Performance Assessment of the C2ISR Enterprise

12th International Command and Control Research and Technology Symposium

Dr. Michael B. Hurley
Mr. Peter Jones

19 – 21 June 2007

This work was supported by the Department of the Navy, Office of Naval Research (ONR) under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Navy or the United States Air Force.
The Problem

• Capability Gap
  – Stovepipes in the ISR community of interest (COI) prevent the timely delivery of the right data to the right recipients

• Solution
  – Use a service oriented architecture to eliminate the stovepipes
    Distributed Common Ground System
    Air Force, Army, Navy, Marines

• New Gap
  – No rigorous methodology for assessing the performance of Multi-INT ISR enterprises

• Proposed Solution
  – ONR funded study
Study Description

- Develop a rigorous methodology for characterizing the performance of Multi-INT ISR enterprises
  - Multi-disciplinary study of assessment methodologies for enterprise and related systems
  - Develop an assessment methodology for ISR enterprises
  - Apply the methodology to a simple demonstration

- Develop objective metrics for Multi-INT ISR enterprises
  - Figure of Merit
  - Measures of Effectiveness
  - Measures of Performance
Outline

• Motivation from other Figures of Merit
  – Radar Equation
  – Sonar Equation

• Review of other models and assessment methodologies

• Conceptual Model for the Multi-INT C2ISR Enterprise

• Mathematical foundations for the C2ISR Enterprise

• Distributed Multi-INT ISR Enterprise scenario

• Summary
Performance Archetypes

• Radar equation

<table>
<thead>
<tr>
<th>Log-Power received by Radar</th>
<th>P_R = Received Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_R = P_T + G_T + \sigma + A_E - 4\ln(R) - 2\ln(4\pi)</td>
<td>P_T = Peak Trans. Power</td>
</tr>
<tr>
<td>G_T = Transmit Gain</td>
<td></td>
</tr>
<tr>
<td>\sigma = Radar Cross Section</td>
<td></td>
</tr>
<tr>
<td>A_E = Effective Area of Receiving Antenna</td>
<td></td>
</tr>
<tr>
<td>(Above in dB)</td>
<td></td>
</tr>
<tr>
<td>R = Target Range</td>
<td></td>
</tr>
</tbody>
</table>

• Sonar equations

<table>
<thead>
<tr>
<th>Active, Noise – background</th>
<th>DT = Detection Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT = SL + DI_T + TS - 2TL - (NL-DI_R)</td>
<td>SL = Source Level</td>
</tr>
<tr>
<td>Active, Reverberation – background</td>
<td>DI = Directivity Index</td>
</tr>
<tr>
<td>DT = SL + DI_T + TS - 2TL - RL</td>
<td>TL = Transmission Loss</td>
</tr>
<tr>
<td>Passive</td>
<td>RL = Reverberation Level</td>
</tr>
<tr>
<td>DT = SL + DI_S -TL - (NL-DI_R)</td>
<td>NL = Noise Level</td>
</tr>
<tr>
<td></td>
<td>TS = Target Strength</td>
</tr>
<tr>
<td></td>
<td>(All in dB)</td>
</tr>
</tbody>
</table>
## Review of Relevant Literature

<table>
<thead>
<tr>
<th>Documents</th>
<th>Good Conceptual Model</th>
<th>Can Model the ISR Enterprise</th>
<th>Contains Quantitative Measures</th>
<th>Strong Mathematical Foundation</th>
<th>Provides Single Figure of Merit</th>
</tr>
</thead>
<tbody>
<tr>
<td>The OODA Loop Boyd</td>
<td>The Classic Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Situation Awareness Endsley</td>
<td>The Classic SA Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silent Hammer Limited Objective Experiment Pomianowski, et al</td>
<td>Hierarchical Taxonomy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Network Centric Operations Conceptual Framework Office of Force Transformation</td>
<td>Complex Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shared Awareness Perry, Signori, Boon</td>
<td></td>
<td>Probability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Situation Assessment Mahoney, Laskey, Wright, Ng</td>
<td></td>
<td>Probability &amp; Utility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complexity Theory; Network Centric Warfare Moffatt</td>
<td></td>
<td></td>
<td>Information Theory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed sensor networks Kadambe and Daniell</td>
<td></td>
<td></td>
<td>Information Theory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Information Quality Business Research Community</td>
<td></td>
<td></td>
<td>~20 Information Quality Attributes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Survey found either good models with weak mathematical foundations or good mathematical foundations with weak models.
Conceptual Model Construction

- Adopt Boyd’s OODA loop and Endsley’s SA loop as a template
  - The Multi-INT ISR enterprise is a decision system or is part of one

- Build in the mathematical foundations from the beginning
  - Probability theory
  - Information theory
  - Utility theory

- Model the enterprise as a state machine
  - Environmental states
  - Decision system states

- Assume that the true environmental state is unique

- Represent all other states by Probability Density Functions (PDFs)
Goal: Transition the environment to the most advantageous state
Decision Process Model
Level Two

Decision systems are composed of multiple transforms with data storage
The definition of a Figure of Merit for Multi-INT ISR Enterprises is complicated by the boundaries in the decision process.
Archetypal Figures of Merit evaluate sensor performance
Figures of Merit

*Traditional FoM, MoE, MoP*

Archetypal Figures of Merit evaluate sensor performance

Traditional FoM, MoE, MoP have focused on performance of sensors and actuators
Archetypal Figures of Merit evaluate sensor performance

