SoSECIE Webinar

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2021 System of Systems Engineering Collaborators
Information Exchange (SoSECIE)

National Defense Industrial Association

We will start at 11AM Eastern Time

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NDIA System of Systems SE Committee

- **Mission**
  - To provide a forum where government, industry, and academia can share lessons learned, promote best practices, address issues, and advocate systems engineering for Systems of Systems (SoS)
  - To identify successful strategies for applying systems engineering principles to systems engineering of SoS
- **Operating Practices**
  - Face to face and virtual SoS Committee meetings are held in conjunction with NDIA SE Division meetings that occur in February, April, June, and August

NDIA SE Division SoS Committee Industry Chairs:
Mr. Rick Poel, Boeing
Ms. Jennie Horne, Raytheon
OSD Liaison:
Dr. Judith Dahmann, MITRE

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- If you need to contact me during the briefing, send me an e-mail at sosecie@mitre.org.
- Download the presentation so you can follow along on your own
- We will hold all questions until the end:
  - I will start with questions submitted online via the CHAT window in Teams.
  - I will then take questions via telephone; State your name, organization, and question clearly.
- If a question requires more discussion, the speaker(s) contact info is in the brief.

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2022 System of Systems Engineering Collaborators Information Exchange Webinars

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January 25, 2022
Applying SoSE in Healthcare: the case for a soft systems methodology approach to Digital-first Primary Care
Iqra Shahzad, Melanie King, and Michael Henshaw

February 8, 2022
Empowering Adaptive Human Autonomy Collaboration (DUAL) with Artificial Intelligence
Dr. Mark Chattington

February 22, 2022
System of Systems Engineering Conference (SoSE) and Industry Perspectives and the Role of SoSE: INCOSE and IEEE Collaborations
Paul Hershey, Garry Roedler, and Mo Jamshidi

March 8, 2022
An Event-based Microservice Platform for Autonomous Cyber-Physical Systems: the case of Smart Farming
Mara Nikolaidou

March 22, 2022
Mission Engineering Digital Ecosystem
Owen Eslinger

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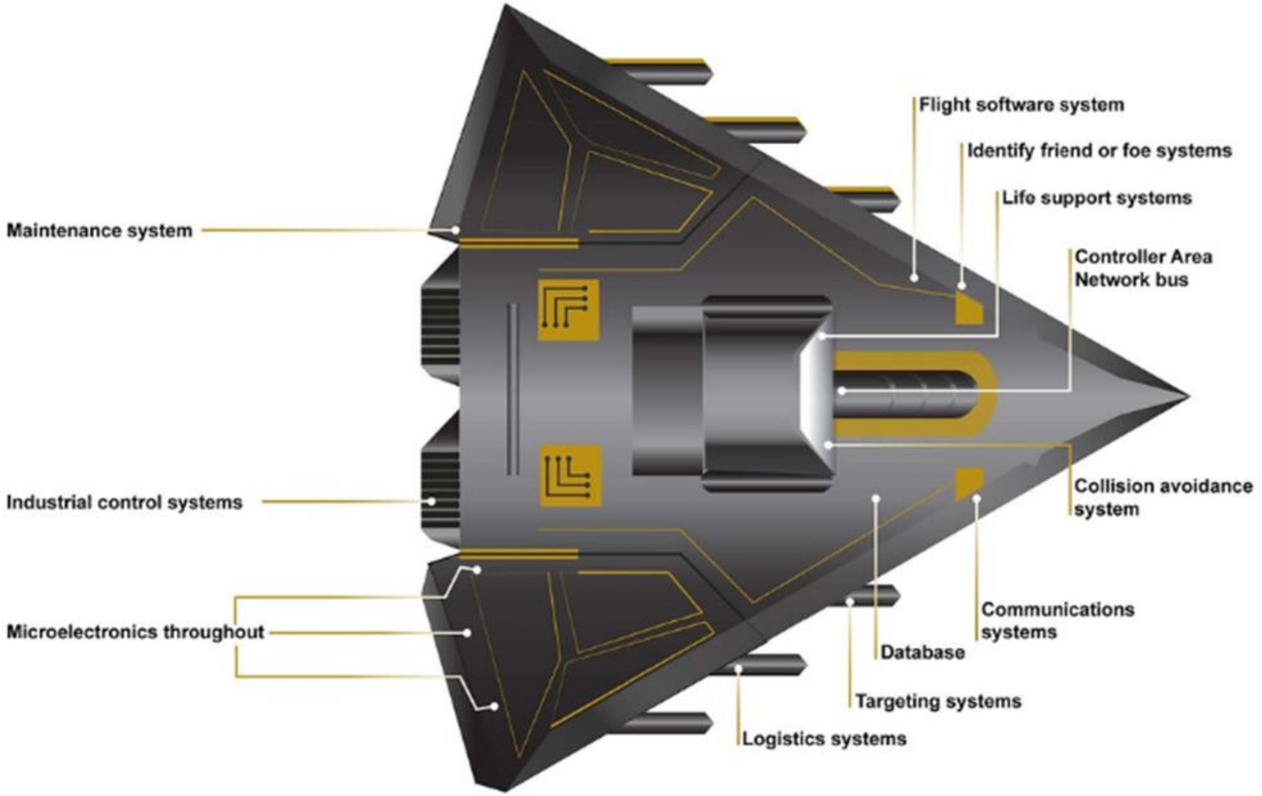
System of Systems Engineering Approach for Complex Deterministic and Nondeterministic Systems (ACDANS)

