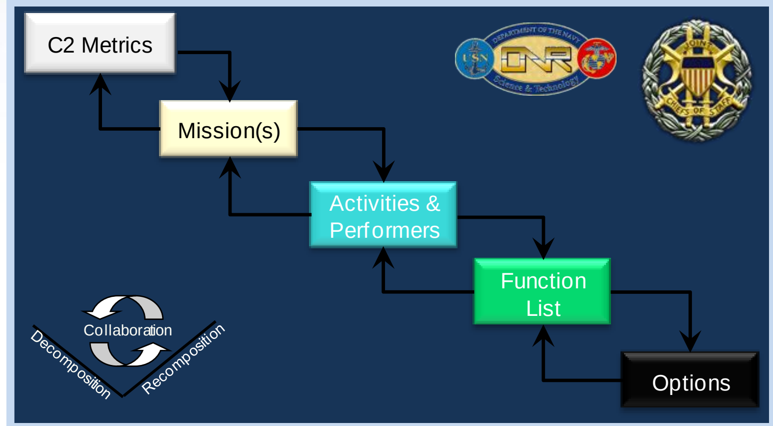
Background & Motivation

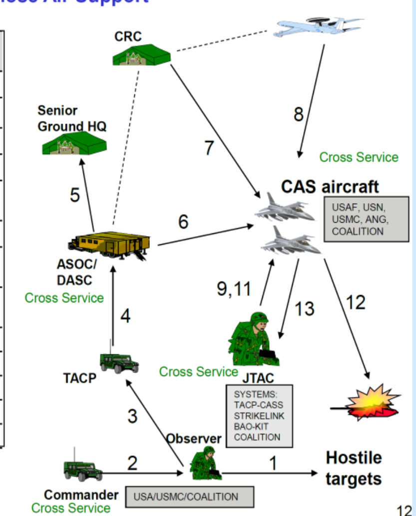
- Previous work (May 2009) with Office of Naval Research & JFCOM/Joint Staff (J6)
  - Development began in May 2009
  - Acquisition standpoint to determine a streamlined yet robust C2 systems portfolio → Visual Command & Control Capabilities Tradeoff Suite (VC3ATS)
  - Primary focus on creating the best mapping of systems to C2 functions:
    - "The quality of C2 should be directly measured by examining how well the functions of C2 have been performed." [1]
    - Essential C2 functions described in more specific mission & system terms
    - USJFCOM Joint Common System Function List (JCSFL) & Joint Mission Threads[2]
  - System-of-Systems (SoS)/System architecting approach



Joint Mission Thread

Joint Close Air Support

Mission Event No.	Description
1	Unit detects target
2	Commander decides to request CAS
3	Unit notified TACP
4	TACP passes request to ASOC < 5 min
5	ASOC coordinates with senior ground HQs which approve request
6	ASOC assigns on-call aircraft
7	CRC send aircraft to contact point (CP)
8	AWACS passes critical updates to aircraft > 95% Acrcy
9	JTAC briefs aircraft < 3 min
10	Aircraft depart initial point (IP)
11	JTAC controls CAS aircraft
12	Bombs on target > 98.9 % PK
13	Assessment



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1. Alberts, David S. and Hayes, Richard E. *Understanding Command and Control*. CCRP, 2006.
2. Behre, Christopher. http://www.dodenterprisearchitecture.org/pastmeetings/Documents/Tutorial_3_9.pdf.

Background & Motivation

- Developed 3 separate categories of metrics:
  1. **Functional Coverage**: How well are critical C2 functions being performed?
  2. **Functional Allocation**: How many functions are performed by a given C2 system within the portfolio of systems?
  3. **Performance**: How "good" are the C2 systems at ensuring mission success?
     - Official DoD Definition provides only one way to measure performance: Quality = Mission Success[1,2]
     - A list of 12 Senior Warfighter Forum (SWarF) approved attributes help define a "good" C2 solution[3]
     - Need exists to transform these attributes into usable metrics to aid decision makers
     - Attributes are properties of the portfolio of systems as a whole → impacts M&S efforts

