

The Role of Modeling and Simulation in Supporting the Internet of Things as a System of Systems

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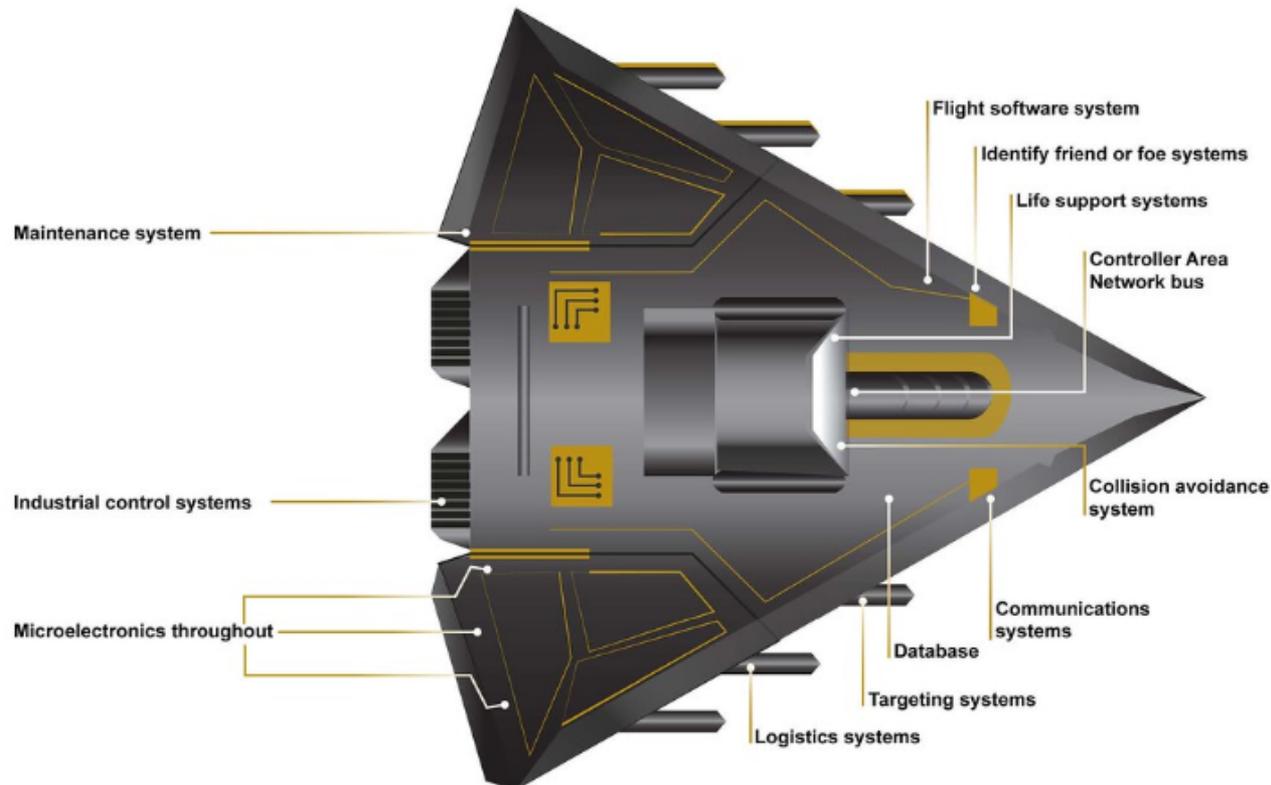
May 21, 2019

Outline

<input type="checkbox"/> Introduction	15 Minutes
<ul style="list-style-type: none">- Why is Modeling and Simulation (M&S) Critical to Supporting the Internet of Things (IoT) as System of Systems (SoS)?- Where does M&S fit in IoT SoS?	
<input type="checkbox"/> Types of M&S to support IoT as SoS and Real-life examples	25 Minutes
<ul style="list-style-type: none"><input type="checkbox"/> Design and Development M&S<ul style="list-style-type: none">▪ Model-Based Engineering (MBE)▪ Agent-based Models▪ Real-life examples:<input type="checkbox"/> Analytic<ul style="list-style-type: none">▪ Data Analytics Modeling▪ Real-life examples<input type="checkbox"/> Production M&S<ul style="list-style-type: none">▪ Component Modeling - Cars, Planes, Ships, Satellites▪ Real-life examples<input type="checkbox"/> Training<ul style="list-style-type: none">▪ Remote training▪ Real-life examples:<input type="checkbox"/> Planning<ul style="list-style-type: none">▪ Systems Modeling▪ SoS Modeling▪ SoS modeling for experimentation and exploration of emergent behavior▪ Real-life examples:	
<input type="checkbox"/> Future M&S to Support IoT as a SoS	10 Minutes
<ul style="list-style-type: none"><input type="checkbox"/> M&S with Artificial Intelligence and Machine Learning<input type="checkbox"/> Using M&S to identify and exploit Emergent Behavior of Complex SoS	
<input type="checkbox"/> Questions and Comments	<u>10 Minutes</u>
Total Time	60 minutes

What is a System of Systems (SoS)?

- Department of Defense (DoD) and commercial systems engineers face significant challenges with respect to producing and using System of Systems (SoS) applications and products.
- SoS comprise constituent systems that are operationally independent, managerially independent, physically decoupled, and geographically distributed.
- SoS as a whole exhibit evolutionary development that can produce system to systems issues such as complexity, phasing, and emergent behavior.



What is Emergent Behavior in System of Systems (SoS) Capabilities?



Swirling fish schools by Phil Manker; https://en.wikipedia.org/wiki/Shoaling_and_schooling#/media/File:Swirling_fish_schools.jpg;
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- New behavior that develops from the interactions among constituent systems produce emergent behaviors.
 - Cannot be deduced from the behaviors of the constituent systems themselves, considered individually or in subgroups.

Why are We Interested in Emergent Behavior in SoS Capabilities?

1. DoD and commercial solutions require SoS capabilities to last many years
 - Lengthy procurement cycle
 - Extensive systems engineering in all phases
 - Large investment
2. SoS producers must understand Emergent Behavior to deliver SoS applications that will:
 - Reduce procurement cycle
 - Streamline system engineering activities
 - Produce longer life, more sustainable systems
 - Improve product cost-effectiveness



The flock of starlings acting as a swarm by John Holmes;
[https://en.wikipedia.org/wiki/Flocking_\(behavior\)#/media/File:The_flock_of_starlings_acting_as_a_swarm._-_geograph.org.uk_-_124593.jpg](https://en.wikipedia.org/wiki/Flocking_(behavior)#/media/File:The_flock_of_starlings_acting_as_a_swarm._-_geograph.org.uk_-_124593.jpg); CC license: <https://creativecommons.org/licenses/by-sa/2.0/legalcode>

What is the Internet of Things (IoT)?

- IoT may be defined as the network of devices such as vehicles, and home appliances that contain electronics, software, sensors, actuators, and connectivity which allows these things to connect, interact and exchange data requiring little to no human-to-human interaction.