Paul Hershey, Ph.D.

January 11, 2022

Problem

- As new commercial and military systems evolve to support challenges of ever-increasing complexity, System of Systems Engineering (SoSE) must likewise evolved to support complex architectures and designs.
- This paper presents a SoSE Approach for Complex Deterministic and Nondeterministic Systems (ACDANS) to address some of these challenges.
  - Describes possible Modeling and Simulation (M&S)-based solutions for three presently unresolved, complexity-related SoSE problems:
    1. How to model and build a reliable SoS if many of the systems are either deterministic or non-deterministic
    2. How to apply Machine Learning (ML) to support such systems
    3. How to model and build these systems at scale in an era of Internet Battlefield of Things, particularly with open architectures and legacy components, including cyber physical systems

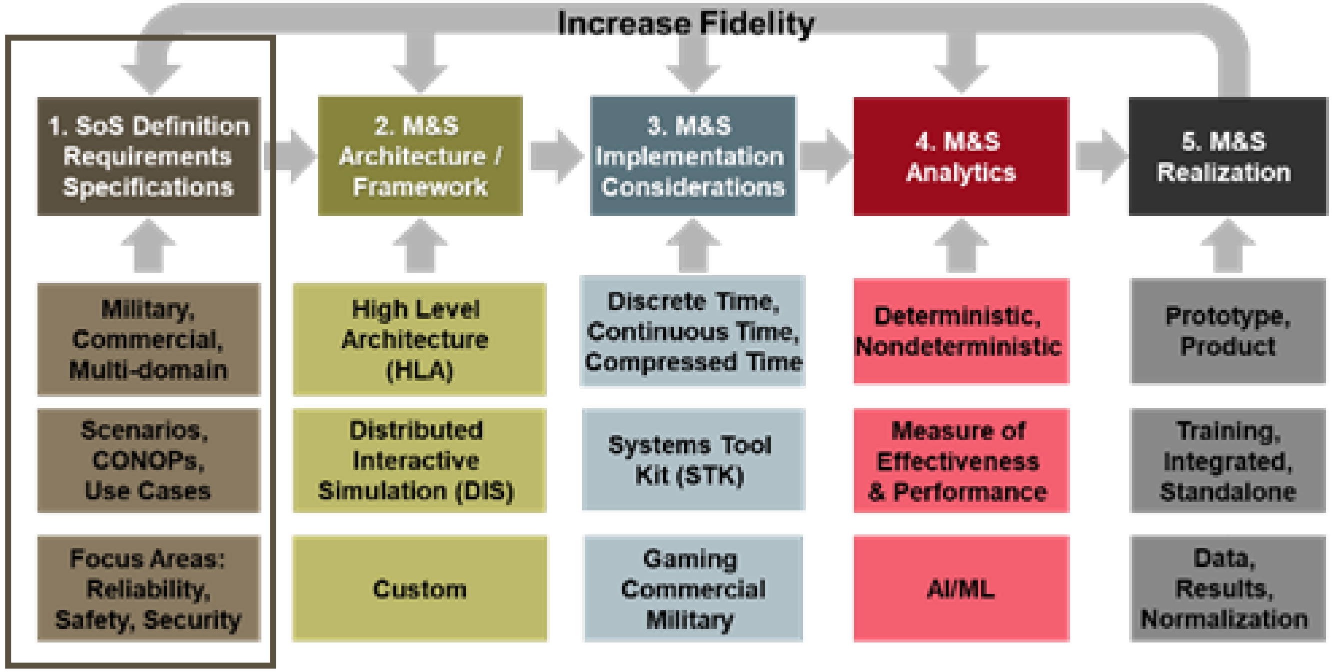


Prior Approaches and Related Works

- Beautement presents an approach for exploiting the capabilities of highly interconnected, heterogeneous, ever-changing SoS that comprise complex military operational environments.
  - Observes that the battlespace is everywhere and that absolutely any system or SoS is potentially a weapon.
  - Discusses equivalent mechanisms for cyberspace that indicate how run-time behaviors can augment activities in the real world to enable adaptation to unexpected events in military operations.
- The Guide to Modelling & Simulation (M&S) for NATO Network-Enabled Capability (“M&S for NNEC”) describes an international, complex, adaptive SoS environment that contains numerous agents that interact within diplomatic, social, economic, and military domains.
  - Describes SoS models as abstractions that reduce complexity of a system to enable a better understanding of the specific aspects of interest and their impact on performance.
  - Combines modeling with simulation to create an enabler to provide a low risk and low consequence of failure environment that simplifies complexity of adaptive environments.
- Leveson points out that as system complexity increases, so do problems associated with safety and reliability
  - Considers computers and software as part of nearly every major complex system in the world, and therefore applies principles and techniques from system safety engineering to these systems.
  - Shows that assurance of reliability is essential for the adoption of complex systems into military and commercial applications.

- Lee and others identify security as another critical factor for complex SoSE
  - Describes cyber-physical systems interfaces with computer systems through physical processes.
  - Validates that when computer systems are coupled with physical systems, a broader attack area exists than for pure computer systems, therefore complexity is reduced for security and safety threats.

Approach – ACDANS Step 1



ACDANS Step-by-Step Approach Flow Diagram

- **Problem definition, requirements, and specifications**
  - Research to consider prior approaches,
    - Commercial and military capabilities
    - Programs that could be integrated to solve a portion of the problem.
    - Interviews with Subject Matter Experts (SMEs) from which to compose scenarios, Concepts of Operations (CONOPs), **Use Cases**, and possible Courses of Action (COAs)
  - As research progresses, specific focus areas emerge to better solve the problem.
    - Example Areas: safety, reliability, and security
    - Continuous feedback increase fidelity of results