SWarF Approved Attributes

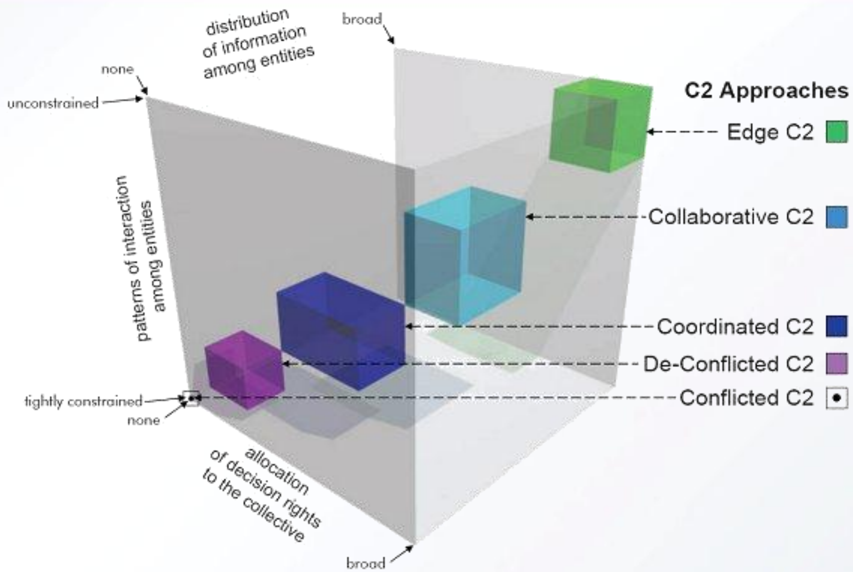
- **Interoperability**
- **Understanding**
- **Timeliness**
- **Accessibility**
- **Simplicity**
- **Completeness**
- **Agility**
- **Accuracy**
- **Relevance**
- **Robustness**
- **Operational Trust**
- **Security**

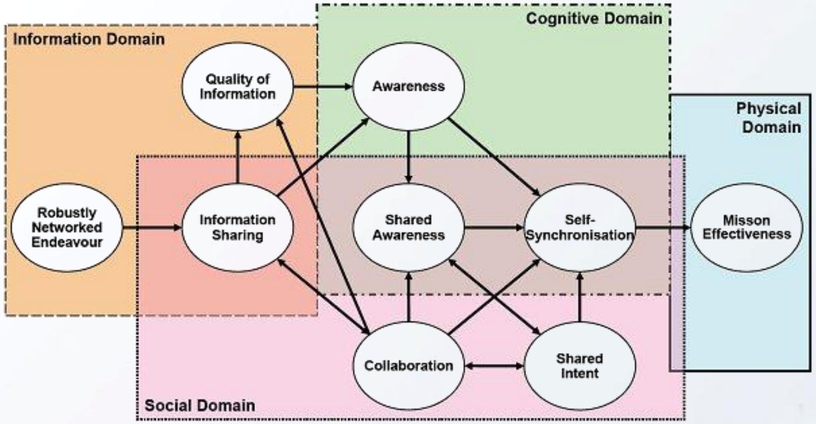
The C2 portfolio is a complex system-of-systems architecture comprised of many networked systems that must collaborate to ensure mission success within a dynamic threat environment.

1. Joint Publication 1-02
2. Alberts, David S. and Hayes, Richard E. *Understanding Command and Control*. CCRP, 2006.
3. JCIDS Manual. 19 Jan 2012

Problem Formulation

- Functions can be accomplished in many different ways
  - Differences in **C2 approaches** must be considered as part of SoS architecture
- End goal is to ensure mission success
- The use of mission success as a measure of the "goodness" of C2 is problematic[1]:
  - The very definition of the mission is a function of command
  - While C2 may be necessary, it is not sufficient to guarantee mission success, which depends on many factors
  - For example, the availability of appropriate means and the capabilities and behaviors of adversaries and others
- ***Research Question: How do we incorporate these factors into the M&S environment to measure C2 performance independent of mission success?***





Images from: http://www.opmexperts.com/nato_opm3.html

1. Alberts, David S. and Hayes, Richard E. *Understanding Command and Control*. CCRP, 2006.

Understanding C2: Uncertainty & Time

- "Our efforts to establish effective command and control are shaped by two fundamental factors that define the environment of command and control in every military operation - uncertainty and time."
  - Uncertainty: The difference between what we actually know and what we want to know about any situation
  - "What is reported about the battlefield or the airspace, and the actual fact of the case, may be two entirely different things." – General Richard H. Ellis, U.S. Air Force (Ret.)
- Information and derived knowledge is both limited and perishable
  - Enemy may take new actions to change the current situation
  - Rapid tempo of modern operations limits the amount of information that can be gathered and processed before having to make another decision
  - If taken to the extreme, the pursuit of more and more information can lead to operational paralysis

> "The key to achieving effective command and control will always come down to finding a way to cope with the effects of uncertainty and time."

1.Department of the Navy. Naval Doctrine Publication 6: Naval Command and Control. May 1995.

