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**Standard Form 298 (Rev. 8-98) Prescribed by ANSI Std Z39-18**
New Metrics and MOEs for Unmanned, Distributed Forces

Jeffrey R. Cares

73rd MORSS
Introduction

- Existing models focus on attrition and cannot adequately represent proposed Information Age combat processes.

- Three views of a Distributed Networked System:
  - Structure
    - What are the links, nodes, boundaries and rules for connection?
  - Dynamics
    - Do actual or potential networked effects exist?
  - Evolution
    - What trajectories do the descriptive characteristics take?
      - Do they converge, diverge or cycle?

- These three perspectives are used to create the Information Age Combat Model
Structure
Combat Network

Basic Network:
Passive Target (T),
Autonomous Sensor (S),
Simple Decider (D),
Autonomous Influence (I)
Two-Sided Simple Combat
Allowable Connections

Simplest complete combat network

S: Sensor
D: Decision Maker
I: Influencer
T: Target
## Adjacency Matrix for Simplest, Complete Combat Network

<table>
<thead>
<tr>
<th></th>
<th>$S_x$</th>
<th>$D_x$</th>
<th>$I_x$</th>
<th>$T_x$</th>
<th>$S_y$</th>
<th>$D_y$</th>
<th>$I_y$</th>
<th>$T_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_x$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$D_x$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$I_x$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$T_x$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$S_y$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$D_y$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</tr>
<tr>
<td>$I_y$</td>
<td>1</td>
<td>1</td>
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<td>$T_y$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

row maps directionally to column = 1, 0 otherwise
Combat Model Potential Complexity

Digraph Complexity

Number of Nodes

Magnitude of Combinations

# of Particles in $\Omega$

$2^N^2$

$N!$
Buttons and Strings

Ratio of Strings to Buttons

Number of Buttons Connected

Kauffman, *At Home in the Universe*, p.57
Catalytic Control Cycles

Diagram showing network of nodes labeled S, D, T, I, and S with arrows indicating flow or connections between them.
Catalytic Competitive Cycles

- $D_X$ to $T_X$ to $S_X$ to $I_X$ (blue)
- $I_Y$ to $S_Y$ to $T_X$ to $D_Y$ (red)

A and B represent the competitive cycles.
Combat Cycles
No Cycle

\[ \lambda_{\text{PFE}} = 0 \]

\[
\begin{pmatrix}
T & S & D \\
T & 0 & 0 & 0 \\
S & 1 & 0 & 0 \\
D & 0 & 1 & 0
\end{pmatrix}
\]
Cycle

\[ \lambda_{PF} = 1 \]

\[
\begin{pmatrix}
T & S & D & I \\
T & 0 & 0 & 0 & 1 \\
S & 1 & 0 & 0 & 0 \\
D & 0 & 1 & 0 & 0 \\
I & 0 & 0 & 1 & 0 \\
\end{pmatrix}
\]
Autocatalytic Set

\[ \lambda_{PFE} = 1.19 \]
Autocatalytic Set

\[ \lambda_{PFE} = 1.35 \]

\[
\begin{align*}
T & | S_1 | S_2 | D | I \\
T & | 0 | 0 | 0 | 0 | 1 \\
S_1 & | 1 | 0 | 0 | 0 | 0 \\
S_2 & | 1 | 0 | 0 | 0 | 1 \\
D & | 0 | 1 | 1 | 0 | 0 \\
I & | 0 | 0 | 0 | 1 | 0
\end{align*}
\]
Autocatalytic Set

$\lambda_{PFE} = 1.19$

$PFE = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 
\end{pmatrix}$
Evolution
Core Shift

Time Step 1

\[ \lambda_{PFE} = 1.73 \]
Core Shift
Time Step 2

\[ \lambda_{PFE} = 1.52 \]
Core Shift
Time Step 3

\[ \lambda_{PFE} = 1.19 \]
Core Shift
Time Step 4

\[ \lambda_{PFE} = 1.50 \]
# Network Metric Thumb Rules

## Experimentation and Analysis

<table>
<thead>
<tr>
<th>Metric</th>
<th>Range</th>
<th>Operational Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes, $n$</td>
<td>$n &gt; \sim 100$</td>
<td>Network effects unlikely to occur with $n &lt; 50$</td>
</tr>
<tr>
<td>Number of links, $l$</td>
<td>$l &lt; \sim 2n$</td>
<td>$l &lt; 2n$, too brittle</td>
</tr>
<tr>
<td></td>
<td>$l &gt; 2n$, too much overhead</td>
<td></td>
</tr>
<tr>
<td>Degree distribution</td>
<td>Skewed</td>
<td>Adaptivity, modularity</td>
</tr>
<tr>
<td>Largest hub</td>
<td>$&lt; 100$ links</td>
<td>Hub appears, recedes by reconnection 5% of links</td>
</tr>
<tr>
<td>Average path length</td>
<td>$\log(n)$</td>
<td>Short distances even for large networks (e.g., $10^4$ nodes $\Rightarrow$ Average path length $= \sim 4$)</td>
</tr>
<tr>
<td>Clustering</td>
<td>Skewed</td>
<td>Hierarchy, organization</td>
</tr>
<tr>
<td>Betweenness</td>
<td>Skewed</td>
<td>Cascade control</td>
</tr>
<tr>
<td>Path horizon</td>
<td>$\log(n)$</td>
<td>Self-synchronization</td>
</tr>
<tr>
<td>Susceptibility/Robustness</td>
<td>Low (random removal)</td>
<td>Hubs should be kept obscure until needed, damage abatement/repair schemes</td>
</tr>
<tr>
<td>Neutrality Rating</td>
<td>$(0, 1)$</td>
<td>Increased network effects, decreased susceptibility, tipping points</td>
</tr>
<tr>
<td>Coefficient of Networked Effects</td>
<td>$(0, 1)$</td>
<td>Network effects</td>
</tr>
</tbody>
</table>

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Complex Systems Research
Process Innovation & Analysis
Strategic Investment Advice
Future Concept Generation
Corporate/Government War Games & Events

Questions?