Evaluation of the enterprise requires measures of the decision process between the sensors and actuators (Information Theory)

Traditional FoM, MoE, MoP have focused on performance of sensors and actuators
Archetypal Figures of Merit evaluate sensor performance

The closest match to a single Figure of Merit is Total System Cost (Utility Theory)

Evaluation of the enterprise requires measures of the decision process between the sensors and actuators (Information Theory)

Traditional FoM, MoE, MoP have focused on performance of sensors and actuators
Figures Of Merit
Evaluation of Complete Systems

Archetypal Figures of Merit evaluate sensor performance

The closest match to a single Figure of Merit is Total System Cost (Utility Theory)

Evaluation of the enterprise requires measures of the decision process between the sensors and actuators (Information Theory)

Utility assessments require evaluation of the entire C2ISR enterprise

Traditional FoM, MoE, MoP have focused on performance of sensors and actuators
Archetypal Figures of Merit evaluate sensor performance

The closest match to a single Figure of Merit is Total System Cost (Utility Theory)

Utility assessments require evaluation of the entire C2ISR enterprise

Evaluation of the enterprise requires measures of the decision process between the sensors and actuators (Information Theory)

There is no universal Figure of Merit because utility is relative. There may be a universal methodology.

Traditional FoM, MoE, MoP have focused on performance of sensors and actuators
Probabilistic Measures of Performance

- Correctness
  - Probability Integral
    \[ D_B = \int_x P_S P_E dx \]
    \[ D_B = \int_x P_S \delta_E (T - x) dx \]

- Confidence (or Uncertainty)
  - Shannon information
    \[ D_{SI} = -\int_x P_S \ln(P_S) dx \]
  - Fisher information
    \[ D_{FI} = -\int_x P_S \left( \frac{\partial \ln(P_S)}{\partial x} \right)^2 dx \]

- Consistency
  - Kullback-Leibler (K-L) distance or symmetric K-L
    \[ D_{KL} = \int_x P_{S_1} \ln \left( \frac{P_{S_2}}{P_{S_1}} \right) dx \]
    \[ D_{SKL} = \int_x P_{S_1} \ln \left( \frac{P_{S_2}}{P_{S_1}} \right) dx + \int_x P_{S_2} \ln \left( \frac{P_{S_1}}{P_{S_2}} \right) dx \]
  - Mutual information
    \[ D_{MI} = \int_x P(x, y) \ln(P(x | y)) dxdy - \int_x P(x) \ln(P(x)) dx \]
Enterprise Assessment Demonstration

• Demonstrate the evaluation of a C2ISR enterprise that is constructing a Common Operational Picture (COP)

• Build a conceptually simple simulation
  – Five sensors, each with a different sensory profile
  – Three target classes
  – 5x5 cellular grid representing Area of Interest
  – Sensors take cellular measurements and estimate Probability Density Functions (PDFs) for the content of each cell

• Evaluate the differences between different communications architectures
Simple Multi-INT Enterprise Model

- **Detection and Discrimination Task**
  - 5 sensors, 3 target types, 5x5 grid world
- **Heterogeneous Sensor Mix**
  - Synoptic detectors
  - Soda-straw discriminators
- **Decision types**
  - Movement
    (North, South, East, West, Stay)
  - Communication
    (which metadata / data / queries to what node)

**Sensor Modalities**

<table>
<thead>
<tr>
<th>Strength</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

Sensor Equation

\[ z = (\text{strength}) \pm (\text{noise}) \]

**Extent Equation**

\[ E = \text{NxN sub-grid} \]

**Coverage**

**Placment**
Decision Process in Action

C2ISR
Enterprise Performance Metrics

World Truth

World Model

"Traditional ISR"

P(z|x)

Bayesian Update

p(x|z) = p_sq, p_tri, ...

Z = 1.358

"Traditional C2"

p(x|z) = δ(x=Truth)

Minimize Expected System Entropy

Move: South
TX: Metadata > A

Sensor

Actuator

070207-21
MBH 5/22/2007
Baseline Communication Architectures

- No inter-sensor communication (worst case)
  - Sensor limitations preclude correct or certain estimation by any single sensor
  - Sensor heterogeneity precludes maintaining enterprise consensus

- Unlimited inter-sensor communication (best case)
  - Sharing non-mutual information leads to correct and confident world model
  - Sharing all information provides uniformity of consensus across the enterprise
Limited Communication:
Push Architecture

- Limited inter-sensor communication
  - Bandwidth constraints prevent the sharing of all information
  - Communication bottlenecks result in long, un-prioritized queues

Information architectures that work well in unconstrained systems may not work well in constrained systems
Limited Communication: Pull Architectures

- **Blind pull (requests/no metadata)**
  - Requests take up a small amount of bandwidth relative to data (1:10)
  - Without knowledge of available data requests may or may not be feasible

- **Informed pull (requests/published metadata)**
  - Metadata information pushed to all nodes, small relative to data (1:10)
  - Informed requests maximize information utility of transmitted data
Summary

• A conceptual model of the Multi-INT C2ISR enterprise has been constructed

• A mathematical foundation have been developed for the evaluation of the C2ISR enterprise

• Measures integrate disparate contributions to overall system performance
  – Information theory for partial systems and component analysis
  – Utility theory for complete decision systems

• The value of performance metrics has been demonstrated through a simulation of a simple scenario
  – Measurements confirm predictions of communications experts for the limited communications architectures