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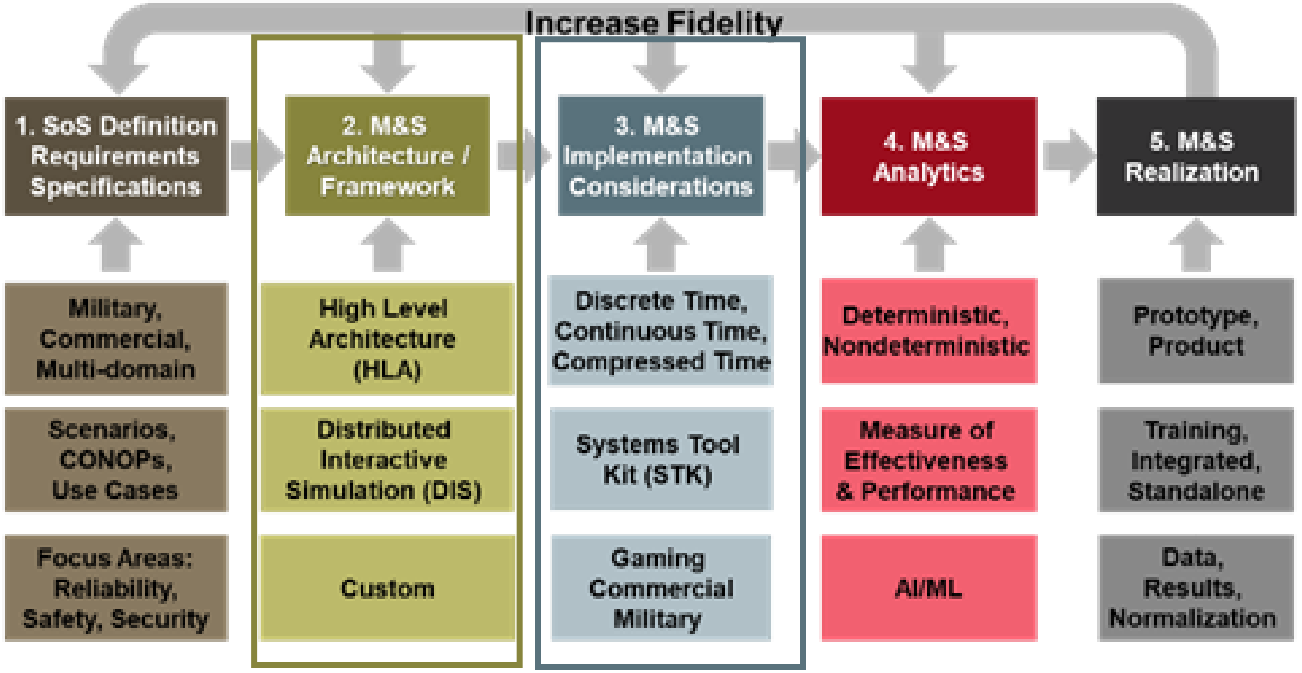
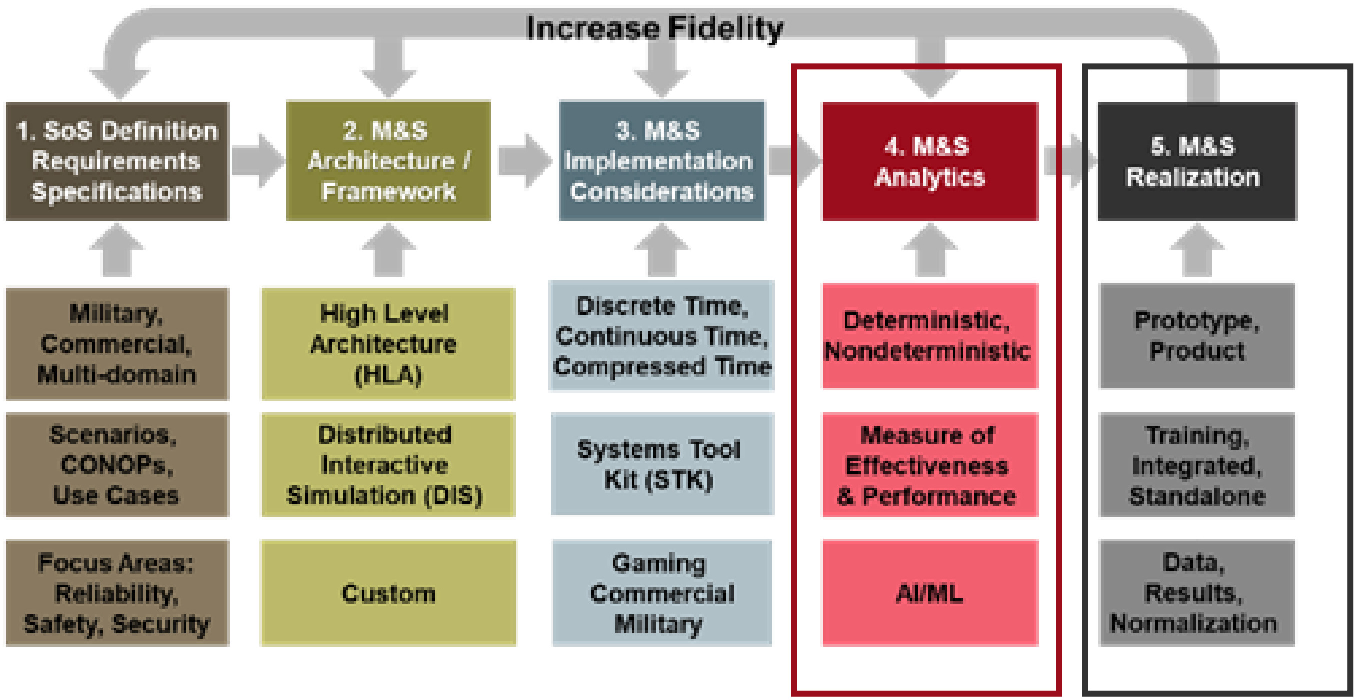
Approach – ACDANS Steps 2 and 3



ACDANS Step-by-Step Approach Flow Diagram

- **Step 2: Selection of the M&S architecture and framework**
  - Depending on the specified SoS, this selection could be:
    - Standards-based:
      - High Level Architecture (HLA)
      - Distributed Interactive Simulation (DIS)
    - Custom
- **Step 3: M&S implementation Considerations**
  - Can the SoS be represented in the simulation using discrete time, compressed time or continuous time simulations.
  - Can the M&S be implemented and provided to end-users as a development tool
    - Example: Systems Tool Kit
    - Example: Gaming or strategy capability, such as a wargame.

