An Application of Agent Based Modeling in the Analysis of Communication Links in Network Centric Operations

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Background

- These models were conducted as part of a case study for SAS-050, an international group established by NATO’s Research and Technology Organization’s Studies Analyses and Simulation Panel in 2003 for the purpose of exploring new Command and Control concepts.

- The objective of these experiments is to
  - Identify advantages and limitations of the Conceptual Model of Command and Control being developed by SAS-050.
  - Generate NCO/C2 related studies within the Project Albert Modeling community.

Project Albert

www.projectalbert.org

Project Albert is the research and development effort whose goal is to develop the process and capabilities of Data Farming, a method to address decision-maker's questions that applies high performance computing to modeling in order to examine and understand the landscape of potential simulated outcomes, enhance intuition, find surprises and outliers, and identify potential options.
Modeling Efforts

- Simple comparison of C2 information network arrangements – no terrain, no complex behaviors, no doctrinal specifications. Test insights and compare network arrangements across a variety of mission objectives.

- Investigate social and cognitive impacts of organizational structure within the context of a simple cognitive task – Comparison of Two organization structures:
  - Command and Control Organization (Hierarchical Network)
  - Edge Organization (Complete Network)
MANA, Map-Aware Non-Uniform Automata (New Zealand)
  – Detailed communications for various levels of networked forces
  – Behavior state changes for coordinated movement of forces

• NetLogo (Northwestern University)
  – Fully Programmable
  – Modeling complex systems developing over time
  – Can give instructions to hundreds or thousands of independent "agents" all operating concurrently and observe behavior patterns

• Project Albert Data Farming Environment (International)
  – Leveraging High Performance Computing
  – Question based collaboration
Distillation Advantages/Disadvantages

• **Advantages:**
  – Ease of use for quick scenario modeling
  – Quick turnaround cycle for data farming
  – Ability to conduct visual analysis of scenario in addition to data analysis – intermediate behaviors visually present via playback but may be overlooked or summarized via data examination

• **Disadvantages:**
  – Ability to model both communication aspects combined with leadership aspects not present in a single model
  – Artifacts in model difficult to trace without direct contact with developers
  – Too much data and too little time
Network Centric Operations Conceptual Framework

1. Quality of Organic Information
2. Quality of Individual Information
3. Quality of Individual Sensemaking
   - Individual Awareness
   - Individual Understanding
   - Individual Decisions
4. Quality of Networking
   - Degree of Networking
   - Net Readiness of Nodes
5. Degree of Information "Share-ability"
6. Degree of Shared Information
7. Degree of Shared Sensemaking
   - Shared Awareness
   - Shared Understanding
   - Collaborative Decisions
8. Quality of Networking
9. Degree of Decision Synchronization
10. Degree of Actions/Entities Synchronized
11. Degree of Effectiveness

Domains:
- Physical Domain
- Information Domain
- Cognitive Domain
- Social Domain

Force and C2 Agility

Value Added Services

Information Sources
Network Centric Operations Conceptual Framework

Quality of Organic Information

Quality of Individual Information

Quality of Individual Sensemaking
- Individual Awareness
- Individual Understanding
- Individual Decisions

Quality of Networking
- Degree of Networking
- Net Readiness of Nodes

Degree of Information “Share-ability”

Degree of Shared Information

Degree of Shared Sensemaking
- Shared Awareness
- Shared Understanding
- Collaborative Decisions

Degree of Decision Synchronization

Degree of Actions/Entities Synchronized

Degree of Effectiveness
Four Network Topologies
Reference *Power to the Edge* (pg. 182)
Hypotheses

• Shared information leads to better performance
• Broader or earlier information sharing leads to better performance as individuals have common picture of enemy contacts before getting caught up in battle
• Full connectivity leads to better performance
• Perfect is preferable to degraded communications
Overview of Experiment I

• Experimental objective:
  – Scenario A: Get to goal at whatever cost (optimal path at shortest time, no consideration for losses; no maneuvering behaviors)
  – Scenario B: Get to goal with minimal losses (maneuvering behaviors with consideration of friendly losses; time to complete mission not a major factor)
  – Scenario C: Deplete enemy forces (from USMC Tactical Decision Game - execute major enemy losses; no established physical goal; no consideration for friendly losses except to have initial advantage in the fight)

