Virtual System of Systems Analysis of Advanced Technologies for Joint All Domain Command and Control (JADC2)

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ABSTRACT

Future conflicts involving Joint All-Domain Command and Control (JADC2) will require integration and control of sensing, C2, and targeting assets across multi-domain (space/air/ground/sea) kill chains, enabled by technologies such as Autonomy, Data Fusion, and Artificial Intelligence. To support decision making about where and how to apply these technologies, BAE Systems developed a System of Systems Digital Testbed to enable *mission level* analysis of multi-domain systems of systems integrated with Model Based System Engineering (MBSE) tools. It provides a level of mission flexibility lacking in simulations intended for high fidelity performance analysis, while allowing incorporation of advanced algorithm capabilities (e.g. Autonomy, AI/ML) not possible in high level campaign simulation or ops analysis tools. The testbed utilizes the U.S. Air Force Advanced Framework for Simulation, Integration and Modeling (AFSIM) as well as Bohemia Interactive's VBS4 game engine to model scenarios. An Information Management framework uses information extracted via the VBS4 Simulation SDK to model sensor, effector, and C2 information processing and the flow of information through the kill chain. The simulation suite is DIS/HLA compliant, to permit incorporation of other simulations to further increase fidelity, and also provides a messaging gateway to allow information to be exchanged in standard C2 and messaging formats such as OMS/UCI. Crucially, the Information Management layer also allows flexible incorporation of technologies to automate information management and enhance the C2 process. In this paper, we describe the challenges posed by JADC2 and the critical importance of system of system analysis to inform the application of advanced algorithmic technologies. We discuss the rationale and architecture of the System of Systems Digital Testbed, the technologies incorporated, and the methodologies for system of systems analysis. We will present results assessing system of systems contribution of these technologies to improving mission-level metrics such as latency, scalability, and robustness of kill-chain response.

ABOUT THE AUTHORS

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INTRODUCTION

Joint All-Domain Operations (JADO)

Joint All-Domain Operations is the United States (US) Department of Defense (DoD) Joint Warfighting Concept, with a goal to align all services and domain (space, air, maritime, land, cyber, and electromagnetic spectrum) capabilities to respond more effectively, efficiently, and quickly to advanced technological threats. JADO includes Joint All-Domain Command and Control (JADC2) [1], which will enable warfighters from all services and at all levels to "Sense, Make Sense, Act" using all available information. To achieve this vision, the forces operating from their individual domains must act as one synergistic group, with access to the same data and ability to coordinate their objectives. US forces have shown the ability in limited exercises and specific operations to coordinate operations across services and domains against a limited number of targets to achieve objectives, but these currently require extensive advanced coordination. Future conflicts will require this coordination to occur "at speed and scale," that is fast enough to respond to rapidly emerging or changing threats, and against hundreds or thousands of targets at a time.

While there are many elements to this problem, and it must be addressed at all levels, from tactical to strategic, the foundational JADO/JADC2 challenges can be generalized as a sensor-to-shooter kill chain, [2] also referred to as a "Battle Network." [3] By a "kill chain" we mean a chain of systems which receive and process information about individual threats ("sense"), share and interpret information to assess the complete threat picture and its potential impact ("make sense"), and plan and execute effects against the threats ("act"). It is important to note that effects may include a combination of traditional kinetic weapons to destroy or damage enemy assets, electromagnetic disruption such as jamming to disrupt enemy sensors or communications, cyber operations to disrupt enemy information systems, or in some contexts information operations to deceive or mislead enemy personnel. The work presented here does not directly address information operations or cyber operations, but as we discuss in section 4 it has the potential to extend to cover these areas.