Battlespace Awareness

- Battlespace Awareness (BA)[1]: Knowledge and understanding of the operational area's environment, factors, and conditions
- Includes the status of:
  - Friendly and adversary forces
  - Neutrals and noncombatants
  - Weather and terrain
- High levels of shared awareness can lead to:
  - Comprehensive and accurate assessments
  - Aids in successfully applying combat power
  - Helps protect the force and/or complete the mission

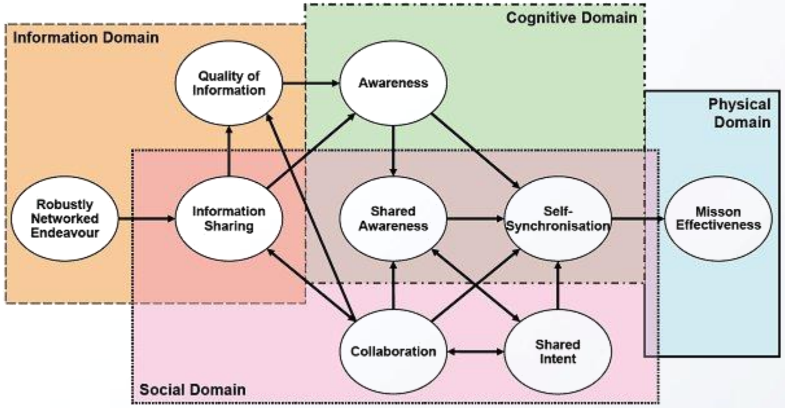


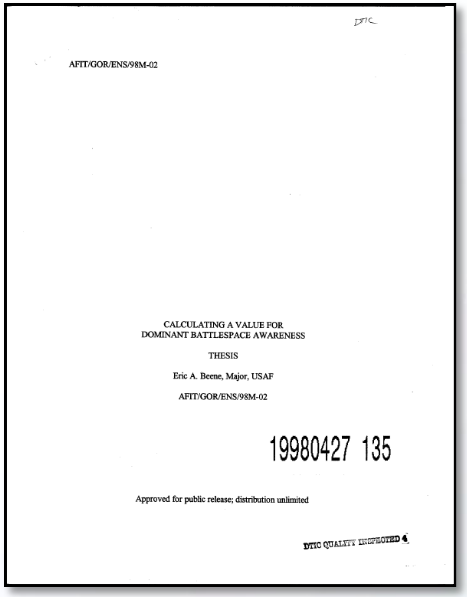
Image from: http://www.opmexperts.com/nato_opm3.html

Establishing and maintaining Battlespace Awareness is crucial to mission success. Measuring BA in terms of uncertainty and time may help in understanding and evaluating C2.

1. Joint Chiefs of Staff. Joint Publication 1-02: DoD Dictionary of Military and Associated Terms (As Amended Through 31 July 2010.

Research Objective

- Conceptual design challenges:
  - Modeling BA in a useful way during conceptual design, with possibly limited system information for C2 system-of-systems architectures
  - Avoiding complex cognitive models of human understanding and reasoning, especially when applied under battlefield conditions
- Research Objectives:
  - Investigate a time-valued information entropy-based method for quantifying battlespace awareness[1]
  - Determine how this method can be extended to aid C2 decision makers in understanding and evaluating military C2 effectiveness independent of mission success


AFIT/GOR/ENS/98M-02

CALCULATING A VALUE FOR
DOMINANT BATTLESPACE AWARENESS

THESIS

Eric A. Beene, Major, USAF

AFIT/GOR/ENS/98M-02

19980427 135

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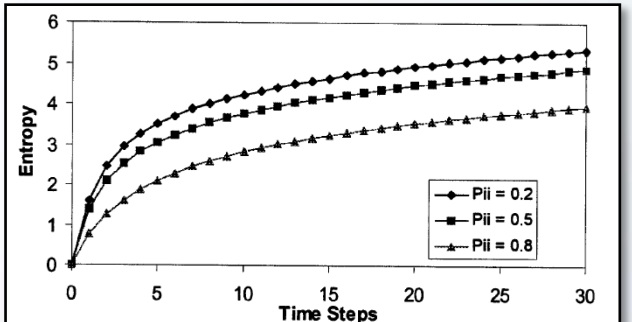
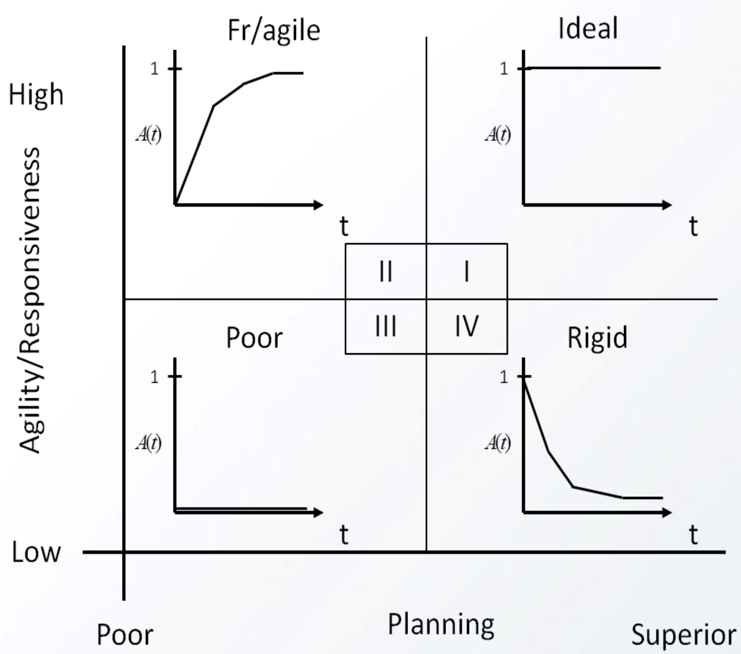


Figure 2-6: Entropy increase over time with four directions of movement at P_{ii} = 0.2, 0.5, 0.8.