• Organization structures
  – Traditional Hierarchy
  – Fully Connected/Web Network

• Scenario
  – Agents receive both organic and inorganic information
  – Information sharing and receiving is constrained by the network structure
  – Each time step an agent will share all of the information it has about the 200x200 map
  – The user has the ability to alter the communication parameters for each agent

• ABM environment: MANA

• Key Questions
  – How does the performance of the Traditional Hierarchical organization compare with that of the fully connected organization under various conditions?
  – How are the performance and situational understanding achieved by each affected by various factors, such as the communication accuracy, reliability, range, etc.?
  – Do these factors affect the organizations differently?
Clustered enemy force around Blue goal.

Blue has centralized node, 2 mid-level nodes, each linked to 2 subordinate units.
MANA Traditional Network Example
Optimal Path at Shortest Time

End of Run
Data Farming Parameters

- Comms Range (100-200 grid cells, in increments of 100 cells)
- Comms Capacity (25-100 messages passed through the comms link, in increments of 25 messages)
- Comms Latency (0-15 time step delay, in increments of 5 time steps)
- Comms Accuracy (25-100% accurate passage of information for correctly detected and classified contacts, in increments of 25%)
- Comms Reliability (25-100% reliability that messages made it through the comms link, in increments of 25%)
- Red Sensor Range (15-20 grid cells, in increments of 5 cells)
Traditional Network
Full Distribution of Data Across All Variable Settings
For Fixed Comms Range = 200 Grid Cells

Can select set of particular input values or specific threads through the distribution, (e.g., all records where Red sensor range is 15)
Low Blue killed linked to high Red Killed and lower time to get to goal. In this case Blue always gets to goal. Low Blue killed happens only when Red sensor range is 15 grid cells (which is less than Blue sensor range of 20).
Low Red casualties occur for all parameters except for comms accuracy of 100% and comms latency of 15 time step. Low Red casualties prevents Blue from getting to goal and causes heavy losses for Blue.
Low Blue killed is linked to high Red Killed. Blue always gets to goal, although on a more variable time period. Low Blue killed happens only when Red sensor range is 15 grid cells.
Low Red casualties occur for all parameters except for comms accuracy of 100%, comms capacity less than 75 messages per time step, comms latency greater than 10 time steps, and comms reliability less than 75%. Low Red casualties prevents Blue from getting to goal and causes heavy losses for Blue.
Low Blue killed linked to mix of low and high Red Killed and lower time to get to goal. In this case Blue does not always get to goal and no distinguishing input parameter identified as possible driver of outcomes.
Low Red casualties occur for all parameters except for comms accuracy of 100%. Low Red casualties prevents Blue from getting to goal and causes range of losses for Blue from min of 0 to max possible of 40.
Low Blue killed linked to mix of low and high Red Killed and lower time to get to goal. In this case Blue does not always get to goal and Red sensor range is not the main indicator of outcomes. Low Blue casualties happen for all parameters except for comms accuracy of 25%.
Low Red casualties occur for all parameters except for comms accuracy of 100%. Low Red casualties prevents Blue from getting to goal and causes range of losses for Blue from min to max.
Looking at the thread for perfect comms under our variable settings, we see that Blue suffers minimal casualties, inflicts maximum casualties on Red, and gets to the goal in a very short period of time.
When comms have been degraded by about 25%, we see that Blue suffers heavy casualties, although not the maximum number possible. Blue is able to inflict maximum casualties on Red and still get to the goal in a shorter period of time.
In the case of fully degraded comms, we see that Blue suffers minimal casualties, inflicts maximum casualties on Red, and gets to the goal in a short period of time. This is an interesting anomaly, that contradicts the logical hypothesis that fully degraded comms lead to the inverse outcome for Blue than indicated in this chart. Cannot say with certainty that this is not an artifact of the model, however, if not an artifact, could indicate behaviors that we were not expecting.
In the case of the web network for perfect comms, we see the same pattern that occurred for the traditional network. Blue suffers minimal casualties, inflicts maximum casualties on Red, and gets to the goal in a very short period of time.
When comms have been degraded by about 25%, we see that Blue suffers close to maximum casualties, and inflicts a range of casualties on Red, however less than with perfect comms. In this case, slightly degraded comms prevent Blue from getting to the goal in almost every case.
Patterns of Movement
Maneuvering Behaviors with Consideration of Friendly Losses
Traditional Network without UAV
Web Network without UAV
Web Network with UAV
<table>
<thead>
<tr>
<th>Without UAV:</th>
<th>With UAV:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Without UAV:</strong></td>
<td><strong>With UAV:</strong></td>
</tr>
<tr>
<td>All Blue agents head straight up the middle of the battlefield, without maneuvering to avoid enemy</td>
<td>All Blue subordinates initially move in the opposite direction of the goal, away from enemy</td>
</tr>
<tr>
<td>The Subordinates receive no Inorganic SA until the Mid-Level Nodes encounter Red, within their sensor range of 20</td>
<td>The Mid-Level Nodes often lose communication with their respective squad, the distance between them is greater than the comms range of 100</td>
</tr>
<tr>
<td>Mid-Level Nodes are often killed before any other agents</td>
<td>Blue travels in squads as opposed to one large group</td>
</tr>
<tr>
<td>Blue suffers great loss (more than half)</td>
<td>Upon close contact with the enemy, the Blue squads move away from Red so much that they go far out of their way, in turn taking a long time to reach the goal</td>
</tr>
<tr>
<td>Successful in reaching the goal and require little time</td>
<td>Blue suffers great loss (more than half)</td>
</tr>
<tr>
<td></td>
<td>Successful in reaching the goal, requires a lot of time</td>
</tr>
</tbody>
</table>