Application/Deployment of Advanced Algorithms in JADO Scenarios

AI, Machine Learning, and other advanced algorithmic techniques play critical enabling roles in JADO and JADC2 [4]. "Sense, Make Sense, and Act" each involve the processing of massive amounts of data on very rapid time scales, requiring algorithmic processing at multiple points in the kill chain to achieve the speed and scale necessary for conflict against an adversary with a large, well-equipped, and agile military force. Further, conventional algorithms designed based on pre-defined requirements and validated using traditional techniques are not capable of addressing conflict situations involving adaptive threats. In the following subsections, we present three notional scenarios representative of the challenges the US military faces in JADO, illustrating the advanced algorithms that enable kill chains at speed and scale. While there are many ways of categorizing such algorithms, for purposes of assessing their utility in JADO Kill Chains it makes sense to consider them broken down by the "Sense," "Make Sense," and "Act". It is important to note that in almost all cases, human warfighters will remain "on the loop," supervising the operation of the algorithmic components, and in some cases "in the loop," where human confirmation of a target ID will be required prior to engagement.

Another key point to make is that the "Sense, Make Sense, Act" construct, as with the related "Observe, Orient, Decide, Act" (OODA) construct commonly used by the US and other military forces, represents a decision loop that is inherently hierarchical in two ways. First, different levels of command will conduct their decision loops nested within the time cycle of the decision loops of higher levels of command. More importantly for the examples shown here, the "Make Sense" or "Orient" elements of the loop often require actions to improve understanding or gather additional information. A common example of this is repositioning a sensor platform or changing configuration of a sensor. This in turn requires a second order decision/action loop in service of the "Make Sense" function. We see examples of this in the three scenarios below, where we consider such steps as "Make Sense" elements. We have implemented all three scenarios in the System of Systems Digital Testbed described in Section 2, and we present preliminary results from System of Systems analysis of the first scenario in section 3.

Air/Sea Defensive Counter Air (DCA)
In this scenario, a friendly Carrier Strike Group (CSG), consisting of an aircraft carrier supported by multiple guided missile destroyers, operates in international waters off an adversary coast. The CSG includes dedicated Air Battle Management (ABM) aircraft, such as the US Navy E-2D Hawkeye, and a wing of fighter aircraft such as the F/A-18 or F-35. The CSG is also supported by a High-Altitude Long Endurance (HALE) aircraft capable of operating for long periods over threat areas with limited exposure to threat air defense systems. The CSG is threatened by an enemy bomber, capable of launching cruise missiles that can damage or destroy CSG assets, and escorted by fighters for protection. Figure 1 below highlights several general capabilities enabled by advanced algorithms, discussed below, that allow the CSG to "Sense," Make Sense," and "Act" to close the kill chain rapidly and with confidence.

SENSE: Sensor Resource Management (SRM) uses autonomous control algorithms, potentially enabled by ML-based techniques, to dynamically manage and control the configuration of platform sensors to optimize sensor processing to ensure detection and identification of threats in challenging environments. Active SRM can significantly improve ability to detect and identify threats in cases where there are a large number of targets, or where the physical or electromagnetic environment affects sensor processing, such as jamming in the case of a radar sensor.

MAKE SENSE: Automated Team Common Operational Picture (COP) Formation shares information among vehicles and correlates and fuses information from multiple sources to produce a common picture across all vehicles. This ensures that decision-making, both human and automated, on all vehicles is performed with the same information. Team COP Formation includes two separate algorithmic elements. First, ***information dissemination*** algorithms must make decisions about what information to share among members of the team. This is critical because in conflict environments, jamming and interference will limit the ability to share information, and so each element of the kill chain must select and prioritize information for sharing with its peers based on the value of that information in forming a consistent COP across the team. Second, ***sensor fusion*** [5] algorithms at each kill chain element correlate and fuse information from local sensor sources and other team members in ways that ensure that each platform "sees" the same number of threats, and applies the same identifier to each threat.

MAKE SENSE: Sensor Repositioning algorithms recommend updated routes for airborne sensors, including the ABM and fighter aircraft, to provide more rapid refinement of target location and identification. These "auto-routing" algorithms use known characteristics of sensors, platforms, and threats to optimize look angles or sensing baselines. As discussed above, this rerouting of sensor platforms is a form of "Act", but because it is service of improving the COP we consider it a "Make Sense" step.