Approach – ACDANS Steps 4 and 5



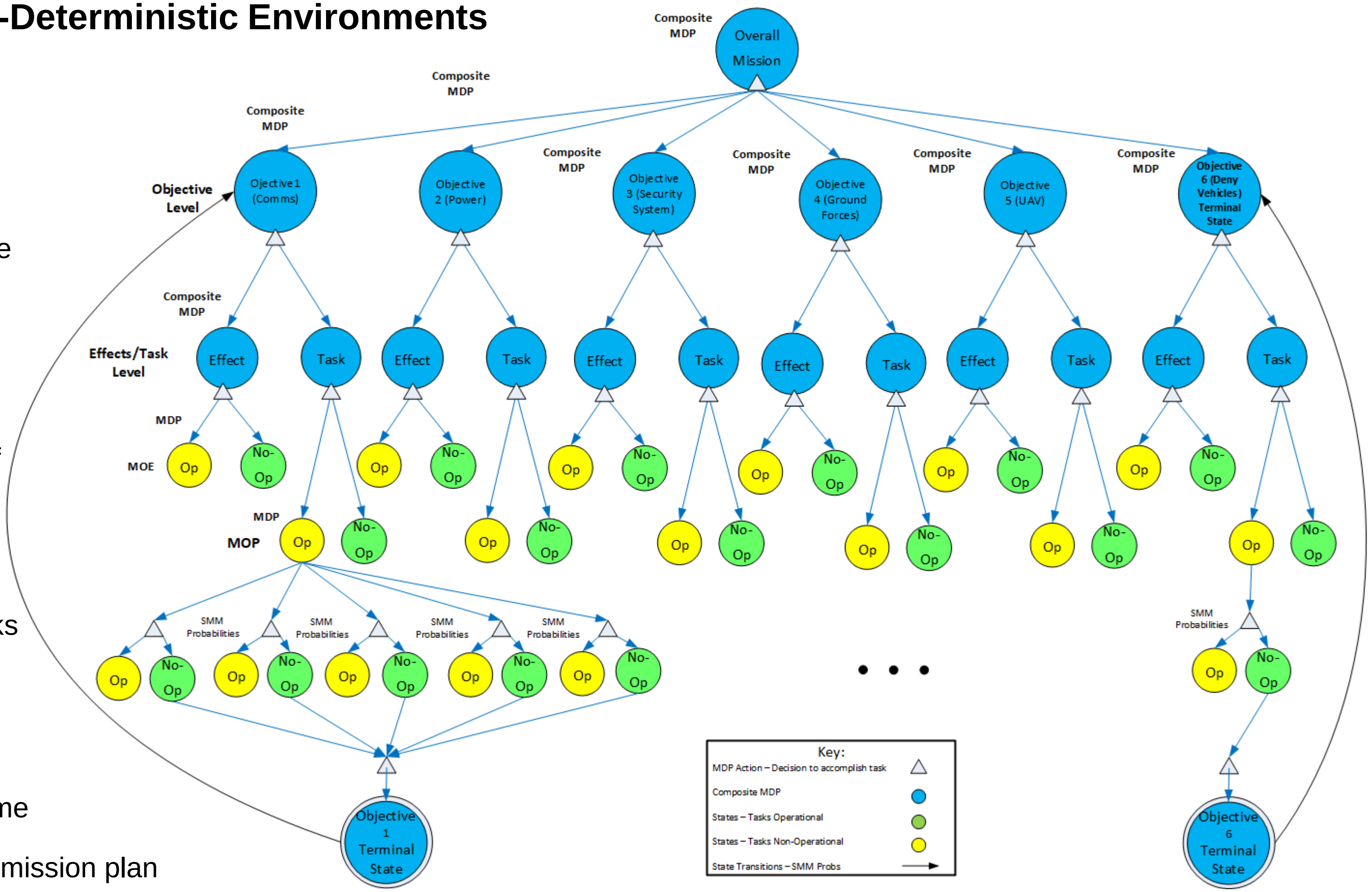
ACDANS Step-by-Step Approach Flow Diagram

- **Step 4: M&S Analytics**
  - Examination of mathematical functions / algorithms that characterize use cases and associated entities and assets
  - Application of deterministic and non-deterministic analysis
  - Derivation of mathematical algorithms into which data from multiple, diverse sources (e.g. multi-intelligence sensors) can be ingested
  - Compute Measures of Effectiveness (MOEs) and Measures of Performance (MOPs)
  - Introduction of Artificial Intelligence (AI) and Machine Learning (ML) to increase the level of autonomy
- **Step 5: M&S Realization**
  - Realization and application of SoS M&S capability to support defined uses cases
  - Extension of original concept to create prototype for a single system
  - Evolution of single system to a complex SoS product
    - Integrate a set of M&S models for which data results are normalized (i.e., may be combined with same numerical scale and ontological characteristics)
    - Product may be used by itself (standalone) or integrated with other SoS products
      - Operational (e.g., for a mission) environment
      - Training environment

Use Cases - Problem 1: How to model and build a reliable SoS if subsystems are non-deterministic