**Visual Analysis Summary**

**Traditional**

**Without UAV:**
- All Blue agents head straight up the middle of the battlefield, without maneuvering to avoid enemy
- The Subordinates receive no Inorganic SA until the Mid-Level Nodes encounter Red, within their sensor range of 20
- Mid-Level Nodes are often killed before any other agents
- Blue suffers great loss (more than half)
- Successful in reaching the goal and require little time

**With UAV:**
- All Blue subordinates initially move in the opposite direction of the goal, away from enemy
- The Mid-Level Nodes often lose communication with their respective squad, the distance between them is greater than the comms range of 100
- Blue travels in squads as opposed to one large group
- Upon close contact with the enemy, the Blue squads move away from Red so much that they go far out of their way, in turn taking a long time to reach the goal
- Blue suffers great loss (more than half)
- Successful in reaching the goal, requires a lot of time

**Web**

**Without UAV:**
- All Blue agents head straight up the middle of the battlefield, however upon enemy contact, squads maneuver to avoid enemy
- Each squad supplies the others with Inorganic SA once Red is within their sensor range of 20
- Even though the squads try to avoid the enemy, they are caught in the kill sack since the information was not received prior to Red contact
- Blue suffers loss
- Successful in reaching goal for majority of trials

**With UAV:**
- All Blue subordinates initially move toward the goal
- Each squad maneuvers to the right or left of the enemy, splitting the force across the battlefield
- The split in maneuvers is unique to this scenario
- The mission is accomplished fairly quickly with minor losses to both Blue and Red
Traditional Network
Comms Range = 200 for UAV and Mid-Level Node Red
Sensor Range = 15

Perfect comms with and without the aid of a UAV
- With UAV, less engagements with Red, more maneuvering behavior around Red, indicated by low Red casualties.
- Without the aid of a UAV, more engagements with Red, less maneuvering around Red, indicated by high Red casualties.
Perfect comms with and without the aid of a UAV
- With UAV, less engagements with Red, with some maneuvering behavior around Red, indicated by spread of Red casualties.

- Without the aid of a UAV, more engagements with Red, less maneuvering around Red, indicated by high Red casualties.
Meeting at ‘The Mounds’

by Maj John F. Schmoll, USMCR

This TDG should look familiar. Its scenario is essentially the same as the one encountered in TDG #97-4, for which three solutions are given on the preceding pages. There is one major difference however: this time you are the enemy. How does this sound to you? “Breaking the other guy’s back”, or “wearing his shoes” for a few minutes? Is this the kind of fun you mean by playing a game on the enemy?