ACT: Weapon Selection and Tasking algorithms review the threats, the mission objectives, and the assets available and recommend threats for engagement, with asset and weapon assigned. Upon human approval, they provide tasking to the weapons and oversee the weapon flyout and engagement. In this scenario, the engagement decision involves determining which of the enemy aircraft need to be engaged – in this case only the bomber needs to be engaged to ensure protection of the CSG, and which friendly asset should conduct the engagement – in this case the guided missile destroyer. In more complex scenarios, weapon selection and tasking algorithms may need to mediate across multiple different command structures to find the right asset, often using "auction" techniques in which each potential provider of engagement capabilities "bids" on the engagement. [6]

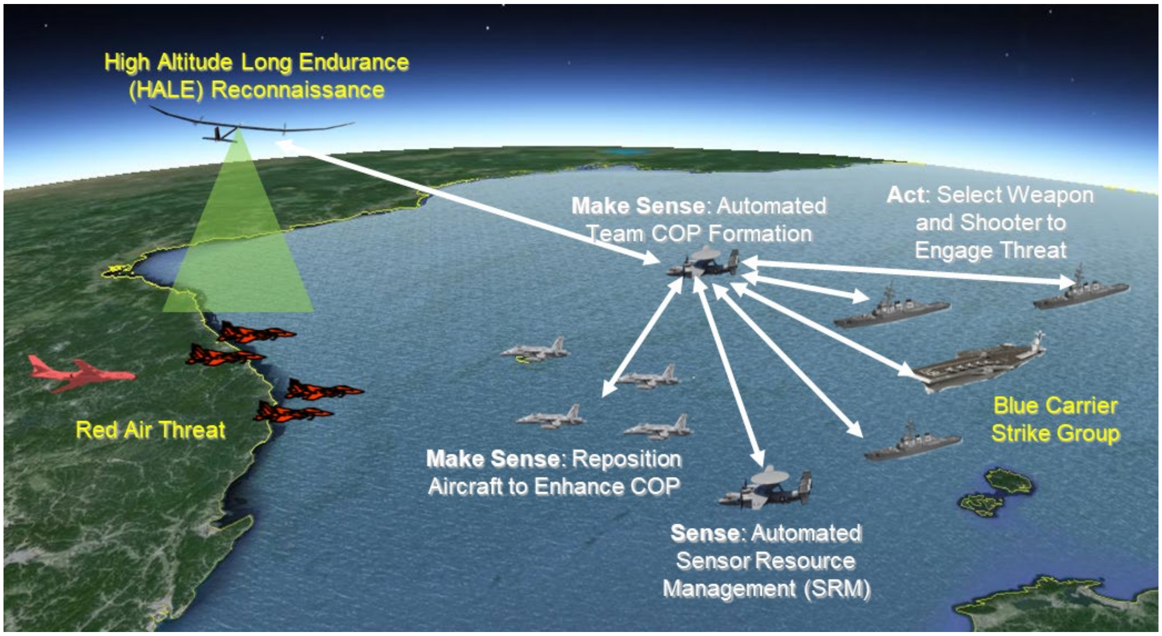

Figure 1. In the DCA scenario, advanced algorithms assist human warfighters to Sense: optimize sensor performance to detect, locate, and identify threats; Make Sense: share information and position assets to ensure a consistent Common Operating Picture (COP) across the team; and Act: select and task appropriate weapons to engage the incoming threat.

Air/Ground Force Protection Scenario

The US Army is developing a concept for future air/ground operations involving the deployment of a family of Air-Launched Effects (ALE) systems [9], unmanned air systems (UAS) that can be launched from larger manned or unmanned aircraft, such as the Grey Eagle UAS used by the Army for theater Intelligence, Surveillance, and Reconnaissance (ISR). ALEs operate in teams, independent of human control, to perform a range of missions for both reconnaissance and attack in support of Army air and ground operations. Central to the ability of the ALE teams to perform these missions is the use of AI-based algorithms for situational awareness and understanding, assessment and allocation of targets for ALE tasks, and teamed operation or swarming to accomplish shared tasks.