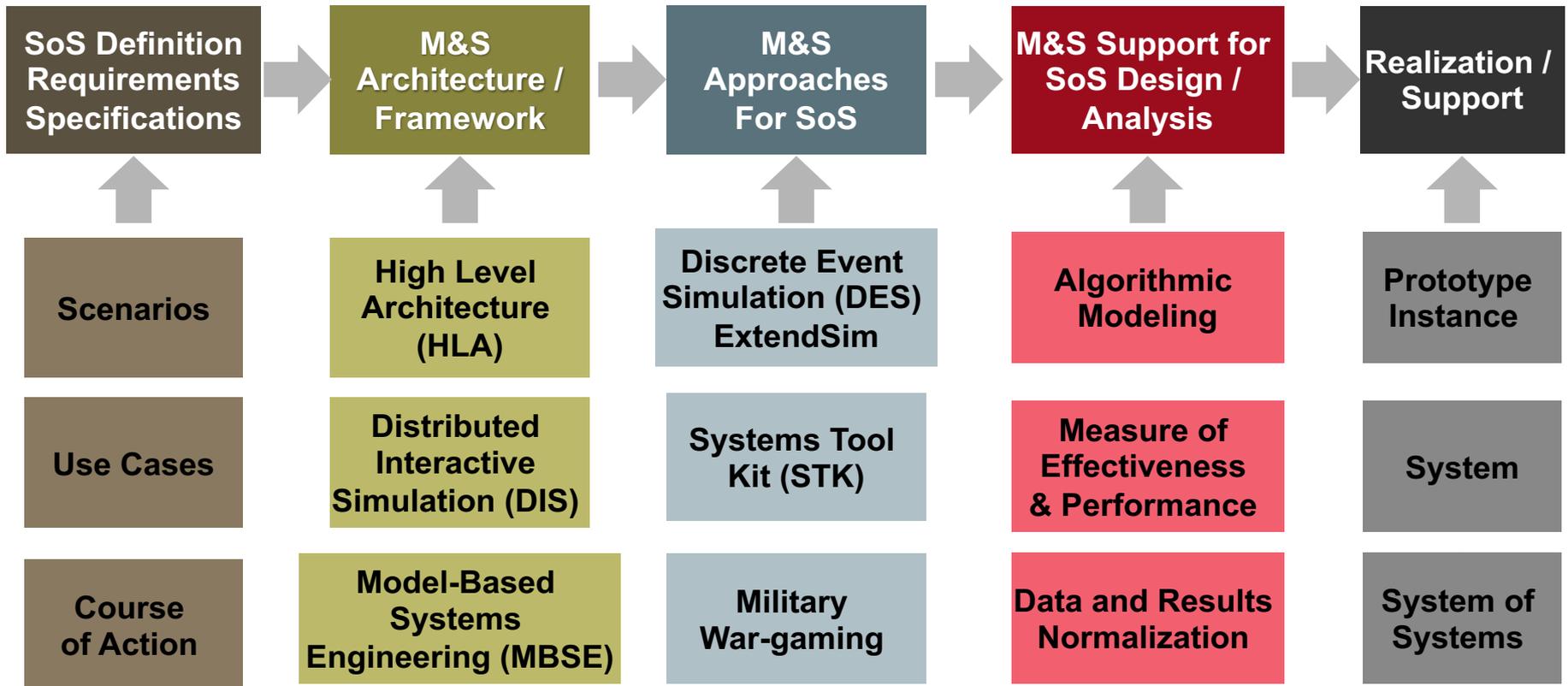


- Therefore, the IoT qualifies as a complex System of Systems and therefore can be represented accordingly.

Why is Modeling and Simulation (M&S) Critical to System of Systems (SoS)?

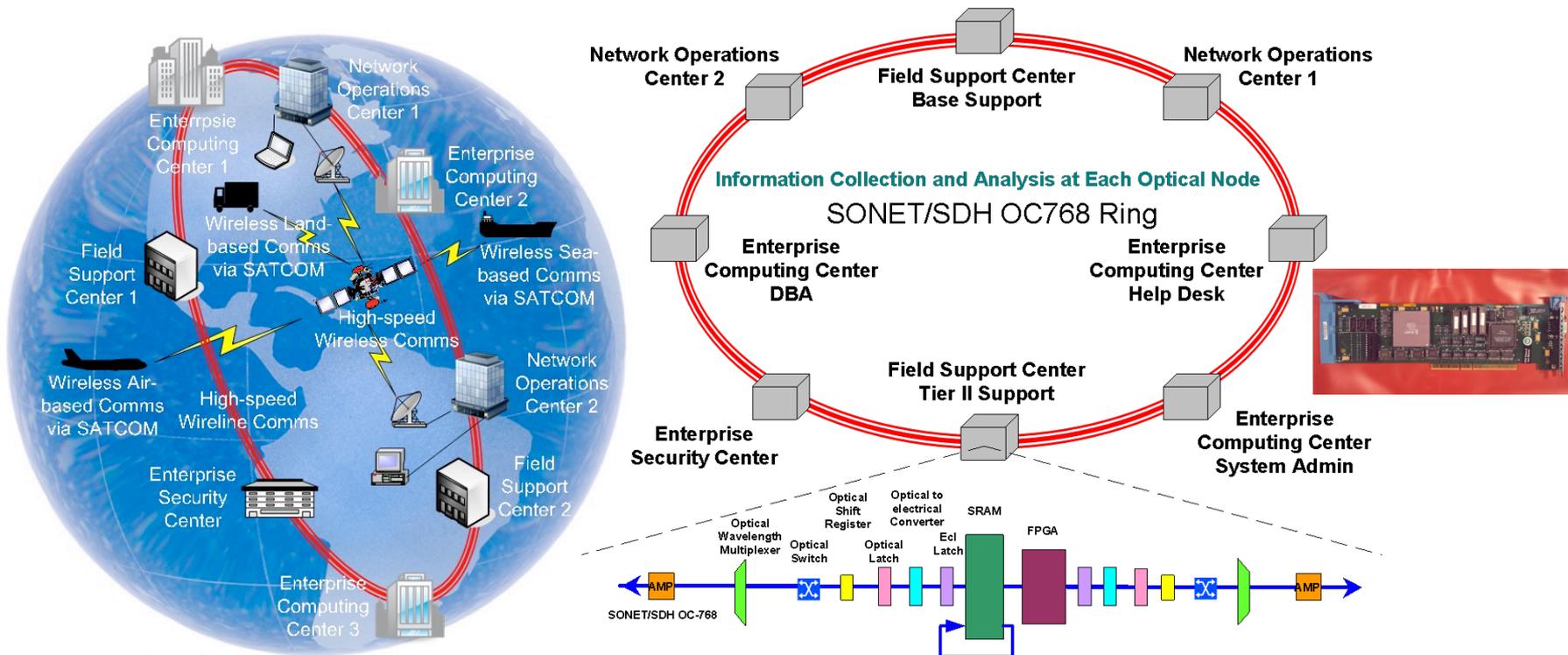
- **Role of M&S in representing the IoT as a SoS**
 - Assist with device design and decision-making processes for developers, service providers, and end-users
- **Representing an IoT-based SoS is complex**
 - Difficult to create a comprehensive hardware testbed to test all possible conditions
 - Expensive to create software to model all systems and their interactions
- **Alternative approach: fuse existing component models to create an overall SoS model**
 - Complicated by issues such as model pedigree and lineage, fidelity of input data, and normalization of data
- **Other Challenges of Applying M&S to SoS**
 - Most simulation systems are designed to work standalone
 - Existing simulation standards were not designed with a SoS approach
 - Interoperability is limited and usually only at a systems level
- **Approach to Solve Problem**
 - Build assets with open architecture
 - Design with data-centric architecture
 - Encapsulate the standards into the platform

SoS / M&S Emergence Flow Diagram



Information Collection Architecture (ICA) - System of Systems Approach for Design and Development in High Speed Communications Systems

- Objective: Monitor and analyze failure causing events in communications systems that have traditionally been done in isolation using processing and tools available only to a particular operations center or administrative domain.
- Solution: ICA information collection system allows end-users to monitor, collect, and analyze data from global enterprise SoSs.



Example Mathematical Characterization: Stochastic Math Model (SMM) for Analysis of Ballistic Missile Negation

- SMM computes Probability of Ballistic Missile Negation, P_n , against ballistic missile threats
 - Techniques are developed to exploit specific vulnerabilities, referred to in the paper as vulnerability-technique (VT) pairs.
 - Vulnerabilities determined by missile design and manufacturing engineers
 - Techniques against each vulnerability are identified by cyber engineers
 - A dot in a cell represents a “VT Pair”

Determined by missile/mfgr engineers (RMS)