1. Beene, Eric A., “Calculating a Value for Dominant Battlespace Awareness”. DTIC. 1998.

Technical Approach: TABS

- Tracking Awareness in the Battlespace during Simulation
- An analytic approach applied to M&S for estimating C2 effectiveness and attributes
  - Utilizes the mathematical theory and concepts of Information Entropy to model Battlespace Awareness
- Provides a way to:
  - Measure the effectiveness of a particular C2 systems architecture and C2 approach
  - Compare & contrast changes in C2 system architecture/C2 approach independent of mission success
  - Helps classify different C2 alternatives according to exhibited C2 characteristics or “C2 Signatures”

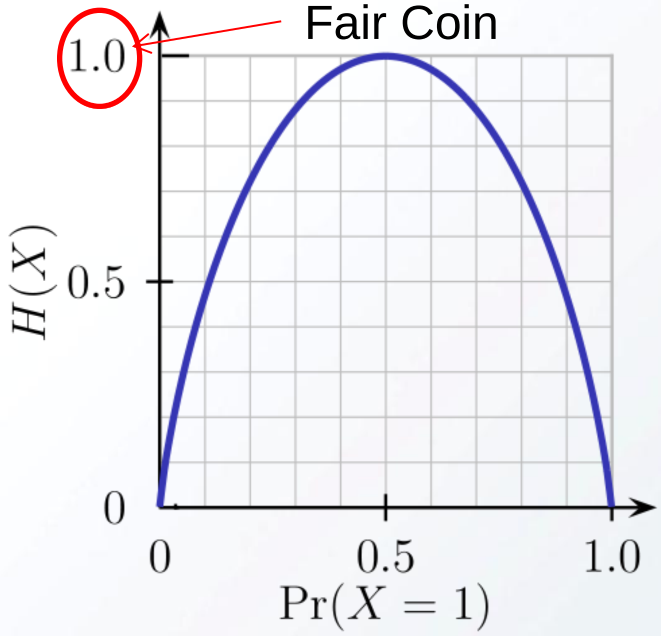


C2 Signature Classification

Technical Approach: Information Entropy

- Shannon's Information Entropy:
  - Entropy is a measure of disorder/unpredictability
  - Shannon applied the concept of Entropy to the uncertainty associated with a random variable
  - Quantifies the expected value of the information contained in a message
- Can be applied to discrete or continuous distributions
  - The Normal distribution maximizes the differential entropy for a given variance
  - x_i = 1/n gives maximum entropy for a discrete distribution of n possible outcomes.

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



Entropy H(X) (i.e. the expected surprisal) of a coin flip, measured in bits, graphed versus the fairness of the coin Pr(X=1), where X=1 represents a result of Heads and X = 0 represents a result of Tails.

Image & Caption from: Wikipedia.org

Differential form of Information/Shannon Entropy:

$$H(x) = -\int_{-\infty}^{\infty} \ln[f(x)] f(x)\,dx$$

1. Shannon, C. E. "A Mathematical Theory of Communication". October 1948.

Technical Approach: Information Entropy

Some amount of $ hidden in one of three locations

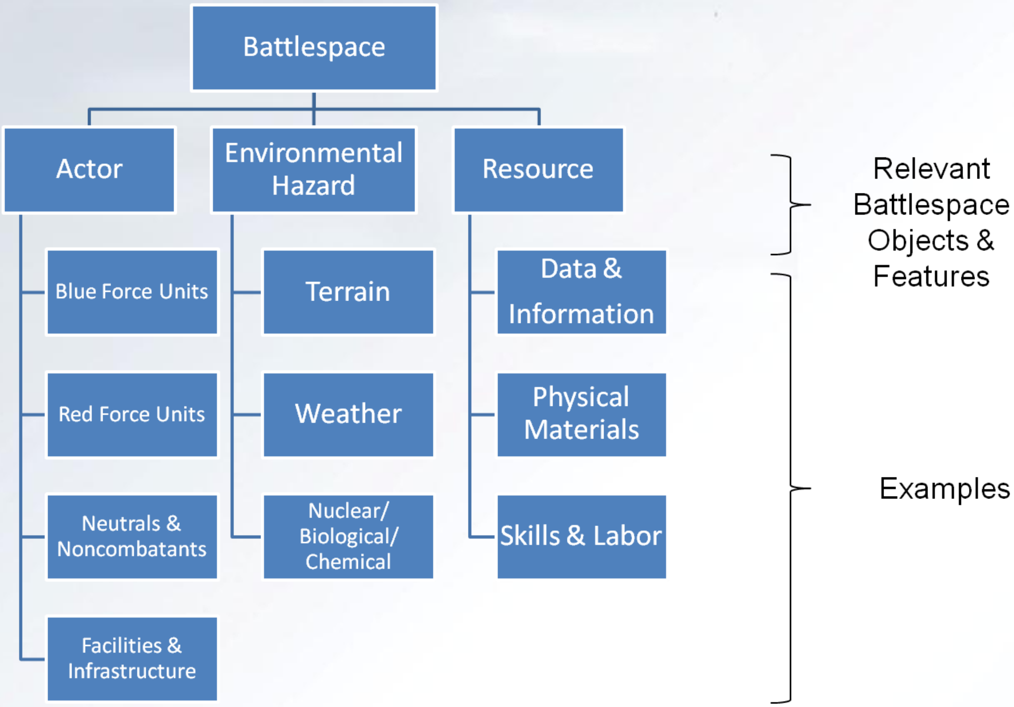
$$H(x) = -\sum_{i=1}^{n} p(x_i)\log_b p(x_i); \{x_i : i = 1,\dots,n\}$$

Estimated likelihood money is located behind each specific door

Case #	Door 1 x_1	Door 2 x_2	Door 3 x_3	Entropy H(X) in bits
I	1/3	1/3	1/3	1.585
II	1/10	3/10	6/10	1.2955
III	0	1/2	1/2	1
IV	0	1	0	0

The greater the Entropy, H(X), the greater the amount of uncertainty

Technical Approach: Quantifying Battlespace Awareness



Example Actor State Properties

$$S_i^A(t) = \begin{bmatrix} \text{Location} \\ \text{Threat ID} \\ \text{Type} \\ \text{Operational Level} \end{bmatrix}$$

(Red, Blue, Neutral/Noncombatant)

(Aircraft, Tank, Facilities/ Infrastructure)

(Fully operational, disabled, destroyed/neutralized)

Example Environmental Hazard State Properties

$$S_i^H(t) = \begin{bmatrix} \text{Location} \\ \text{Type} \\ \text{Hazard Level} \end{bmatrix}$$

(Terrain, Weather, NBC)

(Low, Medium, High)

Example Resource State Properties

$$S_i^R(t) = \begin{bmatrix} \text{Sender} \\ \text{Receiver} \\ \text{Type} \end{bmatrix}$$

(Specific actors within the Battlespace)

(Data Link: Payload Control, Jet Fuel, Senior Watch Personnel, etc.)

- Each Battlespace Feature can be represented by a State Matrix, $S_i(t)$ → Discrete Probability Distribution
- <u>The State Matrix is composed of relevant variables critical to decision making within the context of military operations</u>
- “Total awareness” of the Battlespace means having complete certainty with respect to each State Matrix variable at a certain point in time