Many of the functions shown in Figure 2 are similar to those in the air/sea scenario, but face unique challenges due to the nature of the System of Systems and mission:

- The ALE systems are intended to operate in the near-ground space where Army aviation currently operates. The survival of Army aviation in conflict situations depends on avoiding detection and targeting by enemy forces, which drives operations as close to terrain as possible. Near ground operations increases the differences in observed information across the ALE team, due to terrain obscuration and widely different perspectives.

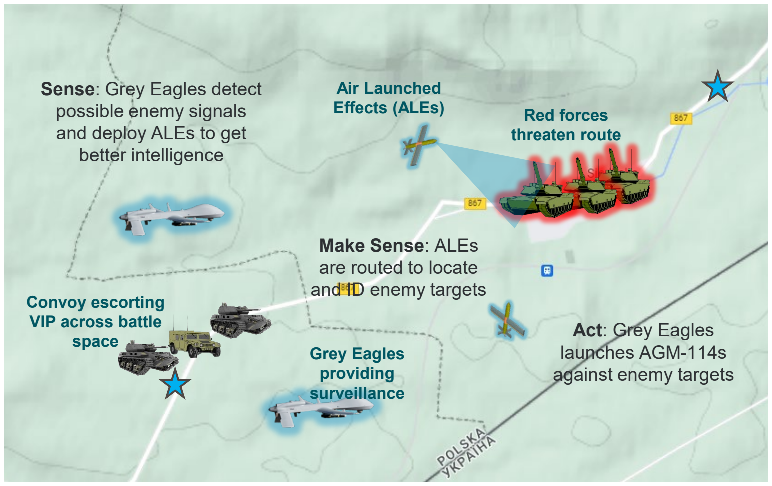

Figure 2. The US Army Air Launched Effects (ALE) aircraft collaborate in teams with larger manned and unmanned helicopters to conduct reconnaissance and strike missions.

- ALE systems are intended to operate in the forward edge of the battle, where the electromagnetic environment is most likely to be contested, resulting in limited ability to exchange information reliably and at high volumes. Low probability of intercept (LPI) communications are also more likely to be interrupted by terrain and other obstacles, further degrading the ability to reliably share information.

These factors mean both that the ALE teams must employ algorithms that are not dependent on identical information on each platform for effective joint execution of tasks.

Missile Defense Scenario

The United States is developing concepts for use of long range Over-The-Horizon Radars (OTHR) for early warning and cueing of defensive systems to protect the continental United States from threats such as cruise missiles. In the missile defense scenario (Figure 3), the north-east ground command and control (C2) station is supported by terrestrial radars (TR) off of Massachusetts and Virginia coasts and OTHR positioned in Ontario, CA and North Carolina. The C2 station is also supported by Space Based infrared Surveillance (SBIRS) satellites of opportunity in the area. In the scenario, an enemy bomber is flying over the North Atlantic and deploys two hypersonic cruise missiles. At the same time, a submarine just offshore surfaces and launces two standard cruise missiles. Each of these four missiles are coordinated to aim at a single terrestrial target. The ground station is able to task its TR and OTHR sensors based on cues received from SBIRS satellites. All of the data received by the ground station is processed into a centralized Common Track Picture (CTP) to allow for quicker decision making. If an incoming threat approaches the east-coast and is sensed by SBIRs, OTHR, and then local TRs the threat can be maintained as it travels through each sensors field of view (FOV) enabling quicker ID and response times. When the CTP achieves ID and confidence on the incoming target, the ground station is able to launch interceptors to nullify the incoming threat before they reach their intended targets.