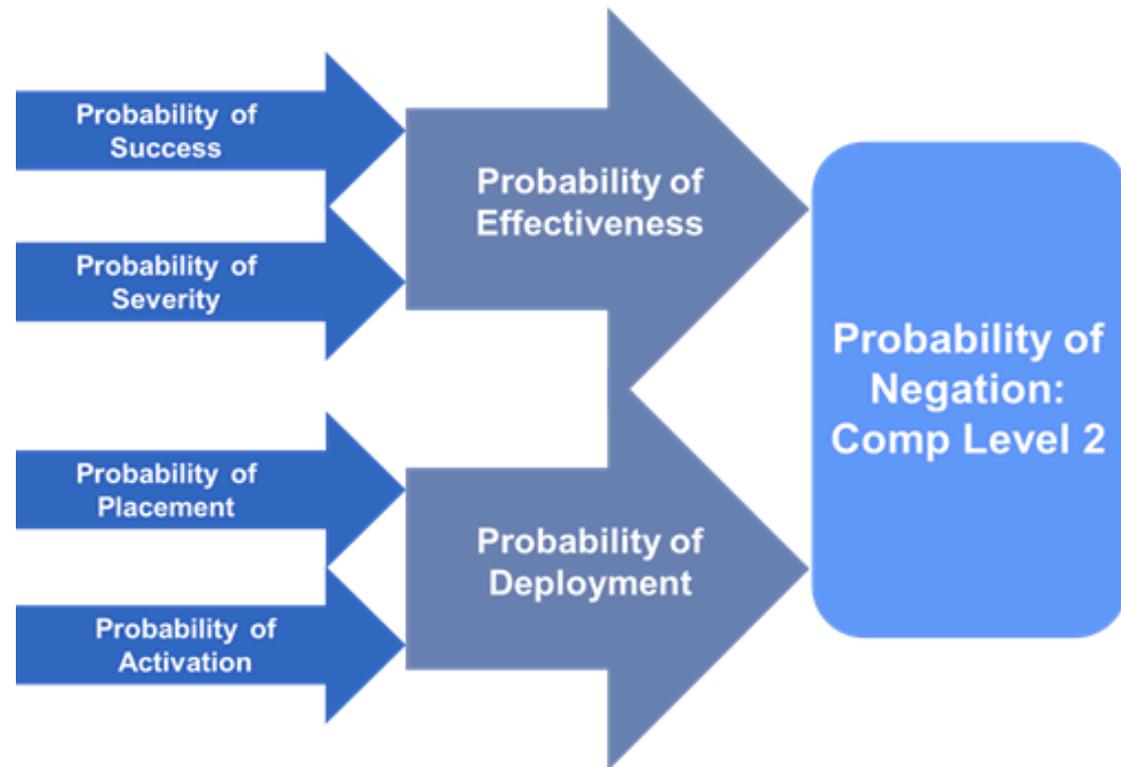
Vulnerability-Technique Pairs	Mfgr/Prod		Test			Fielding			Boost			
	Vulnerability #1	Vulnerability #2	...	Vulnerability #3	Vulnerability #4	...	Vulnerability #5	Vulnerability #6	...	Vulnerability #7	Vulnerability #8	...
Technique #1	•						•					
Technique #2					•							
Technique #3		•										
Technique #4				•								
Technique #5												
Technique #6		•					•					
Technique #7												
Technique #8					•							
Technique #9												
Technique #10	•				•		•					
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Technique #17										•		
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Technique #19											•	
Technique #20											•	

Determined by cyber engineers (IIS)

Multiple Techniques against 1 Vulnerability

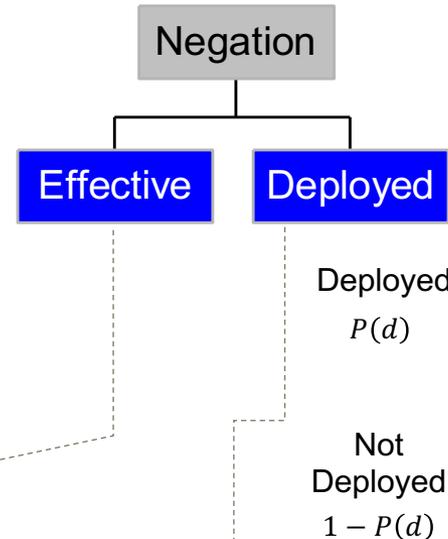
Probability of Negation Decomposition

- Negation --> 1) Deployment, 2) Effectiveness | Deployment
- Effectiveness is decomposed into 1) Successful, and 2) Severe | Successful
 - Peffectiveness is analogous to the Pe for kinetic weapon.
 - Psuccess is the probability that the vulnerability with a given severity could be successfully exploited (with any technique).
 - “Severity” refers to the severity of the vulnerability if it exists
- “Deployment“ is decomposed into 1) Placement , and 2) Activate | Placement
 - “Placement” and “activate“ are different, recognizing that the timing of placement and activation are not always the same.

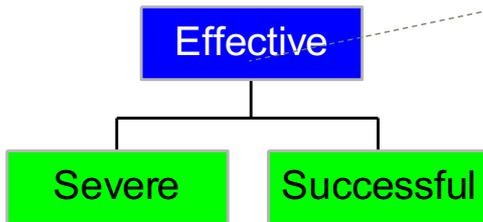


Probability of Negation Decomposition

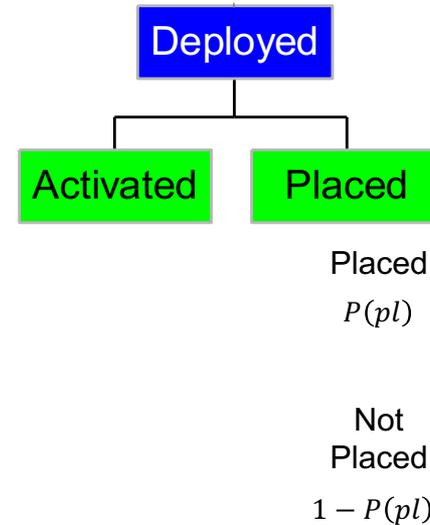
- For a VT pair to negate a missile, it must be both **Deployed and Effective**
- For a VT pair to be effective, it must be **Successful and Severe**
 - Successful: Do what it was supposed to do
 - Severe: Have a significant impact on missile performance
- For a VT pair to be Deployed, it must be **Placed and Activated**



Effective $P(e)$	Not Effective $1 - P(e)$
$P(e, d) = P(e d)P(d) = P(e)$	$P(\sim e, d) = P(d) - P(e)$
$P(e, \sim d) = 0$	$P(\sim e, \sim d) = 1 - P(d)$

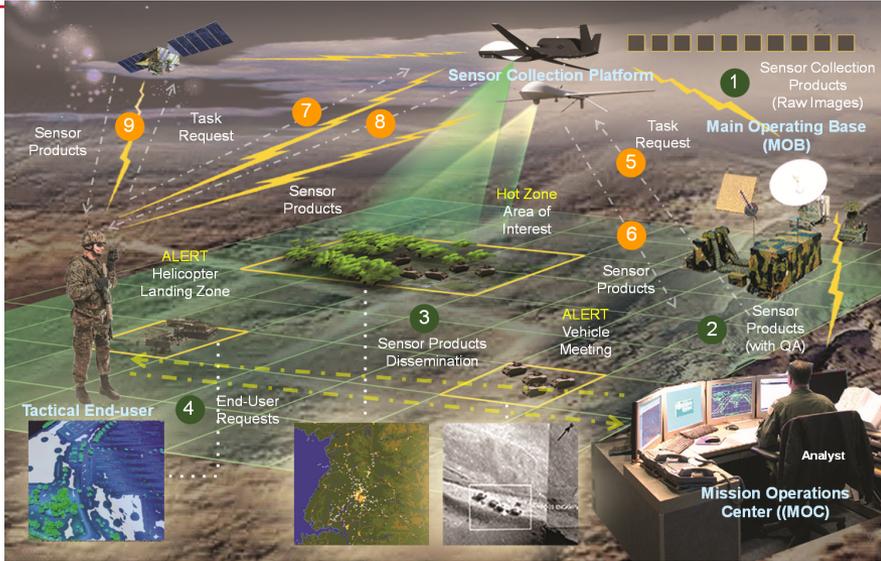


	Severe $P(sv)$	Not Severe $1 - P(sv)$
Successful $P(su)$	$P(sv, su) = P(sv su)P(su) = P(sv)$	$P(\sim sv, su) = P(su) - P(sv)$
Not Successful $1 - P(su)$	$P(sv, \sim su) = 0$	$P(\sim sv, \sim su) = 1 - P(su)$