Simulation
You are a squad leader in Company K, 3d Battalion, 4th Marines. The company is making a movement to contact, moving south toward Liberty. The company’s mission is to locate and destroy any sizable enemy forces in the area. The company commander has directed the squad to move to the south and strike the enemy in the area.

Your platoon is the advance guard, and your squad has the point. Your historian has given you the following instructions:

I’m relying on you to develop the situation to the best of your ability whenever you make contact. If you can overpower the enemy yourself, fine. If it’s a sizable enemy force, my intent is for you to develop the situation advantageously for the rest of the company. To do this, you must delay the enemy so that they cannot concentrate and the CO can bring the rest of the company to bear. I’ll support you with the other two squads.

Your squad is in a wedge formation with its Fire Team on the left, 3d Fire Team in the center leading, and 4th Fire Team on the right. The attached machinegun squad is located with you behind 2d Fire Team.

Your squad is moving in a line across the road, one Fire Team on each side of the road and one Fire Team covering the ground behind them. As 2d Fire Team reaches one of the mounds, you see 1st Fire Team drop quickly out of the formation and begin firing. You can see the enemy fire from a safe distance.

A second enemy platoon is seen about 800 meters south. Another position opens up from a mound to the left front. You examine them close and determine that they are about 500 meters south.
With the introduction of the UAV (Increase in Information) the Blue Force Suffered Fewer Casualties and Accomplished the Mission in Less Time.

Without UAV

Blue Casualties: 11-25

With UAV

Blue Casualties: 4-15
Scenario Objective: Deplete enemy forces. Variable parameter is time when Blue reserve forces called in to support the main effort. In the traditional network, enemy forces killed spans from a min of 9 to a max of 41, versus 40 to 41 in the web network.
Network Centric Operations Conceptual Framework

- **Quality of Organic Information**
  - Degree of Networking
  - Net Readiness of Nodes
  - Degree of Information “Share-ability”

- **Quality of Individual Information**
  - Quality of Individual Sensemaking
    - Individual Awareness
    - Individual Understanding
    - Individual Decisions
  - Degree of Networking
  - Degree of Information “Share-ability”

- **Quality of Networking**
  - Shared Awareness
  - Shared Understanding
  - Collaborative Decisions

- **Force Agility**
  - Degree of Actions/Entities Synchronized
  - Degree of Effectiveness

- **C2 Agility**
  - Degree of Networking
  - Net Readiness of Nodes

- **Effectors**
  - Degree of Decision Synchronization

- **Physical Domain**
  - Information Domain
  - Cognitive Domain
  - Social Domain
Overview of Experiment II

• Experimental objective:
  – Investigate social and cognitive impacts of organizational structure within the context of a simple cognitive task

• Two organization structures
  – Command and Control Organization (hierarchical network, fixed-task)
  – Edge Organization (complete network, simple task adaptation)

• Scenario
  – Agents receive information about a future attack
    • The information facts have been separated into four task categories, notionally: who, what, when, and where
    • Facts are periodically distributed among the agents
  – The goal of each organization is to build awareness in each knowledge area
  – Agents transmit known facts to other agents or websites
  – Agents build awareness by interacting with agents, websites
  – The receiving, sharing, and posting of facts is constrained by the network structure

• ABM environment: NetLogo

• Key Questions
  – How does the performance of the CC organization compare with that of the edge organization under various conditions?
  – How are the performance and situational understanding achieved by each affected by various factors, such as the rate and form of data distribution, the propensity to interact via 1-to-many websites, etc.?
  – Do these factors affect the organizations differently?
Organizational Types Considered

- Groups can only work on designated tasks
- Success achieved when CDR gains required level of situational awareness

- Each agent decides which task to work on based on knowledge level
- Success achieve when any agent gains required SA awareness
Parameters of Interest

- **Currently farmable**
  - Use of websites
  - Task difficulty
  - Frequency of fact distribution
  - Alignment of fact distribution with organizational structure
  - Propensity to share superfluous information

- **Effects to be considered this week**
  - Reliability of communications
  - Reliability of information internalization
  - Information overload
  - Information misclassification
  - Fidelity of message direction
  - Organizational/task scale
    - Number of facts, agents
    - Number of hierarchical layers
Agent Tasks and Task Execution (Hierarchical)

ClueNet Model

- distribute factoids
  - to whom?
  - how often?