Use Case 1: Markov Decision Processes (MDPs) for Non-Deterministic Environments

- Step 1: assume a military mission
- Step 2: Assume a custom M&S framework.
- Step 3: Assume a discrete time, wargaming M&S implementation.
- Step 4: M&S Support for Analysis
  - – Represent mission as a non-deterministic SoS comprising cooperative multiple agents, where each agent is a subsystem
  - – First challenge is to coordinate the learned behavioral strategies of multiple subsystems
    - Cooperative agents can be modeled as agents working towards a common goal
  - – Second challenge: escalating computational complexity as number of interacting agents increases along with the corresponding number of mission tasks
    - ACDANS applies MDPs to addresses this complexity problem
      - – Represents tasks of mission as a non-deterministic state machines in which both expected and unexpected mission tasks are distinct states.
      - – Applies MDPs to determine all possible state transitions
      - – Stochastic Mathematical Model (SMM) to compute transition probabilities for each sequential task
      - – Concludes with computation of overall mission success over time



- Figure: notional MDP representation of the tasks of an end-to-end mission plan
  - – Tasks are hierarchical, beginning with the overall mission, from which a composite MDP is created to transition to next lower level, objective level.
  - – Additional composite MDPs are created for mission objectives (e.g., Security Systems)
  - – Composite MDPs again transition to next level of composite MDPs that include effects (e.g., weapons) and associated tasks
  - – Next level computes Measures of Effectiveness (MOEs) and Measures of Performance (MOPs)

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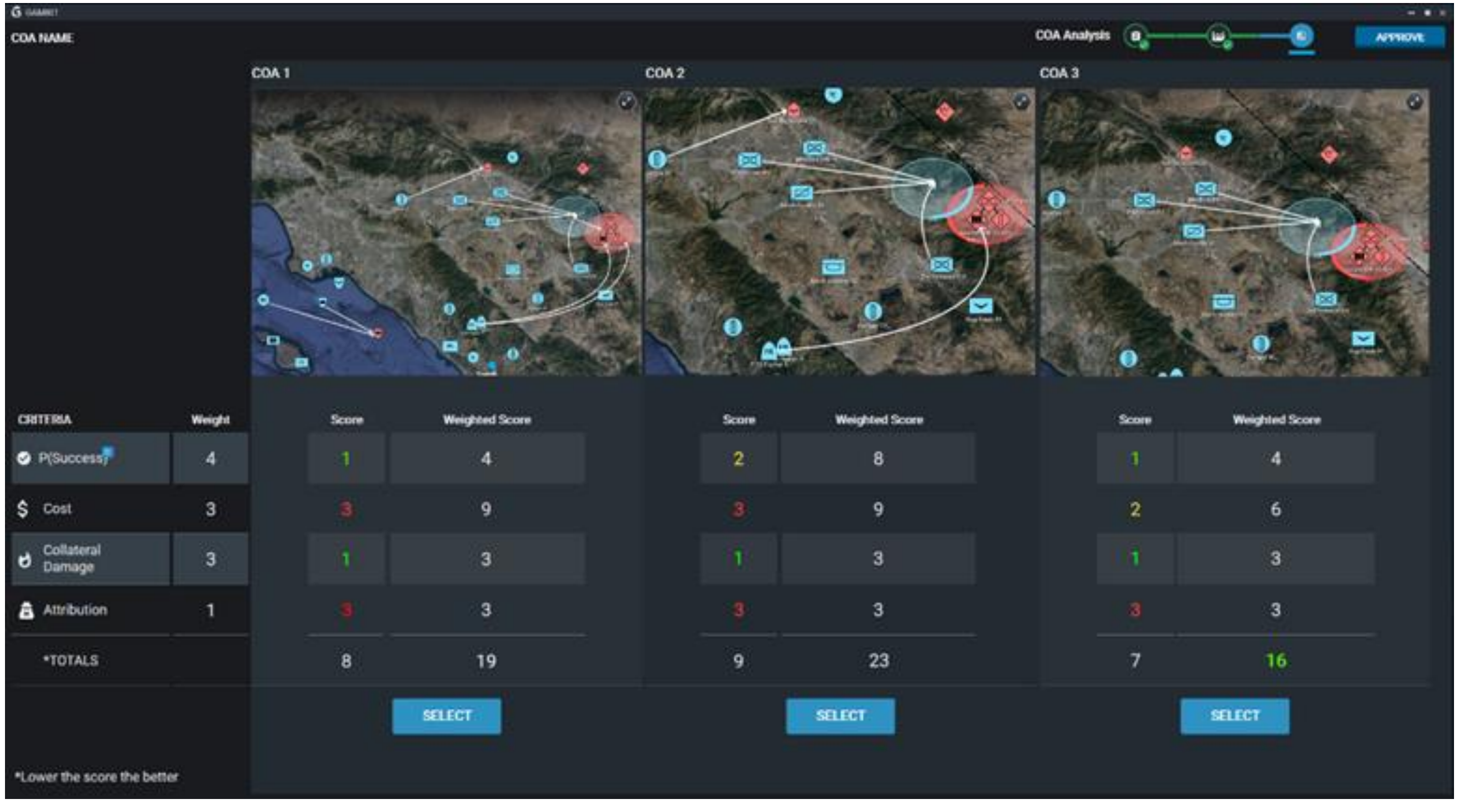
Use Cases - Problem 1 (continued): How to model and build a reliable SoS if subsystems are non-deterministic