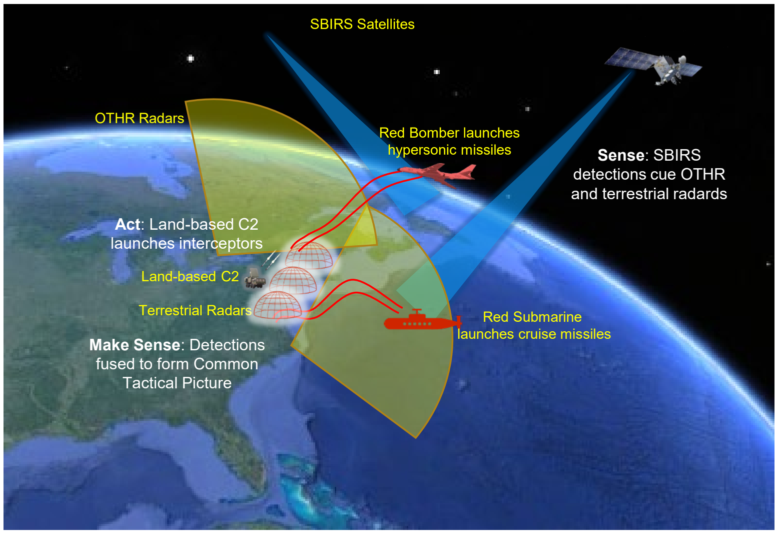

Figure 3. The US Army Air Launched Effects (ALE) aircraft collaborate in teams with larger manned and unmanned helicopters to conduct reconnaissance and strike missions.

This scenario involves similar capabilities for sensor management, data fusion, and threat engagement as the other scenarios, but is noteworthy because it lays out a *layered sensing architecture*, in which multiple sensors of different types and different capabilities are employed in complementary ways. This idea of a layered sensing architecture is central to many modern defense concepts, but sophisticated analysis is required to determine the optimal architecture (types of sensors, arrangement of sensors, and number and capabilities of each type) to meet a set of threats.

System of Systems, Mission, and Information Content Analysis

While algorithms for AI, Machine Learning, or Autonomy can add significant value to the operation of complex systems of systems such as JADO kill chains, their application requires a full understanding of the benefits, costs, and risks of the use of such algorithms. Our work is predicated on the assessment that three interrelated types of analysis are necessary to optimize the application of these algorithms in such applications: System of Systems analysis, Mission analysis, and Information flow analysis. Each poses some unique requirements for the System of Systems Digital Testbed modeling and analysis capability we are building (Section 2).

Our observations are complementary to work within the modeling and simulation that discusses differing levels of simulation, reflected in a recent article published by the Cybersecurity and Information Systems Information Analysis Center (CSAIC) [10]. This work discuss four levels of simulation, with differing levels of complexity and time scales. These levels of simulation map to our levels of analysis as shown in Table 1.

Table 1. Our proposed levels of analysis align with levels of simulation discussed within the modeling and simulation community.

Simulation Level	Complexity Scale	Time Scale	Analysis Level
Campaign	Many v. Many	Days	System of Systems
Mission	Several v. Several	Hours	Mission
Engagement	One v. One	Minutes	Information Content
Engineering	Subsystem Interaction	Seconds	Information Content

System of Systems Analysis evaluates the architecture of the system of systems – the elements that make up the system of systems, their interconnectivity, and the placement of information processing capabilities within that architecture. System of Systems analysis requires explicit modeling of both the physical and information flow elements of these, and the ability to vary these elements easily, e.g. exploring different connectivity architectures or strategies for placement of capabilities. For example, in the Missile Defense scenario, the overall ability to detect and defeat incoming threats is a complex function of the performance of the individual sensors and the C2 capabilities that act based on information from all sensors, and defining the optimal architecture requires modeling all these elements.

Mission Analysis assesses the performance of the System of Systems against mission level metrics. Our work has been informed by the emerging discipline of Mission Engineering, as reflected by the Department of Defense's Mission Engineering Guide released to the public in 2020 [11]. Our work reflects two central elements of Mission Engineering: Concept of Operations (CONOPS) Analysis and mission-level metrics.