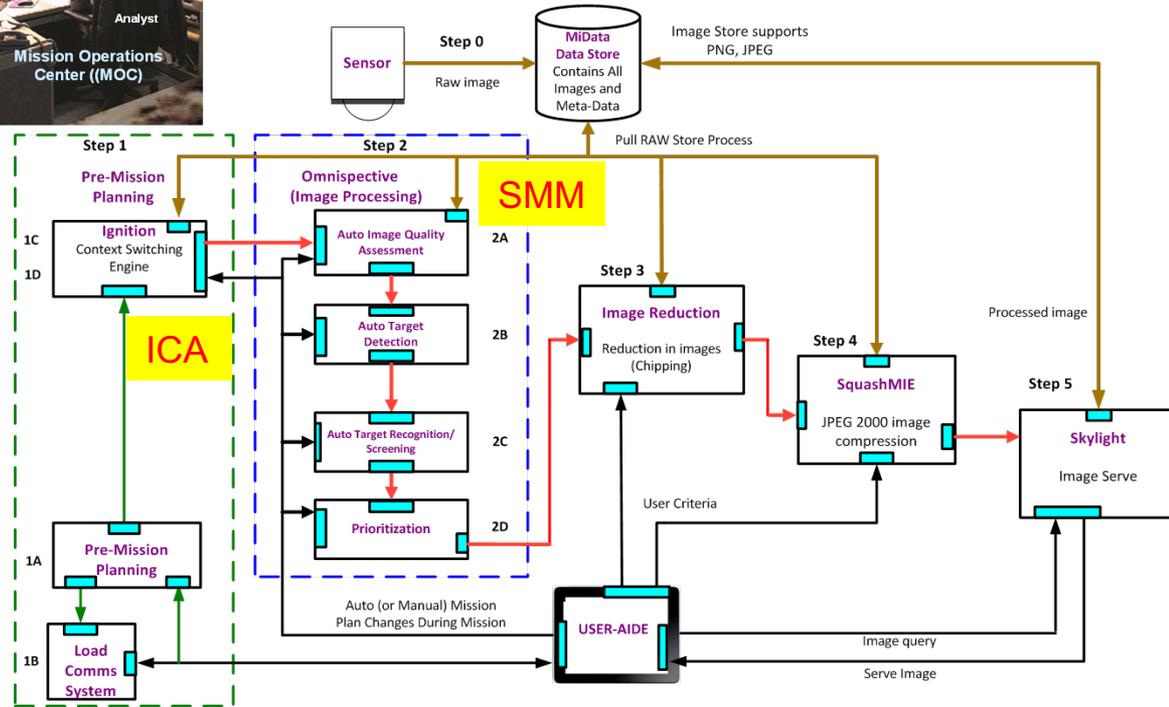
Activated $P(a)$	Not Activated $1 - P(a)$
$P(a, pl) = P(a pl)P(pl) = P(a)$	$P(\sim a, pl) = P(pl) - P(a)$
$P(a, \sim pl) = 0$	$P(\sim a, \sim pl) = 1 - P(pl)$

Multifactor Information Distributed Analytics Technology Aide (MiData) - Analysis of Composable, Distributed SoS to Derive Actionable Mission Information from Intelligence, Surveillance, and Reconnaissance (ISR) Data



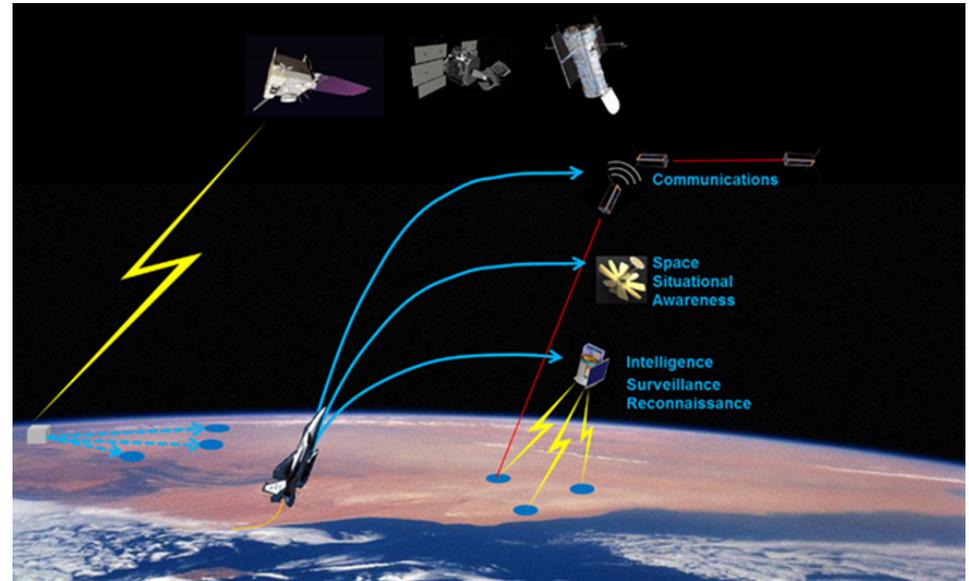
Objective: Customer is drowning in data and seeks solution to reduce vast amount of ISR data to actionable information

Solution: MiData SoS screens and assesses data from multiple diverse sources

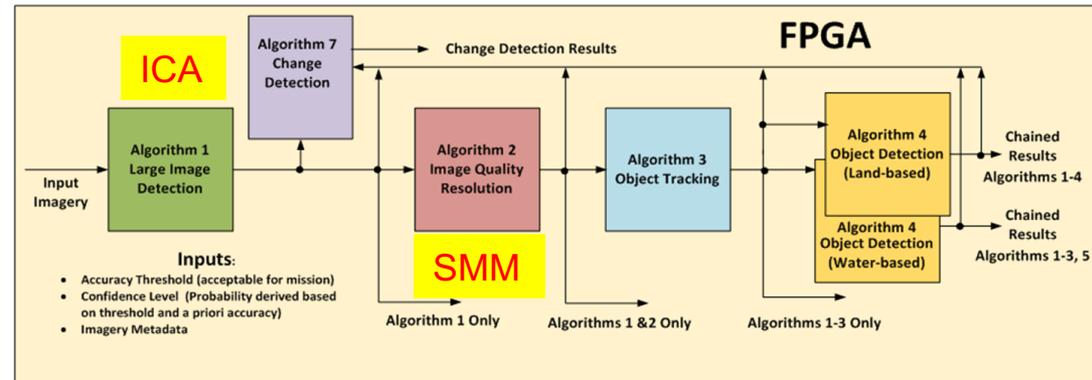


System of Systems for Small Satellite Onboard Processing (S3OP) – Analysis

- Objective: Use Small Satellites (Small Sats) weighing less than 100 kg for:
 - Space-based data collection (e.g., imaging)
 - Intelligence, Surveillance, and Reconnaissance (ISR)
 - Communication
 - Links or Relays
 - Space situational awareness
 - Note: Emerging missions use constellations of greater than 100 Small Sats



- Solution:
 - S3OP constructs an algorithm chain to optimize the amount of data reduction and the corresponding processing and power requirements

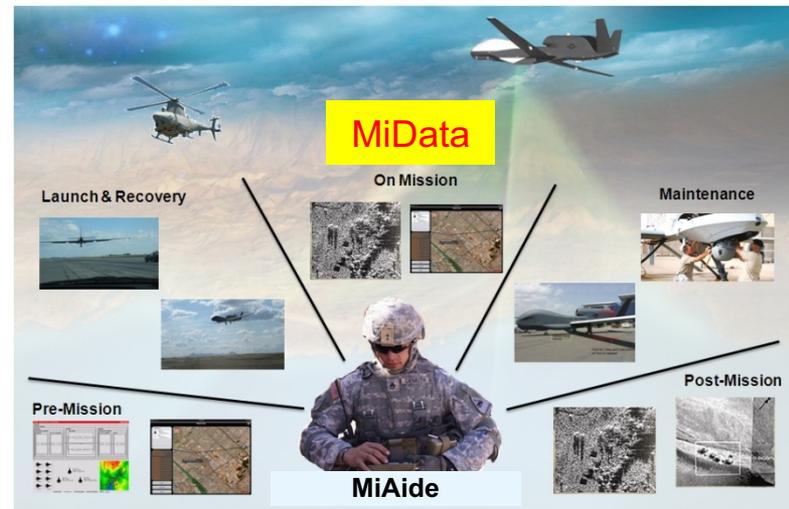


Mission Information Autonomous Intelligent Decision Engine (MiAide) - System of Systems for Autonomous Mission Decisions - Production

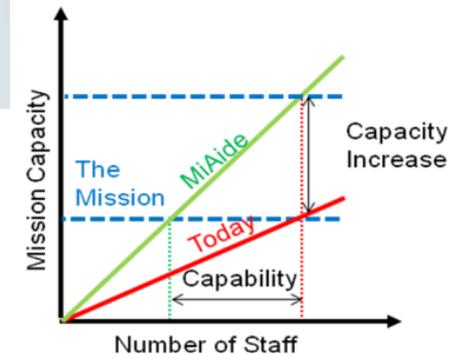
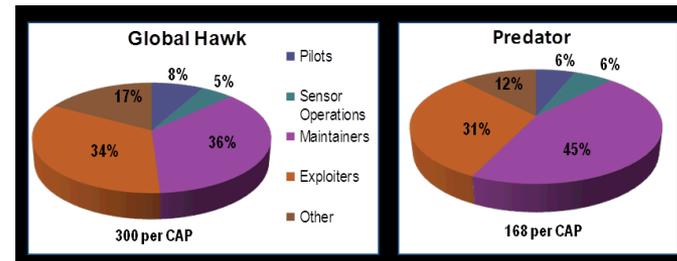


- Objective: Create SoS of applications to provide Automatic Decision Aide for manned & unmanned systems to reduce staffing while improving mission capacity
- Solution: MiAide SoS provides unified decision support for each mission phase through integrating phase-specific applications within and services oriented architecture

Intelligent Mission Console (IMC): Mobile computing user environment that fosters trusted human-system collaboration, and optimizes human response time per mission phase.