– Step 5: M&S prototype realization

- Generates MOEs and MOPs (Psuccess, Cost, Collateral Damage, Attribution) with Confidence Interval results for three alternative mission plans (i.e., Courses of Action (COAs))
  - Figure compares selected COA results with respect to meeting commander's criteria
  - Each COA score was a weighted score that helped determine if revised COA resulted in a better plan
  - COAs 2 and 3 were revised as the battlefield environment dynamically changed during the simulated battle
  - Results showed that COA 3 best improved the overall mission success for the metrics considered

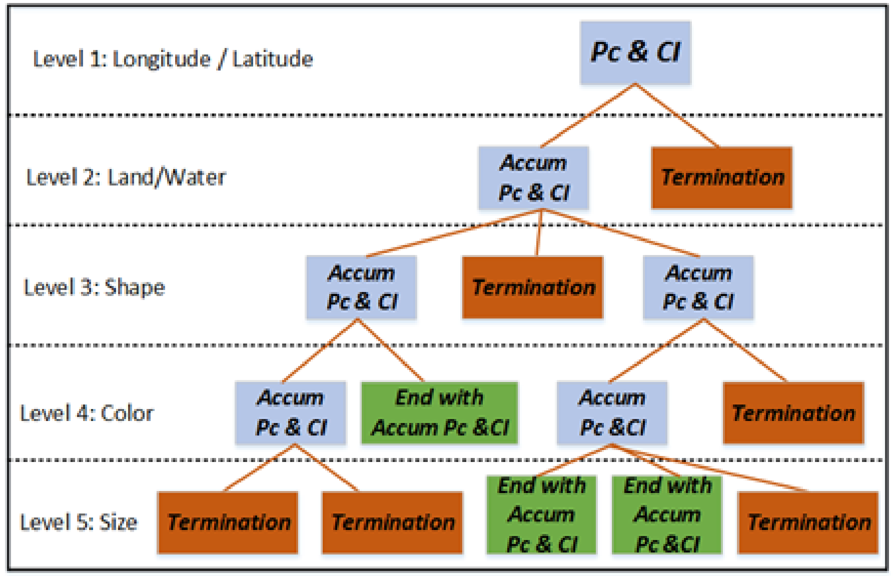


COA Results and Comparison

Use Cases - Problem 2: How to apply Machine Learning (ML) to Support M&S for SoS

- **Use Case 5: Object Recognition and Detection Enhancement via Reinforcement Learning Yield (ORDERLY)**
  - Step 1: Assume a commercial environment
  - Step 2: Assume a custom M&S framework
  - Step 3: Assume a compressed-time commercial environment
  - Step 4: M&S Support for Analysis
    - Use deterministic state machines and Reinforcement Learning (RL)
    - ORDERLY autonomously screens massive collections of sensor data from multiple and diverse data sources in order to transform raw data into actionable information
      - Uses algorithm chaining to concatenate the most relevant algorithms for efficient data analysis
      - Uses SMM to compute Probability of Correctness (Pc) and the associated Confidence Interval (CI)
        - Whether or not an algorithm correctly recognizes that an image contains the objects of interest
    - Figure: Hierarchical levels that correspond to increasing levels of fidelity in the algorithm chain
      - Compares reference algorithm Pc and CI results in algorithm chain at each level and then selects those algorithms with the highest Pc and CI.
      - Responds to dynamic changes in mission objectives, e.g., changes in types of objects to be recognized and detected, using Reinforcement Learning (RL)
        - Enables an agent (e.g., a processing node) to learn by interacting with its environment (i.e., images to be processed)
        - Provides a reward (“feedback”) signal. Agents learn by doing, hence learn by trial and error.
        - Basic ORDERLY RL model we apply is defined as follows:

          1. State Space: Two state values: 1-Pc and CI below threshold or not
          2. Actions: All possible choices of algorithms designed to classify the object and which will improve the values of 1-Pc and CI.
          3. Reward: Difference between a target (1-Pc, CI) threshold and the pair of values expected to be obtained after application of each algorithm
          4. Q-learning process: Through trial and error, learn how each possible algorithm choice decreases or increases the cumulative reward
  - Step 5: ORDERLY was realized in an M&S prototype
    - Results achieved processing time reduction and improved analyst time from image ingestion to actionable intelligence by 33%