CONOPS Analysis reflects the differing roles that elements of the system of systems have in the mission. For example, in the Air/Ground scenario, we must model the fact that engagement decisions require human warfighter approval, and thus information flow related to engagement decisions must always include the manned ground platforms.

Mission Level metrics require assessment of overall mission effectiveness, as opposed to individual platform effectiveness or performance. For example, in the Missile Defense scenario, we may wish to understand the relative benefit of increasing the range or accuracy of the terrestrial radars. While at the local level this will certainly increase the range at which the TRs can detect the targets, the fact that the radars are part of a layered sensing architecture means that changes in individual radar performance may not have a corresponding change in mission outcome. Our testbed must be capable of modeling a range of different capabilities and their interdependency, and computing overall mission effectiveness, such as time to achieve objectives, rather than simply assessing local performance.

Information Content Analysis evaluates the information present at each element of the system of systems, and the flow of information between them, to assess the performance of the System of Systems capabilities. Information Content analysis is particularly important in the analysis of advanced algorithms, because of the strong dependence of these algorithms on the information available to them. Algorithm development, refinement, and assessment depends on modeling with high fidelity the factors that drive dissimilar information across platforms, as these factors are likely to be correlated with mission execution in ways that can't easily be predicted from a simple statistical or parametric modeling of information exchange.

For example, in the Air/Ground scenario, the algorithms do not execute centrally and synchronously, but will be running on all platforms in the ALE team on different data, and in conditions where reliable exchange of information may not be possible. Therefore, the behavior of the team, and the effectiveness of the team as a whole, will be critically dependent on differences in information among the team due to different observations of the battle-space and incomplete ability to exchange information between team members. To assess the value of advanced algorithms to the ALE mission, we must explicitly model the information created at each node (e.g. from sensors or onboard navigation systems), the information exchanged between nodes, and the information resulting from the algorithm execution.

SYSTEM OF SYSTEMS DIGITAL TESTBED

Rationale

Understanding the mission effectiveness of all-domain operations has historically been done with table-top, and more recently, computer-based simulations. Campaign-level and mission-level simulators (such as OneSAF, STORM, etc) provide a many-on-many scenario analysis of Operational Plans (OPLANS) and Courses of Action (COAs) to study, analyze and train decision makers. In the majority of computer-based campaign simulators there are two main methods for governing both the closed nature (i.e. introducing the fog of war for players) as well as the action event outcomes:

1) Simple logic for sensors dictates the observability of opponent entities and states, to include estimation of the knowledge an entity exists, the quantity of that entity or the actions/states with which those entities are in.
2) Heuristic-based probabilistic estimation for determining the likely outcome of an event (to include probabilities of detection, hit and kill)

While these tools and methods have been successfully used to conduct wargames, analyze strategies and train decision makers, they have two fundamental limitations. First, the heuristic-based assessments have limited ability to adjust and estimate system performance with modified specifications (e.g. range, speed, and lethality changes can be implemented to study effects, but more complex system enhancements, such as data fusion and autonomy, cannot be assessed using heuristic data). Second, these many-on-many simulations estimate effectiveness at the entity or entity group level, and cannot estimate performance or effectiveness of concepts like mosaic warfare [12] and JADC2. Instead, capabilities are needed that can model platforms, sensors and effectors with enough fidelity to quantitatively estimate performance at the system level, simulate the processing, sharing and actions based on those models, and with the ability to scale to campaign level size.