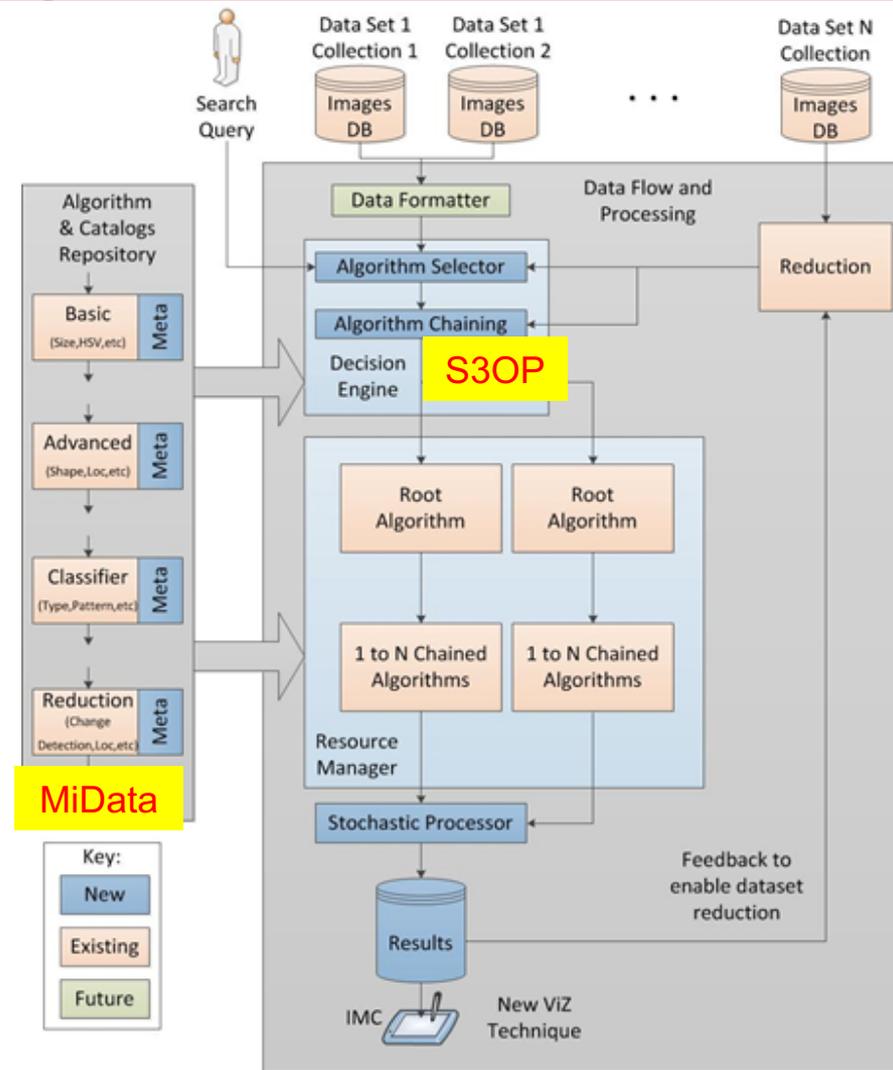
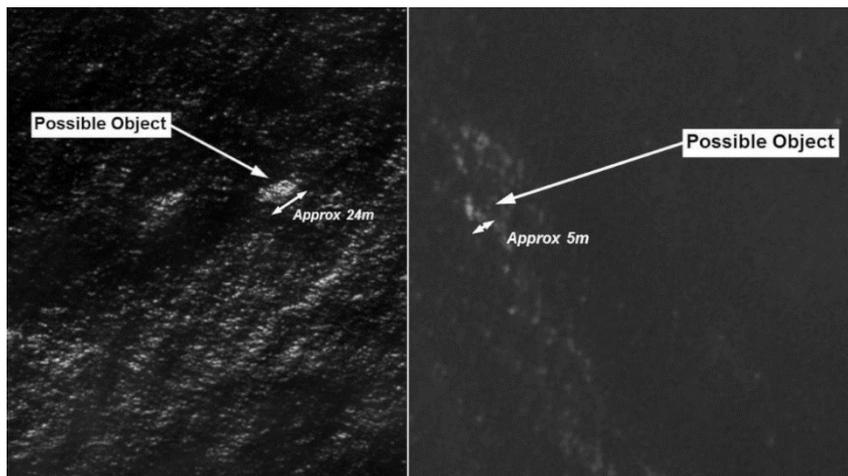


Data Broker Reasoner (DBR): Policy-based context engine to distinguish relevant data per mission phase. Key to adaptability.



MiData Application to Local / Regional / Global Jointed Object Recognition (MAJOR) – System of Systems for Local / Regional / Global Jointed Object Recognition - Production

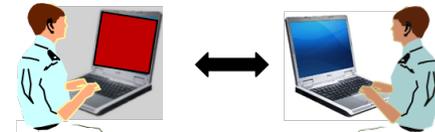
- Objectives:
 - Apply sensors and analytics technology in a new way to create a novel capability to rapidly screen massive collections of sensor images (still and video)
 - Chip out Essential Elements of Information (EIs) that will transform raw data into actionable information
- Solution:
 - MAJOR allows analysts to use Multi-Intelligence information to locate lost objects in arbitrary geographic locations
 - Example: lost jet anywhere on earth



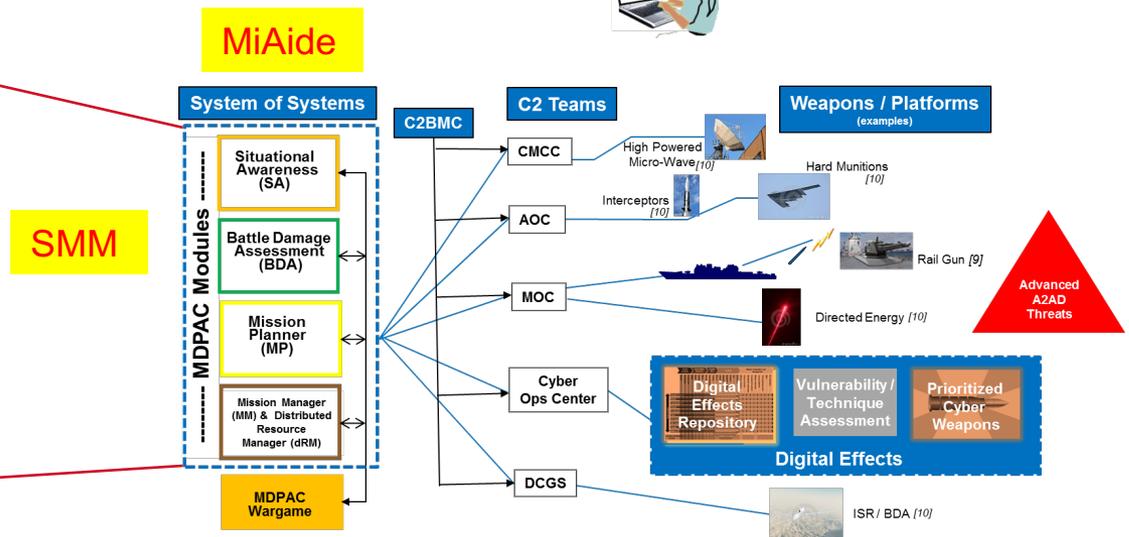
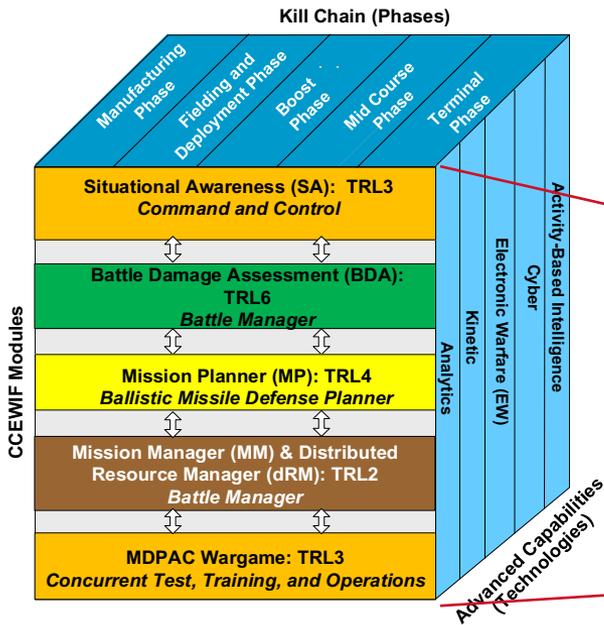
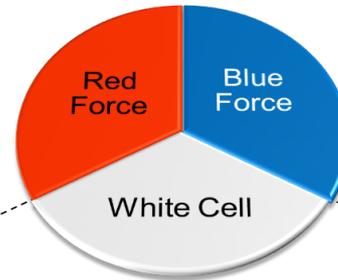
Multi-Domain Probability Assessment Capability (MDPAC) - Training

Objective: Modeling and simulation system-of-systems capability for integrated kinetic / non-kinetic threat / effects pairing assessment

Solution: MDPAC SoS with multi-dimensional framework enables integrated assessment across multi-domain operations centers.