Technical Approach: Quantifying Battlespace Awareness

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

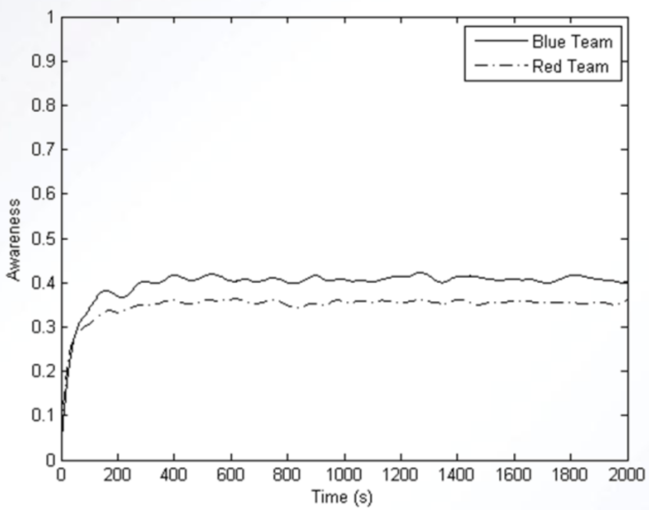
$$U = H(X)_{\max} = \log_b(n_o)$$

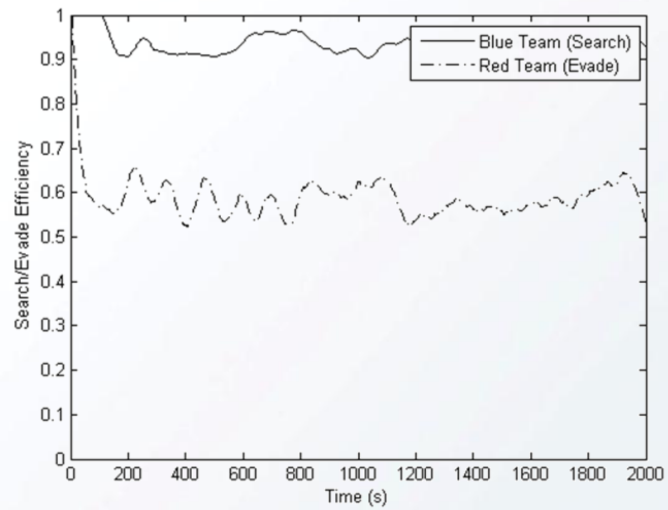
n_o = maximum number of possible outcomes

n = number of non-zero possible outcomes

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

Quantifying Threat ID Awareness	Red Unit x1	Blue Unit x2	Neutral x3	U bits	H(X) bits	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

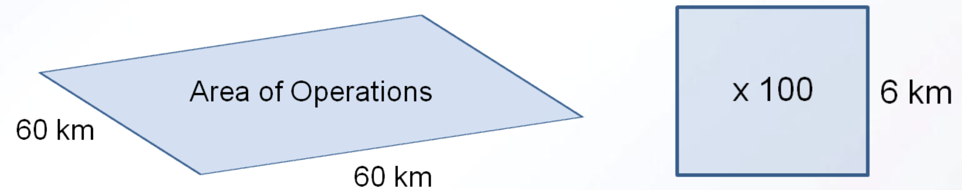




Technical Approach: Quantifying Battlespace Awareness

- Quantifying the uncertainty due to location within the battlespace requires also taking into account:
  - Area & Resolution
  - Speed & Direction
- The battlespace can be divided up into smaller areas, selecting units of area small enough to describe all resolutions with values greater than one[1]
- The probability of locating an object within a cell can be assigned to individual cells
- Over time, the target location may change, increasing the number of cells assigned a non-zero probability, resulting in increased entropy→ "Diffusion Model[1]"

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



$$1\,\text{km}^2 = 1 \times 10^6\ \text{m}^2$$

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

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

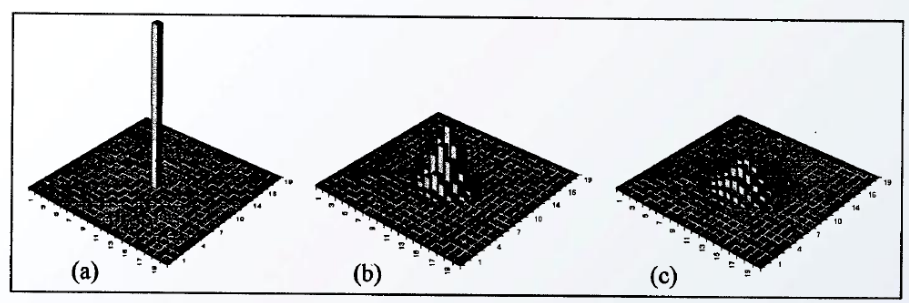
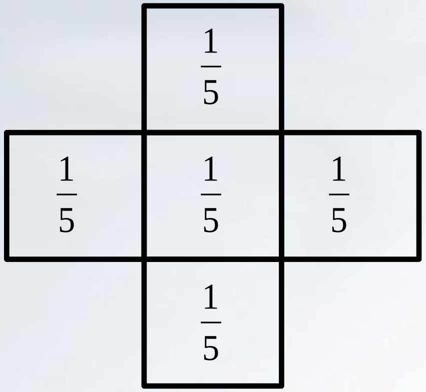


Figure 2-5: Probability that a moving target is located in a particular cell after (a) 0, (b) 10, and (c) 20 time steps. Probability is indicated along the vertical axis.

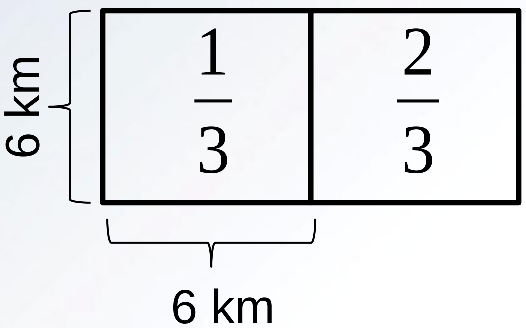
1. Beene, Eric A., "Calculating a Value for Dominant Battlespace Awareness". DTIC. 1998.