Website B

- post factoid to website
- poll website for information

Agent B1

- Add factoid to list

Agent Bx

- Processes facts

Task Leader

- Standard B agent tasks
- Receive “noise” facts and send to CDR

Commander

- Achieves success upon accumulation of sufficient factoids
- to achieve knowledge threshold

facts required in each task for success

Do nothing

- how often?

web v. 1/1 interaction %

send & forget?

Other fact

task focus

B fact

site check order?

CDR post?

- how often?
Agent Tasks and Task Execution (Edge)

ClueNet Model

- distribute factoids
  - how often?

Website

- post factoid to appropriate website
- poll website for information

Agent

- Add factoid to list
- Decide which task on which to focus

A  B  C  D

Success achieved upon any agent’s accumulation of sufficient factoids to achieve knowledge threshold

- facts required in each task for success

Do nothing

- how often?

Agent Bx

- Processes facts

B task fact

• web v. 1/1 interaction %
  - randomly choose

• select an agent at random
  - send factoid

• B fact or random fact

• facts required in each task for success
Summaries (over replications)

<table>
<thead>
<tr>
<th>Moments</th>
<th>Mean(solution_time)</th>
<th>Moments</th>
<th>Mean(avg_understanding)</th>
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<tr>
<td>Mean</td>
<td>5078.6096</td>
<td>Mean</td>
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<td>Std Dev</td>
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<td>Std Dev</td>
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<td>Std Err Mean</td>
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<td>132</td>
<td>N</td>
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</table>

<table>
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<tr>
<th>Moments</th>
<th>Mean(solution_time)</th>
<th>Moments</th>
<th>Mean(avg_understanding)</th>
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<tr>
<td>Mean</td>
<td>224.25784</td>
<td>Mean</td>
<td>44.699342</td>
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<tr>
<td>Std Dev</td>
<td>151.08901</td>
<td>Std Dev</td>
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<td>Std Err Mean</td>
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<td>upper 95% Mean</td>
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**Summaries: a closer look**

### Moments

#### Mean(solution_time)
- Mean: 224.25784
- Std Dev: 151.08901
- Std Err: 13.15061
- Mean upper 95%: 250.27288
- Mean lower 95%: 198.24279
- N: 132

#### Mean(avg_understanding)
- Mean: 200.88737
- Std Dev: 274.14974
- Std Err: 33.7455
- Mean upper 95%: 268.28179
- Mean lower 95%: 133.49296
- N: 66

### Distributions

#### CC (ordered)

- Mean(solution_time): 224.25784
- Std Dev: 151.08901
- Std Err: 13.15061
- Mean upper 95%: 250.27288
- Mean lower 95%: 198.24279
- N: 132

#### edge

- Mean(solution_time): 250.27288
- Std Dev: 198.24279
- Std Err: 13.15061
- Mean upper 95%: 268.28179
- Mean lower 95%: 133.49296
- N: 132

*surprise!*
### Oneway Analysis of Av(adj_soln_time) By post method

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<thead>
<tr>
<th>Av(adj_soln_time)</th>
<th>intelligent</th>
<th>original</th>
<th>post method</th>
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</table>

Tukey-Kramer
0.05

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### Oneway Analysis of Av(av_understand) By post method

<table>
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<tr>
<th>Av(av_understand)</th>
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<th>original</th>
<th>post method</th>
</tr>
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<tbody>
<tr>
<td>20</td>
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<tr>
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<tr>
<td>70</td>
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</tbody>
</table>

Tukey-Kramer
0.05

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*surprise!*
Scatterplot Matrix

Multivariate

nothing_prob

_understandin

toids_every

ebpost_prob

adj_soln_time

av_understand
Edge: Av Solution Time (Regression Tree)