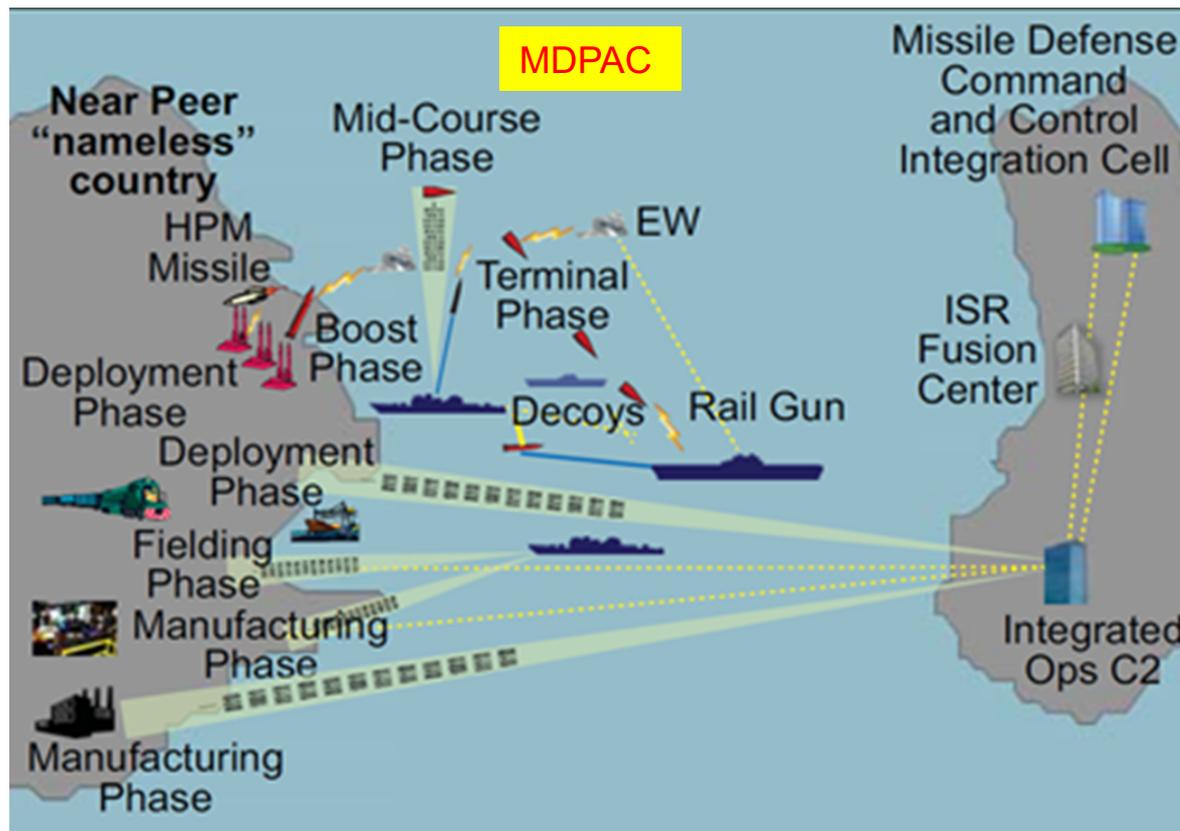


War Game

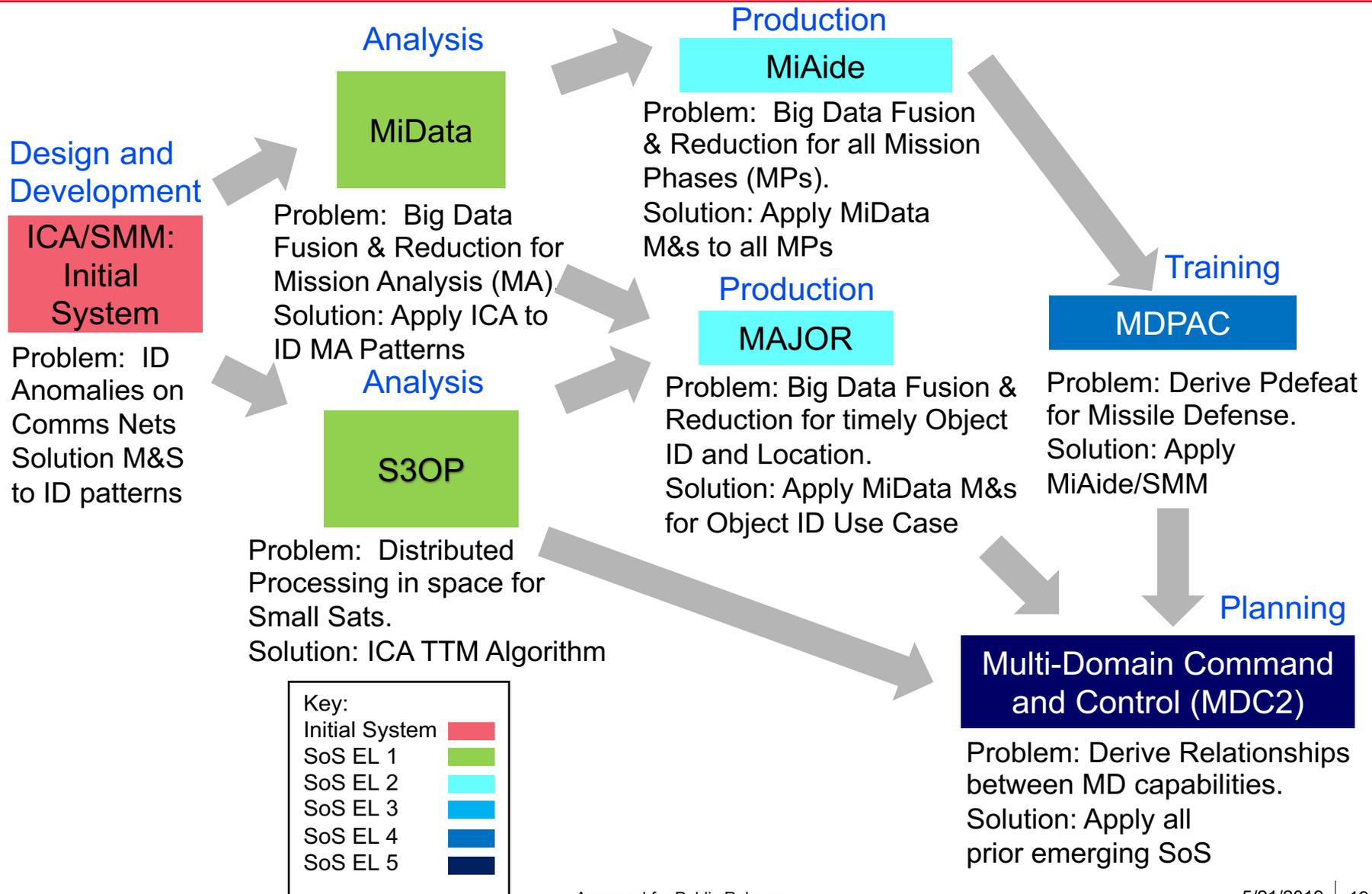


Emergent Behavior: Multi-Domain Command and Control (MDC2) - Planning **Raytheon**