ORDERLY Hierarchical Structure

Use Cases - Problem 3: How to model and build secure systems at scale in an era of Internet Battlefield of Things particularly with open architectures and legacy components

- **Use Case 6: Modeling Secure, Reliable, Safety-Critical Systems**
  - Step 1: Assume secure, reliable, and safety-critical civilian and multi-domain military systems
    - Examples: medical systems, energy and power systems, transportation systems, chemical and hazardous material systems, industrial process systems, and air-, land-, and sea-based military systems
  - Step 2: Assume a custom architecture and framework
  - Step 3: Assume gaming implementation environment
    - Figure: multi-domain Red Force / Blue Force wargame
  - Step 4: M&S Support for Analysis
    - Analyze each entity and asset in Figure with respect security based on its respective Cyber-Physical System (CPS)
      - Each CPS interfaces with computer systems through physical processes that provide broad attack area for security and safety threats
      - For all subsystems, safety and reliability of each entity and asset are analyzed based on adherence to safety-critical and reliability system standards
    - Provide feedback to Step 1 so that subsequent model development applies standards to improve both safety and reliability
  - Step 5: Use case was realized in an operational prototype

Red Force – Blue Force Wargame

Conclusions and Areas for Future Work

- This paper presented a new System of Systems Engineering Approach for Complex Deterministic and Nondeterministic Subsystems (ACDANS)
- Through uses cases, this paper illustrated how ACDANS could be used to address three topics relevant to Modeling and Simulation of SoS
  - Use case 1 described a discrete-time M&S implementation for a cooperative multi-agent SoS that operated within a non-deterministic SoS environment
  - Use cases 2-4 (see *backup slide*) and 5 described information acquisition in deterministic and non-deterministic environments, multi-objective algorithms based on Q-learning, and algorithms for distributed reinforcement learning in cooperative multi-agent systems
    - Use case 5 provided an ACDANS realization for applying AI/ML to support complex SoS
  - Use case 6 described how to model and build secure systems at scale in an era of Internet Battlefield of Things
    - Considered models for safe and reliable subsystems, including those for multi-domain military environments, as well as Cyber-Physical Systems (CPS)
- Suggestions for future ACDANS extensions
  - Use case 2, 3, and 4 M&S realizations (i.e., Step 5)
  - ACDANS extensions to support decision enhancement for Joint All Domain Command and Control (JADC2) military environments

Backup - Additional Use Cases - Problem 2: How to apply Machine Learning (ML) to Support M&S for SoS

- Use Case 2: Reinforcement Learning (RL) in Non-deterministic Environments
  - Step 1: Assume a military mission
  - Step 2: Assume an M&S framework
  - Step 3: Assume a continuous time commercial gaming M&S implementation
  - Step 4: Assume non-deterministic analysis along with the application of AI/ML
    - Extends Use Case 1 for cooperative multi-agents operating within a non-deterministic Markov environment
    - To this environment, apply (RL) combined with information gain to improve real-time mission decisions execution
    - Experimental results demonstrate significant advantages of Q-learning to support this goal with agent modeling
  - Step 5: realization is a future task
- Use Case 3: Multi-objective Algorithm Based on Q-learning
  - Step 1: Assumes a commercial environment
  - Steps 2 and 3: Assumptions similar to Use Case 2
  - Step 4: Build upon contribution of Q-learning and MDPs to investigate the incorporation of the multi-objective virtual network embedding (VNE) algorithm.
    - This algorithm uses Q-learning for improving the performance of the SoS by optimizing conflicting objectives (i.e., energy savings with improved acceptance rate)
    - The proposed algorithm uses Q-learning, MDPs, and a curiosity-driven mechanism by considering other non-deterministic factors. Initial calculations suggest that the proposed method can improve the performance of the SoS in terms of conflicting objectives.
  - Step 5: realization is a future task
- Use Case 4: Algorithms for Distributed Reinforcement Learning in Cooperative Multi-Agent Systems
  - Steps 1, 2 and 3: Assumptions similar to Use Case 2
  - Step 4: Incorporates a model-free distributed Q-learning algorithm for the cooperative multi-agent-decision-processes
    - Uses a model that extends Markov Decision Processes for multiple agents
    - In deterministic environments, this method solves two problems: Suitable Q-tables and Coordination
  - Step 5: Investigating this approach for incorporating distributed RL to enhance cooperative multi-agent-decision-processes