Technical Approach: Quantifying Battlespace Awareness

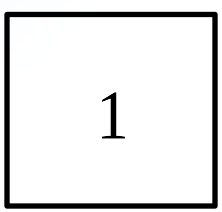
1)



2)



3)



Quantifying Location Awareness	U bits	H(X) bits	A(t)
Case 1: Undetected in Wide Search Area (A_R = 180 km^2)	38.39	29.74	0.23
Case 2: Undetected in Narrower Search Area (A_R = 72 km^2)	38.39	27.02	0.30
Case 3a: Positive Detection (A_R = 10 m^2)	38.39	3.32	0.91
Case 3b: Positive Detection (A_R = 1 m^2)	38.39	0	1

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

$$A_R = \text{Resolution (Units of Area)}$$

Note: Cell shapes other than square are possible for defining a grid.

Technical Approach: Analysis of C2 Signatures

- Signature Analysis:
  - Awareness profile of each unit over time
  - Overall awareness profile of the system as a whole
  - Changes in C2 performance with changes in C2 approach or changes to included systems & system performance
- Summary statistics can be used (mean, median, mode, standard deviation, etc.)
  - How even/uneven is the distribution of awareness across units?
  - Does the awareness of a particular unit(s) seem to contribute more (or less) to overall mission success and why? → determining impact of "weak links", drop in capability from removing key units, etc.
  - Is there an average awareness "threshold" that must be achieved for mission success?
  - Does the C2 signature change significantly under different circumstances → robustness

Technical Approach: Shared Awareness

- Other aspects of Network Centric Operations can be modeled and investigated as well
  - Size and Complexity of information sharing architecture
    - Network Latency
    - Connectivity
    - Bandwidth
  - Experiments can be conducted to determine impact on Battlespace Awareness and therefore C2 effectiveness

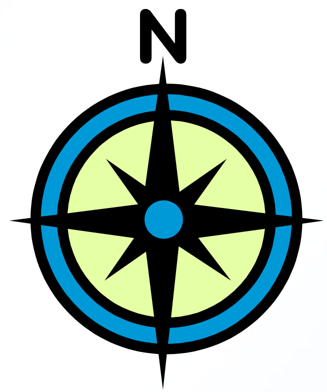
Technical Approach: Shared Awareness

- Measuring entropy gives a sense of “Expected Surprise”
- This measure of entropy is based on one’s own beliefs that are then translated into a probability distribution
- Actual battlespace conditions may vary significantly, leading to “Unexpected Surprise”
- This also provides the opportunity to incorporate and view the effects of deception & misconceptions within the modeling & simulation (M&S) environment
- The impact of information sharing on BA should also be addressed

Technical Approach: Unexpected Surprise

Blue Force believes the following probabilities depict the location of a Red Unit within the battlespace:

0	0	$\frac{1}{3}$
0	0	$\frac{1}{3}$
0	0	$\frac{1}{3}$



However, the Red Unit managed to slip detection and is not located where Blue Force expects:

0	0	0
0	0	0
1	0	0

At this point in time, if Blue Forces were to encounter the Red Unit in the Southwest corner of the battlespace, <u>the amount of unexpected surprise, Δ, can be measured as the difference in probabilities assigned to that cell</u>.

Technical Approach: Unexpected Surprise

I)

Blue Force belief:

0	0	$\frac{1}{3}$
0	0	$\frac{1}{3}$
0	0	$\frac{1}{3}$

Vs.

Actual:

0	0	0
0	0	0
1	0	0

<u>Δ for Event in SW Cell:</u>

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

II)

Blue Force belief:

$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$
$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$
$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$

Vs.

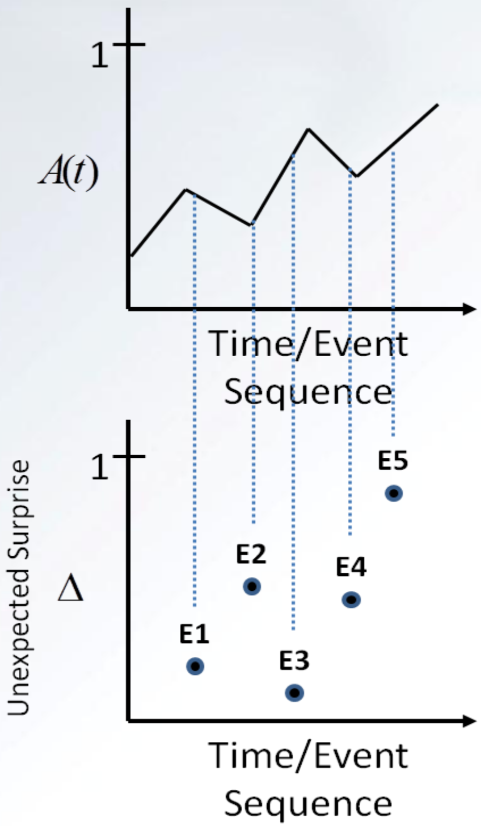
Actual:

0	0	0
0	0	0
1	0	0

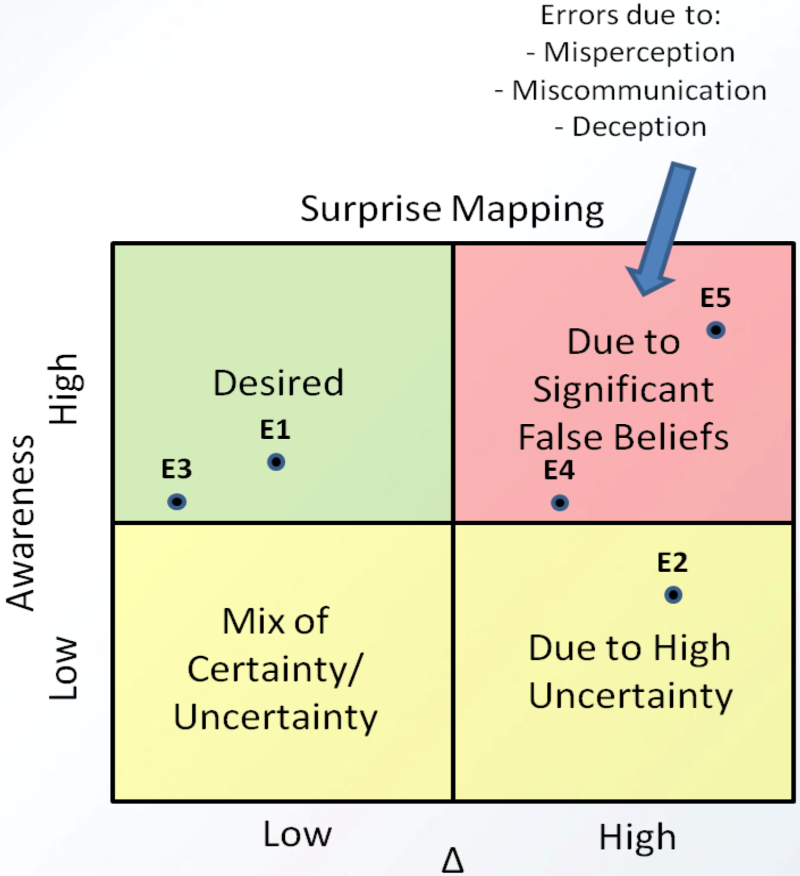
Greater overall uncertainty, but less unexpected surprise

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

Technical Approach: Unexpected Surprise

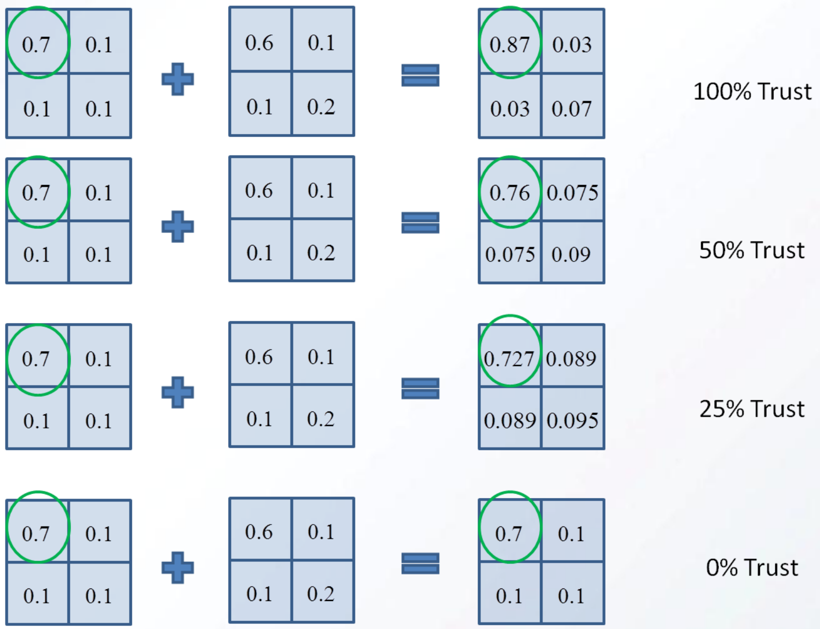


Each point represents an Event (E) occurring within the battlespace



Technical Approach: Incorporating Trust

- Shared information may confirm or conflict with previously held beliefs
  - Quantifying this aspect may require the use of approaches such as Bayesian methods or Kalman filtering
  - Trust may also be an issue and may need to be incorporated into the model 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*



Modeling confirming information with varying levels of trust.

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

Summary

- TABS provides a set of analyses for answering the question: "What does good C2 look like?"
- Utilizes and extends a time-valued information entropy-based method for quantifying battlespace awareness
- Goal is to aid decision makers in acquiring the best portfolio of C2 systems to ensure mission effectiveness
- Provides a means of evaluating C2 effectiveness independent of mission success