Architecture

The JADO framework utilizes a true model-based systems engineering (MBSE) approach combining physics-based simulations and standard SysML modeling with a common data layer to support digital model analysis. The framework enables both static, traceable systems engineering, which links data elements (requirements and specifications) across digital models, as well as dynamic, executable system analysis. For static assessment, data is directly linked using scripts at scenario start, so that changes to architectures and requirements drive updates into the platform/sensor/weapon models that are simulated by the other components. For example, changing a requirement parameter in SysML (such as a platform's max speed or a sensor's accuracy) will cause a model update in those components to directly affect its simulated performance to assess the utility of that change contributing to mission effectiveness. For dynamic assessment, the testbed uses the Google Protocol Buffer (protobuf) format to represent data internally to the testbed. Protobuf is a fast and simple standard format that allows for rapid extensibility to accommodate additional data fields or message types. The testbed utilizes Apache's ActiveMQ and Kafka as message brokers to move data around the testbed in a publication and subscribe (pub/sub) architecture over individual topics. The architecture is integrated into Cameo System Modeler through the use of an API to send and receive messages directly from Cameo SysML event sequence blocks. This approach allows dynamically executable architectures that represent system functionality to play a direct role in real-time simulations that extend to the physical virtual simulations as well as the data layer. Additional software systems, applications, or simulators can be plugged into the architecture via software and applications shims. This data architecture allows additional simulators to be added rapidly when needed, digital models to be integrated when available and facilitates real-time data sharing instead of traditional, off-line serial analysis using different components to model complex systems of systems. This MBSE approach has the additional benefit of being able to apply and trade advanced algorithms (such as data fusion, auto-routing AI) operating on simulated data at relevant locations (platforms or mission systems) within the architecture

Modeling and Simulation Components

The testbed, as shown in Figure 4 has four major groupings of components: 1) a simulation backbone that connects various platform/sensor simulators in real-time to model platforms within the scenarios; 2) Cameo System Modeler to define SysML representations for both static and dynamic representations of systems; 3) a Data/Networking layer that allows for representation of tactical data and an emulation of the communications to facilitate moving that data between entities, and 4) an algorithm layer to integrate and trade real-time AI algorithms (e.g. data fusion, automated sensor-tasking, auto-routing, etc) to optimized system of system performance.

The simulation backbone utilizes the IEEE standard Distributed Interactive Simulation (DIS) protocol to connect multiple real-time simulators within the testbed. Custom faster-than-realtime (FTRT) protocols are employed when system acceleration is required for system evaluation. A simulation manager is used to handle syncing the scenario and data between each simulator as well as to the rest of the system. Currently, AFRL's AFSIM and Bohemia Interactive Simulations Virtual Battlespace 4 (VBS4) are used to model a combination of Air, Sea and Land platforms, all able to be visualized within the 3D game-based rendering engine of VBS4. In addition, we have extended these simulators to allow for physics-based sensor modelling (including radar, ESM, EO/IR) to generate realistic sensor reports in real-time, acting as the blue observable state of the scenarios (a partially observable game problem).

Cameo System Modeler is employed to provide system level representation of critical components within a scenario using the SysML modelling language. Using this model-based system engineering (MBSE) approach, we achieve two things. First, through traceable systems engineering, updates to the system component attributes/requirements have direct effect on platform/sensor performance within the simulation space. For example, adjusting a requirement for a platform to fly 2x faster, or a sensor to see 2x further, as a direct effect of those capabilities within the simulation space.

Vignette metrics are generated and displayed via Elastic's stack (Elasticsearch, Logstash, and Kibana), which provides a stack of tools and libraries to store the data, search over it, and visualize it. The metrics dashboards are utilized for both live and forensics purposes: in-run Kibana dashboards show updating metrics as a run progresses and forensic dashboards to compare performance across multiple runs.

While Vignettes are running, the status of the scenario is visualized in a C2 Display based on NASA WorldWind. The UI primarily shows "Mission Layer" details, namely what the entities actually think they see, which depending on the models being used, can diverge from "reality". This allows deeper insights on what the different entities are seeing and considering based on the information they have available to them.

Second, complex, critical systems can be dynamically modelled using event-sequence diagrams to simulate delays and uncertainty within systems that require automated or semi-automated decisions. For example, we model the Aegis weapon system to dynamically execute the system behavior for receiving a remote engagement track request, through decision to prosecute that target using an available and capable missile system.