- MDC2 is the coordinated orchestration of sensors-to-effectors across all echelons, domains & warfighting functions
- Future wars will be decided by data advantage enabling collection, exploitation, and distribution of actionable information at speed

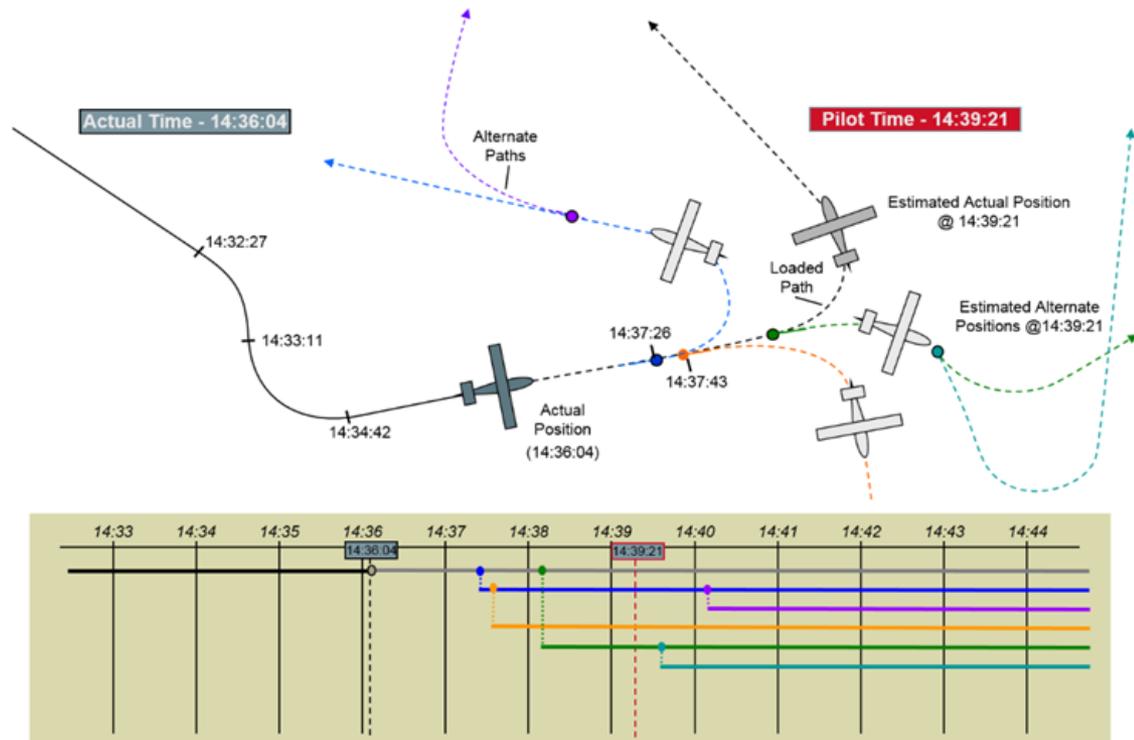


SoS M&S Emergence Levels (ELs) – Evolving SoS Example



Future: M&S to Support SoS for Autonomous Goal Planning using AI/ML

- M&S enables user-in-the-loop autonomy using a genetic algorithm to find optimal combinations of path segments to satisfy mission goals
- Example:
 - Two loaded goals: “Avoid Traffic” and “Collect Image Here”
 - Genetic algorithm forms chains of path segments to maximize route fitness.
 - Some routes are scored higher than others.
 - Mission Commander (MC) has option to operate algorithm in “hands-free” mode or make detailed changes.
 - MC can use fast-forward capability to adjust any path segment along route.

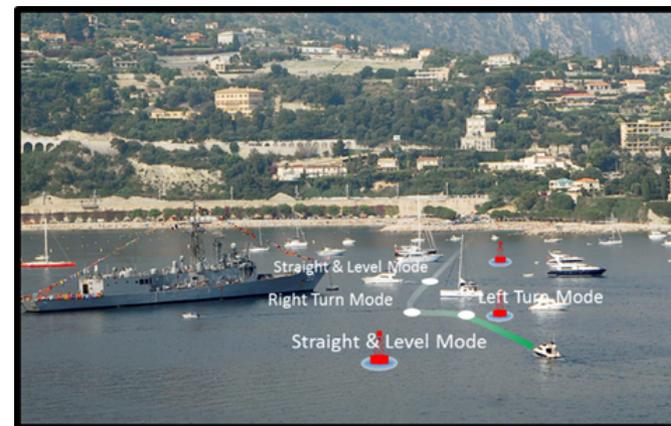


Future : M&S to Support SoS for Emergent Behavior of Complex Civil Sector Applications

- Autonomous cars:
 - Path mode control characterizes possible highway segments over which the car could traverse the highway.
 - MC, operating in hands-free mode, applies highway-oriented constraints (e.g., “Avoid Traffic”, “Follow Correct Lane Direction,” “Operate at Legal Speed”) while autonomously directing the car to achieve its goals (i.e. reach destination X in the shortest time, while not exceeding the speed limit).
 - As car progresses towards goals, vehicle sensors provide real-time feedback to the path planner that dynamically adjusts route plan and notifies MC of plan updates requiring immediate adaptation.
- Autonomous boats in a harbor:
 - Similar to automatus cars except that constraints are oriented differently (e.g., “Navigate within the Channel,” “Avoid Ship Traffic,” “Avoid Buoys and Markers”).
 - Example, as sensors indicate that boat is approaching boat slip, MC activates an autonomous docking procedure to achieve final goal.



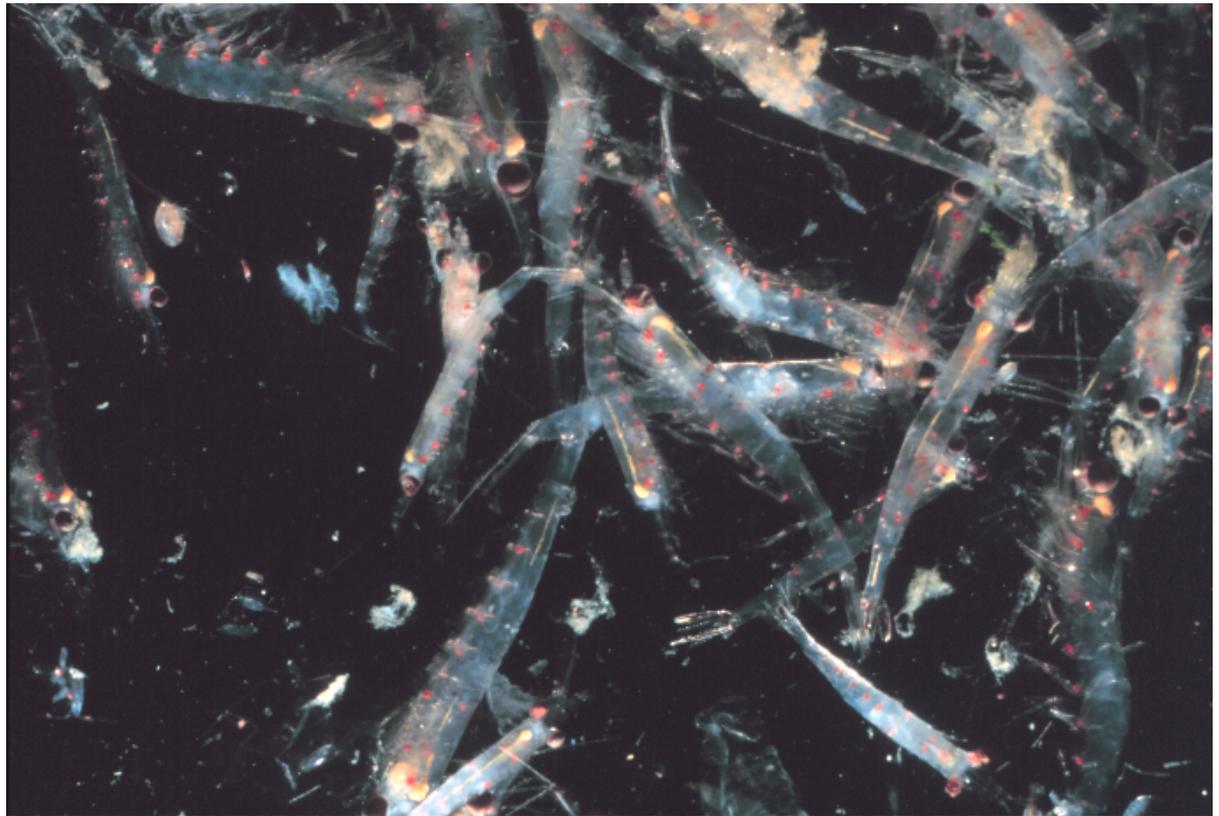
Path Mode Control for Autonomous Cars



Path Mode Control for Autonomous Boats

Summary

- SoS exhibit evolutionary development that can produce system to systems issues such as complexity, phasing, and emergent behavior.
- The IoT qualifies as a complex SoS.
- M&S supports the IoT as a SoS with models and simulations that support decision-making processes for developers, service providers, and end-users.
 - Design and Development
 - Analysis
 - Production
 - Training
 - Planning
 - Understanding Emergent Behavior of SoS
- We presented real-life examples of M&S support for each of these IoT as a SoS areas.



