Informing Joint C2 System-of-Systems Engineering with Agent-Based Modeling: An Analysis and Case Study

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System of Systems (SoS) Definition

- No accepted definition for SoS or SoSE
- Greater than 40 distinct definitions in authoritative open source publications [1]
- System of Systems (SoS) Definition (DoD):
  - Arrangement of interdependent systems connected to provide a capability greater than sum of the member systems
  - Definition is augmented by characteristics
- Family of Systems (FoS) Definition (DoD):
  - Capability is summation of member systems
  - Grouping of systems with common characteristics
  - Does not acquire new properties or capabilities as a result of grouping
[http://akss.dau.mil/dag/Guidebook/IG_c4.2.6.asp]

2006 IEEE International Conference on System of Systems Engineering, Los Angeles, CA.
Systems Engineering for Large Scale System of Systems

- A Department of Defense perspective....

- Autonomous, semi-autonomous, and stand-alone systems
- Legacy systems
- Coalition systems
- Omnipresent protocols
# Systems Engineering vs. System of Systems Engineering

<table>
<thead>
<tr>
<th>Systems Engineering</th>
<th>SoSE</th>
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<tbody>
<tr>
<td><strong>Scope</strong></td>
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<tr>
<td>- Project/Product</td>
<td>- Enterprise/Capability</td>
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<tr>
<td>- Autonomous, well-bounded</td>
<td>- Interdependent</td>
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<tr>
<td><strong>Objective</strong></td>
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<tr>
<td>- Enable fulfillment of requirements</td>
<td>- Enable evolving capability</td>
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<td>- Structured project process</td>
<td>- Guide integrated portfolio</td>
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<td><strong>Timeframe</strong></td>
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<tr>
<td>- System Life Cycle</td>
<td>- Multiple, Interacting system life-cycles</td>
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<td>- Discrete beginning and end</td>
<td>- Amorphous beginning</td>
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<tr>
<td><strong>Organization</strong></td>
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<tr>
<td>- Unified and authoritative</td>
<td>- Important history &amp; precursors</td>
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<tr>
<td><strong>Development</strong></td>
<td></td>
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<tr>
<td>- Design follows requirements</td>
<td>- Collaborative network</td>
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<td><strong>Verification</strong></td>
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<tr>
<td>- System in network context</td>
<td>- Design is likely legacy-constrained</td>
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<td>- One time, final event</td>
<td>- Ensemble as a whole</td>
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<td>- Continuous, iterative</td>
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Source: Systems of Systems Center of Excellence
Network Centric SoS Example
Require Syntactic and Semantic Interoperability

Combat Identification (CID)
- Long Range
- Wide Area
- Improve Shooter Confidence

Integrated Fire Control (IFC)
- Employ independent of organic radar
- Overcome Radar Horizon Limitation

Single Integrated Air Picture (SIAP)
- Common and Complete Pictures
- One Track per Air Object
- Continuous Track

Automated Battle Management Aids (ABMA)
- Determine Optimum Weapons and Sensors
- Efficient Weapon and Sensor Management

Autonomous and Interdependent Systems To Form Holistic Capabilities
Traditional analysis

- Unbounded
- Solutions reflect modelers bias
- Could be worse than doing nothing since their impression is built that effort expended is productive
Need to expand the scientific and engineering basis for the development of software that is surprise free.

Validation of theoretical research principles.

Relate research to real world applications
  – That will provide understanding about which architectural approaches work the best
Conclusion

- These metrics may be a first in quantifying the effectiveness of systems engineering and software engineering.
- It will provide a baseline to measure future applied research projects
- Paper will be prepared to submit to Systems Engineering, the Journal of the International Council Of Systems Engineers (INCOSE)
CCID-CRA ABM Overview
ABM CCID-CRA Model Basics:
Simulation Setting / Ground Truth

■ Agents have attributes specifying their ground truth status
  - Allegiance: FRIEND, NEUTRAL, or FOE
    (Blue, White, or Red, respectively)
  - Nationality: FRNAT1, FRNAT2, NUNAT3,
    NUNAT4, FONAT5 or FONAT6
  - Type:
    ■ Air: JSF, E-2C, F6, etc.
    ■ Surface: CVN, DDG, LCS, FFG, etc.
    ■ Subsurface: Kilo, SSG, SSK, etc.

■ Agent populations specified on a per-agent basis
  - 11 Agent sets defined for two run matrices

■ Speed and Movement
  - Agents have a specified min and max speed range
  - Agents, upon creation, have a random heading
    (static) and are assigned a random speed value
    within their range
  - Agents move in a straight line at constant speed
ABM CCID-CRA Model Basics: Two Communicating Blue Nodes (I)

- Consider two blue agents, “A1” and “A2”, not within mutual sensor range, but have one sensed object in common

- A1 and A2 will detect objects in their range and produce tracks according to their sensor mix (previous example)

- Design Simplification: All agents share track numbers, and these are 100% reliable. Thus, we do not do any real track correlation (we have a simplistic “fusion”)

![Diagram of two communicating blue nodes A1 and A2 with sensed objects 75, 16, and 17]
A track report has the following syntax:

- \([ \text{track\_ID} \ \text{a\_sens\_contrib} \ \text{n\_sens\_contrib} \ \text{t\_sense\_contrib} \ \text{sci\_flag} ]\)

  - Where:
    - \text{track\_ID} is “who” number (natural)
    - \text{a\_sens\_contrib} is Allegiance sensor contribution (float)
    - \text{n\_sens\_contrib} is Nationality sensor contribution (float)
    - \text{t\_sense\_contrib} is Type sensor contribution (float)

A1 and A2 might produce track reports for object 16 such as:

- \([ 16 \ 2.09 \ 2.06 \ 1.48 ]\)
- \([ 16 \ 0.87 \ 0.25 \ 0.78 ]\)
CCID Network Communications Model (IABM model)

- BLUE organic track lists
- BLUE track data communications delay queue
- Integrate BLUE organic and non-organic track data
- BLUE organic CRA reports
- BLUE CRA report delay queue
- Integrate BLUE organic and non-organic CRA reports
ABM CCID-CRA Study

- Allows rapid examination of various CCID-CRA communications architectures
  - Dynamic Network Communications and Information Awareness
    - Captures dynamics of real-world network reconfigurations
    - Allows agents (ships) to exhibit new tactics
    - Allows observation and study of emergent behaviors of agents based upon changes within the operating environment (from both internal and external forces)
  - Provides faster, more reliable analysis of dynamic networks
    - Analysis is scenario independent
    - No need to model specific network configurations -- Dynamic network evolves naturally
  - Explicitly models ship awareness and communications links

- CCID-CRA ABM addresses three questions
  - What is the best strategy to synchronize (mitigate conflicts) between CRA nodes?
  - How do communication delays affect the overall performance?
ABM Experimentation Plan

- **ABM**
  - Vary number of contacts, maximum delay time, and arbitration scheme
  - Baseline Run
    - Multiple ships operating with no final CRA arbitration
    - Expected results: Excessive number of IDs for the same “ground truth” track
  - Arbitration Scheme Runs
    - Determine best arbitration scheme (based upon lowest average number of consensus groups per track)
    - Expected results: Compared to baseline, lower number of IDs for the same “ground truth” track
  - Overall expectation: Higher communications delays produce more IDs for the same track
CCID Network Communications Model (IABM model)

BLUE organic track lists

BLUE track data communications delay queue

Integrate BLUE organic and non-organic track data

BLUE organic CRA reports

BLUE CRA report delay queue

Integrate BLUE organic and non-organic CRA reports
Constraints and Simulation Needs

**Constraints**
- No Existing Operational IABM Architecture
- No multi-platform CRA baseline exists for comparison purposes
- CRA source code within LM exists only in a classified environment

**Simulation Needs**
- Establish baseline for comparison
- Multi-tier Simulation
  - Asses unknown factors at different levels of fidelity
  - Capture the effects of communication systems
    - Effects of bandwidth availability (link connectivity)
    - Effects of Transmitted Data Pedigree
      - Ex. Peer-to-Peer connections transmit more info than Link 16
  - Test scalability of proposed multi-platform CRA
  - Ability to test multiple scenarios under varying conditions
  - Capture the effects of the presence of SCI level information
Experimentation Plan (1 of 2)

ABM used to recommend “best” architecture

■ Preliminary Investigation using Agent-Based Models (ABMs)
  – Enables validation of proposed system architectures
    ■ Allows experimental validation of an architecture under varying, unforeseen conditions
  – Models Dynamic Network Communications and Information Awareness
    ■ Captures dynamics of real-world network configurations
    ■ Allows platforms to execute new ID declaration rules
  – Enables rapid execution of multiple scenarios
  – Explicitly models ship awareness, communication system throughputs
  – Allows for analysis of CRA network architecture (independent, localized, distributed, etc.)

■ Expected Results
  – Recommends the “best” CRA deployment architecture
  – Provides input to CONOPS
  – Recommends best ID declaration rule(s)
ABM CCID-CRA Model Basics: Model of Time (I)

- Blue Agents must transmit track reports and CRA reports (based on those tracks) to each other

- We assume an “IABM” environment
  - Platform Sensors are disjoint from IABM comms
  - “Full Mesh” comms are used; no limit on with whom an agent can communicate
    - All blue forces participate in track report origination
    - Only blue surface agents participate in track sharing, track fusion, CRA report origination, CRA report sharing, and CRA report arbitration
    - \([\frac{n(n-1)}{2}]\) links, \(n = \) blue surface count

- Despite IABM we want “some” delay in communications
  - Model the effect of arbitration on multiple CRA reports for the same track received over time
  - Need a “lightweight” delay model
ABM CCID-CRA Model Basics: Model of Time (II)

- “Time driven”, but no built-in time unit is defined
  - Model execution occurs in “ticks”

- One “tick” is one iteration of the model
  - Of course, finer granularity of time means longer processing
    - Our model has 1 tick = 10s, 5s, 1s, 0.1s
    - OR ticks-per-hour = 360, 720, 3600, 36000, respectively
A preliminary CRA report has the following syntax:

- $[\text{<track_ID>} \text{<allg>} \text{<allg}_b\text{v}> \text{<natl>} \text{<natl}_b\text{v}> \text{<type>} \text{<type}_b\text{v}> \text{<sci_flag>}]$

  Where:
  
  - $\text{<track_ID>}$ is “who” number (natural)
  - $\text{<allg>}$ is Allegiance recommendation (“enumerated”) (similarly for natl = Nationality, and Type)
  - $\text{<allg}_b\text{v}>$ is Allegiance recommendation belief value (float) (similarly for natl = Nationality, and Type)

- Example:
  
  - $[3 \text{ FOE 0.579 FONAT5 0.7071 DDG 0.5322}]$
CRA Belief Value (BV) computation
- We needed a lightweight way of having $BV = f(\text{sensor mix})$
- $BV$ is supposed to represent probability, so $BV$s should asymptotically approach 1
- Sensor mix contributions range:
  - Low end: 0.1
  - High end: 4.4
- We use the following equation, arrived at by trial-and-error:

$$BV = 1 - e^{-\left(\frac{\text{sensor-mix-contribution}}{0.85}\right)^5}$$

- The curve for this eqn looks like:
Simulation Run Matrices
Run Matrices - Overview

- **Macroscopic parameters set for all runs:**
  - Due to processing time constraints, time granularity of 1 tick = 10s is used (360 ticks / hour of model time)
  - Random seed is fixed at 74
  - One run of each configuration (parameter mix below)

- **Varying parameters:**
  - Agent population mix ("Breed Data")
  - Time Delay: 0s, 10s, 60s, 120s (0, 1, 6, and 12 ticks)
  - Arbitration Scheme ("Majority Voting", "Maximum", "Naïve Bayesian", "Weighted Bayesian")
Metrics
Consensus Group Metrics (I)

- **Average Number of Consensus Groups**
  - At the end of each iteration, the number of consensus groups for each track is tallied.
  - These counts are appended to a cumulative global list.
  - At the end of the run, the average of this cumulative global list is computed. This is the Average Number of Consensus Groups metric.
  - Example:
    - The global list might typically look like:
      \[
      [2 \ 1 \ 3 \ 2 \ 1 \ 2 \ 2 \ 4 \ ... \ 3 \ 7 \ 3 \ 6 \ 2 \ 6]
      \] (length usually thousands)
    - The average of this list might be “2.78”

- **Note:**
  - For a time delay of 0, the average number of consensus groups is always 1 (i.e. the ideal case).
Consensus Group Metrics (II)

**Maximum Number of Consensus Groups**
- We comb the same cumulative global list used to calculate the Average Number of Consensus Groups to find the maximum number therein. This is the Maximum Number of Consensus Groups metric.
- Example:
  - The global list might typically look like: 
  
    [ 2 1 3 2 1 2 2 4 ... 3 7 3 6 2 6 ] (length usually thousands)
  
  - Ignoring what might be hiding in the ellipsis, this run’s Maximum Number of Consensus Groups is 7.

**Notes:**
- Same geometric comment as for Average applies here
Correctness Metrics (I)

- **Disclaimer**
  - Without the real CRA in play, “correctness” metrics are dubious
  - Much “tweaking” of calculation details was involved

- **At iteration end, each final CRA report is compared to the Ground Truth of the represented track and scored as follows:**
  - **Overall correctness:**
    - For each CCID attribute correct, the report receives a “1”
    - These sum to the report’s overall score (0 to 3)
    - This score is appended to a global cumulative list:
      
      \[
      [ 0 0 2 0 1 3 2 2 3 3 3 \ldots ]
      \]
  - **Allegiance, Nationality, and Type:**
    - We score a “1” if the attribute is correct, “0” otherwise
    - We append the score to a global cumulative list:
      
      \[
      [ 0 0 1 0 1 1 0 0 1 1 \ldots ]
      \]
    - One list per CCID attribute
Correctness Metrics (II)

End-of-Run Scoring Calculations:

- Overall Correctness:
  - The overall correctness for the entire run is computed as:
    \[
    Correctness = \frac{\sum (Score_n)}{3 \cdot n}
    \]
    where \( Score_n \) represents values in the cumulative global CRA score list mentioned previously. The “3” in the denominator is there because there are three CCID attributes in a CRA report.

- Individual CCID Attribute Correctness:
  - Each is similarly computed using the corresponding cumulative global list, in the Allegiance case, for example, as:
    \[
    Correctness_{\text{Allegiance}} = \overline{Score_{\text{Allegiance}}_n}
    \]
    where the average is over the attribute’s cumulative global list.

Note:
- The correctness metrics just described are reported as percentages
Conclusions

There are obvious trade-offs between correctness and the number of consensus groups.

- Majority Voting creates the largest number of consensus groups (lends to the most confusion) but has good correctness.
- Maximum has the lowest number of consensus groups but the worst correctness.
- Weighted and Naïve Bayesian show both good correctness and good agreement (small number of consensus groups).