RSquare: 0.587
N: 132
Imputes: 0

post method/original:
- Count: 66
- Mean: 203.93182

post method/intelligent:
- Count: 66
- Mean: 794.09091

level_understanding<12:
- Count: 32
- Mean: 519.26771
- Std Dev: 447.22494

level_understanding>=12:
- Count: 34
- Mean: 1052.748
- Std Dev: 496.85905

do nothing_prob>=0.11:
- Count: 26
- Mean: 412.80385

level_understanding<16:
- Count: 24
- Mean: 948.19306

level_understanding>=16:
- Count: 10
- Mean: 1303.68

surprise!
Edge decision factors: Av Solution Time (Regression line)

- little ability to affect solution time
- no model fits well

Regression Plot

Summary of Fit
- RSquare: 0.362078
- RSquare Adj: 0.357171
- Root Mean Square Error: 394.6725
- Mean of Response: 499.0114
- Observations (or Sum Wgts): 132

Parameter Estimates
- Intercept: Estimate = 203.93182, Std Error = 48.58083, t Ratio = 4.20, Prob>|t| = <.0001
- intelligent posts: Estimate = 590.15909, Std Error = 68.70367, t Ratio = 8.59, Prob>|t| = <.0001
Edge: Avg Understanding (regression line)

- high correlation with required level of understanding
- even with this out of the model, nothing else matters

| Term                  | Estimate | Std Error | t Ratio | Prob>|t| |
|-----------------------|----------|-----------|---------|------|
| Intercept             | -1.873632| 0.565622  | -3.31   | 0.0012 |
| level_understanding    | 4.044495 | 0.047175  | 85.73   | <.0001 |
Next steps: Current activity

- Develop a combined Edge/CC model
- Explore space of alternate C2 structures
  - Capitalize on SAS-050 activity
    - C2 conceptual model
    - Description of key dimensions of C2
  - Examine fitness of various structures under different assumptions about task, interaction/decision rules and conditions, etc.
  - Gain insight into required capabilities for execution
    - Cognitive capabilities of individuals (task, team)
    - Potential contributions of technical enablers
- Inform development and execution of associated human experiments
  - Numerical experiments as an element of a campaign of experimentation
- This vignette is modeled after an experimental design developed by OASD/NII (US DOD)
  - A live experiment is planned for June 29, 2005
Special Thanks to:

Dr. Gary Horne, Director, Project Albert
Sarah Johnson, Mitre Corporation
Dr. Jimmie McEver, Evidence Based Research Inc.
NATO SAS-050 Members
Backups
Hierarchical Organization Setup Screen Shot

Central Commander

Website

Filter Agent with Fact and Designated Tasking

Color Key
Where
When
Who
What
Hierarchical, Command and Control Organization

<table>
<thead>
<tr>
<th>C2 Factors</th>
<th>Experimental Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hierarchical Decomposition</td>
<td>The C2 organization is divided into four separate teams of four all coordinated by a sole central coordinator (total of 17 agents)</td>
</tr>
<tr>
<td>Specialization</td>
<td>Each of the four teams in the C2 organization specialize in a different type of information</td>
</tr>
<tr>
<td>Team Leaders</td>
<td>Team leaders have &quot;special expertise&quot;. They begin with an additional fact</td>
</tr>
<tr>
<td>Information Hoarding</td>
<td>Each team's website is visible only to that team and the central coordinator, not to the other teams.</td>
</tr>
<tr>
<td>Fixed Leadership (Leadership by Position)</td>
<td>Subordinate agents can interact with their team members and team leader. The team leaders can communicate with the Central Coordinator.</td>
</tr>
<tr>
<td>Solution Identification</td>
<td>Information is passed up the network to the Central Coordinator. Only once the coordinator has achieved the appropriate knowledge level for each of the four tasks will the organization have achieved their goal.</td>
</tr>
</tbody>
</table>

Information Network Structure

```
A4 A2 A3 B1 B2 B3 C1 C2 C3 D1 D2 D3
```

```
A1
```

```
C5
```

```
B4
```

```
C4
```

```
D4
```

```
C5
```

```
A4
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```
A2
```

```
A3
```

```
B1
```

```
B2
```

```
B3
```

```
C1
```

```
C2
```

```
C3
```

```
D1
```

```
D2
```

```
D3
```
Fully Networked, Edge Organization