Questions?

BACKUP

References

- “Defense Acquisition Guidebook (DAG),” Jan. 2012, [Online], Available: <https://dag.dau.mil/Pages/Default.aspx>, US Dept. of Defense.
- Systems Engineering Guide for Systems of Systems, Version 1.0, ser. OUSD(A&T) SSE. OfficeoftheDeputyUndersecretaryofDefense Acquisition and Technology, Systems and Software Engineering, Aug. 2008.
- Gao, analysis of Department of Defense Information, <https://www.flickr.com/photos/usgao/43415431510>, accessed May 1, 2019.
- Flavio Oquendo, “Architecturally Describing the Emergent Behavior of Software-intensive System-of-Systems with SoSADL,” IRISA – UMR CNRS / Univ. Bretagne Sud, France flavio.oquendo@irisa.fr, 2017 12th System of Systems Engineering Conference (SoSE), June 18-21, 2017 Waikoloa Hawaii, USA
- “Shoaling and schooling,” https://en.wikipedia.org/wiki/Shoaling_and_schooling. Accessed April 12, 2019
- Flocking (behavior),” [https://en.wikipedia.org/wiki/Flocking_\(behavior\)](https://en.wikipedia.org/wiki/Flocking_(behavior)), access 4/12/2019
- Swirling fish schools by Phil Manker; https://en.wikipedia.org/wiki/Shoaling_and_schooling#/media/File:Swirling_fish_schools.jpg; CC license: <https://creativecommons.org/licenses/by/2.0/legalcode>
- The flock of starlings acting as a swarm by John Holmes; [https://en.wikipedia.org/wiki/Flocking_\(behavior\)#/media/File:The_flock_of_starlings_acting_as_a_swarm._-_geograph.org.uk_-_124593.jpg](https://en.wikipedia.org/wiki/Flocking_(behavior)#/media/File:The_flock_of_starlings_acting_as_a_swarm._-_geograph.org.uk_-_124593.jpg); CC license: <https://creativecommons.org/licenses/by-sa/2.0/legalcode>
- Pixabay, <https://pixabay.com/illustrations/iot-internet-of-things-network-3337536/>, accessed May 1, 2019
- thinking. <https://www.slideshare.net/jmlopezrodriguez/applying-internet-of-things-iot-to-the-simulation-domain>, 2014, accessed April 19, 2019.
- P. Hershey, D. Nelson, “Data Analytics Tutorial (Concepts, Techniques, Uses Cases),” *Proc. of the 2016 IEEE Systems Conference*, Orlando, FL, Apr. 18, 2016.
- P. Hershey and J. Chapa, “A Stochastic Model for Estimating Ballistic Missile Negation via Left of Launch Techniques,” *Proc. 82nd MORS (Military Operations Research Society) Symposium*, Alexandria, VA, June 17, 2014.
- P. Hershey, B. Wolpe, J. Klein, “System of Systems to Provide Multi-dimensional Information Filtering for Space-Based Platforms (MIFS),” *Proc. of the 2017 IEEE International System of Systems Engineering Conf.*, Waikoloa, HW, Jun. 21, 2017.
- P. Hershey, B. Wolpe, J. Klein, “System for Small Satellite Onboard Processing,” *Proc. of the 2017 IEEE Systems Conference*, Montreal, Canada, April 25, 2017.
- Defense Science Board (DSB) TASK FORCE REPORT, The Role of Autonomy in DoD Systems, Jul. 2012.
- P. Hershey, J. Dudash, M. Sica, E. Umberger, “MiData Application to Local/Regional/Global Joined Object Recognition (MAJOR),” *Proc. of the 2015 IEEE Systems Conference*, Vancouver, Canada, Apr. 16, 2015.
- N. Macfie, “6 months since MH370 vanished without a trace, grim reminders of aviation mystery linger,” Reuters, accessed September 5, 2014, 1:40P
- P. Hershey, “Multi-Domain Probability Assessment Capability (MDPAC),” *Proc. of National Fire Control Symposium 2019*, Orlando, FL, Feb.5, 2019.
- “Ruin on Rails: The US Navy’s Rail Gun Project,” Jan 20, 2014 15:20 UTC by Defense Industry Daily staff, <https://www.defenseindustrydaily.com/bae-producing-scaled-down-rail-gun-naval-weapon-01986/>, accessed May 23, 2014.
- Dreamstime Free Illustrations & Clipart, Pictures, Photos and Images, accessed Feb. 2019.
- P. Hershey, M. Sica, and M. Lewis, “Common Ground Control System (CGCS) to Support Autonomous Object Observation, Collection, and Response in Multi-Domain Environments,” *Proc. of the 2018 IEEE Systems Conference*, Vancouver, Canada, April 24, 2018.
- https://commons.wikimedia.org/wiki/File:New_road_obstruction_-_geograph.org.uk_-_1240125.jpg, accessed Feb. 9, 2018.
- [https://commons.wikimedia.org/wiki/File:US_Navy_100704-N-7638K-262_The_Oliver_Hazard_Perry-class_guided-missile_frigate_USS_Taylor_\(FFG_50\)_is_moored_at_full_dress_in_honor.jpg](https://commons.wikimedia.org/wiki/File:US_Navy_100704-N-7638K-262_The_Oliver_Hazard_Perry-class_guided-missile_frigate_USS_Taylor_(FFG_50)_is_moored_at_full_dress_in_honor.jpg), accessed Feb. 9, 2018.
- https://en.wikipedia.org/wiki/Swarm_behavior, accessed May 1, 2019.

Abstract

- Department of Defense (DoD) and commercial systems engineers face significant challenges with respect to producing System of Systems (SoS) applications and products.
 - By definition, SoS comprises constituent systems that are operationally independent, managerially independent, physically decoupled, and geographically distributed.
 - Furthermore, a SoS as a whole exhibits evolutionary development that can produce system to systems issues such as complexity, phasing, and emergent behavior.
 - Emergent behavior is defined as behavior that cannot be deduced from the behaviors of the constituent systems themselves, considered individually or in subgroups.
 - Furthermore, an emergent behavior is a global behavior that arises out of the interactions between parts of a whole and which cannot be easily extrapolated from the behavior of the individual parts.
- The "Internet of Things" (IoT) may be defined as the network of devices such as vehicles, and home appliances that contain electronics, software, sensors, actuators, and connectivity which allows these things to connect, interact and exchange data requiring little to no human-to-human interaction.
 - Therefore, the IoT qualifies as a complex System of Systems and therefore can be represented accordingly.
- The topic that we discuss in this presentation is the role of Modeling and Simulation (M&S) in representing the IoT as a SoS.
 - To effectively design devices for the IoT SoS or to create the network infrastructure to allow connectivity and data exchange between these devices; developers, service providers, and end-users must have some means of determining the impact of their design decisions.
 - We propose using M&S to assist with the design and decision-making processes.
- An IoT-based SoS is too complex to create a comprehensive hardware testbed within which all possible conditions can be tested.
 - Likewise, to create the software to model all systems and their interactions is too expensive to create from scratch.
 - Alternatively, one could fuse existing component models to create an overall SoS model. This approach is complicated by issues such as model pedigree and lineage, fidelity of input data, and normalization of data.
- In this presentation, we provide the audience with an understanding of why M&S is useful with respect to design and decision-making for the IoT as a SoS.
 - In doing so, discuss ways in which M&S can overcome some of the issues identified above, focusing on that of emergent behavior.
 - We also provide real-life examples of M&S capabilities that support the IoT as a SoS in the following areas: **training, planning, analysis, design and development, and production.**
 - We conclude our discussion with an investigation of future uses of M&S to support IoT as a SoS including extensions of M&S into artificial intelligence and machine learning and using M&S to identify and exploit emergent behavior of complex SoS.