<table>
<thead>
<tr>
<th>Edge Factors</th>
<th>Experimental Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Networked Organization</td>
<td>Completely flat organizational structure, 17 agent peers</td>
</tr>
<tr>
<td>Information Sharing, Post/Pull</td>
<td>The team is visible. All four community of interest websites are shared and available to be posted to and polled by all agents. Each time step the agent must choose which of these websites to view.</td>
</tr>
<tr>
<td>Expert Agents</td>
<td>4 random agents begin with an additional fact .</td>
</tr>
<tr>
<td>Emergent Control</td>
<td>Instead of being given a designated task, agents are self-directed to work on their highest knowledge area at time t. Once an agent has solved one task he will focus on remaining tasks</td>
</tr>
<tr>
<td>Solution Identification</td>
<td>Information is passed any agent to any other agent in the network. Once one agent has achieved the appropriate knowledge level for each of the four tasks the organization has achieved their goal.</td>
</tr>
<tr>
<td>Universal Factors</td>
<td>Experimental Model</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Multiple types of information</td>
<td>There are four separate dimensions of information (who, what, where and when). These information bands are color coded in the model.</td>
</tr>
<tr>
<td>Factiods</td>
<td>There are 68 unique information facts, 17 factoids for each information band.</td>
</tr>
<tr>
<td>Initial information</td>
<td>Subjects start with 1 factoid. Expert agents start with 2 factiods (expert agents are the team leaders in the C2 organization and 4 random agents in the Edge Organization). The remaining information is dispersed to the agents at time intervals dictated by the user.</td>
</tr>
<tr>
<td>Individual Work</td>
<td>Each timestep, agents choose between sharing a fact from their knowledge base with another agent or posting it to the corresponding website. Only one fact may be shared per time step. Then an agent looks at a website, updating its knowledge with the list of facts posted.</td>
</tr>
</tbody>
</table>
The focus of interaction: share information, develop and share awareness, develop and share understandings, make decisions

**Quality of Interactions**

- Depth
- Breadth
- Intensity
- Agility

**Individual Characteristics**
- Risk Propensity
- Competence
- Trust
- Organizational Identification
- Confidence

**Organizational and Individual Behaviors**
- Cooperation
- Efficiency
- Synchronization
- Engagement
- Team vs. Task Balance

**Organizational Characteristics**
- Risk Propensity
- Competence
- Trust
- Confidence
- More...
Three objectives to scenarios modeled

- Get to goal at whatever cost (optimal path at shortest time, no consideration for losses; no maneuvering behaviors)
- Get to goal with minimal losses (maneuvering behaviors with consideration of friendly losses; time to complete mission not a major factor)
- Deplete enemy forces (from USMC Tactical Decision Game - execute major enemy losses; no established physical goal; no consideration for friendly losses except to have initial advantage in the fight)
Variables Considered

- Speed of movement
- Allegiance
- Stealth
- Sensor Range
- Detection Range
- Weapon Range
- Probability of Kill
- Mission Intent
- Comms Range
- Comms Capacity
- Comms Latency
- Comms Reliability
- Comms Accuracy

- Threat Persistence (Age of Information)
- Probability of Message Delivery
- Inorganic Information
- Collective Squad Information
- Individual Agent Information
- Line of Sight
- Movement Desire
- Mission Intent
- Terrain
- Elevation
- Number of Agents
Conceptual Model

- State (t)
- Individual Characteristics & Behaviors
- Team Characteristics & Behaviors
- C2 Approach
- Decision Making
- Actions

Information

Measures of Effectiveness

Measures of Agility
A NATO study panel

New Approaches: Not “What we do” or “How we do it”

Point of Departure: How could we accomplish the functions we associate with C2?
- Command Functions: Intent, Roles and Responsibilities, Resource Allocation
- Control: Recognize and Respond to Changes, within bounds established by command

C2 Approach = point/region in a space of possibilities
- Delegation of Decision Rights
- Patterns of Interaction: Social domain
- Patterns of Interaction: Information Domain
Data Characterization and Analysis

- NPS design of experiments methodology employed
  - CC: 9 parameters farmed
  - Edge: 6 parameters farmed
  - 132 parameter combinations specified with crossed Nearly Orthogonal Latin Hypercube and factorial designs
  - 30 replications per combination
  - 7920 total model runs (theoretically)