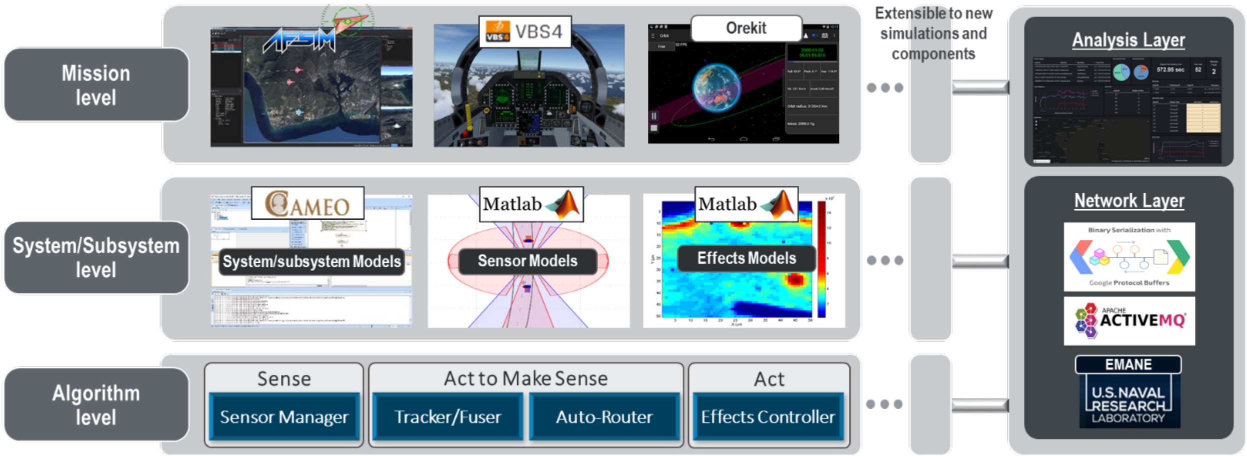

Figure 4. The JADO testbed components and architecture bridging simulation at the mission, system/subsystem and algorithm levels

For the data layer we have implemented a Google Protobuf schema to represent tactical Battle Management Command and Control (BMC2) information (e.g. track updates, task requests, sensor reports) and route that information via a message queuing service to components that subscribe to various message types. We then integrated NRL's Extendable Mobile Ad-hoc Network Emulator (EMANE) framework to emulate networks between the nodes within the scenario, using the Advanced Framework for Simulation Integration and Modeling (AFSIM) and VBS4 real-time updates to model node locations/movement, while defining antenna performance and network models within EMANE. This technique allows us to accurately model throughput and latency effects (to include jamming considerations) for nodes to send/receive information within the scenario.

Algorithmic Components

The algorithm layer where we create AI components that can be attached as autonomous processing capabilities on platforms/systems within the scenario to trade system and system of system performance using advanced AI techniques. One of these components is the previously mentioned CONSENSUS capability, where we implement a data fusion engineer within various nodes and then employ the InfoBroker to optimize message traffic flowing throughout the EMANE network emulation

RESULTS/DISCUSSION

Using the testbed, we implemented the aforementioned defensive counter air scenario. The unclassified toy scenario, as shown in Figure 1, contains a carrier strike group with a carrier, 2 destroyers, 2 cruisers, 2 E-2Ds, and 4 F/A-18s conducted carrier strike group protection. A group of 4 Chinese J-20s are launched escorting an H-6 bomber. The E-2Ds are outfitted with notional radar and ESM sensors, and the F/A-18s are outfitted with angle-only IR sensors. The simulated sensors produce detection reports which are then processed with a tracker and distributed fuser. Fusing the reports from the E-2D's and the F/A-18' provide improved kinematic accuracy as well as IDs on the targets. This scenario executes through three processing steps.

1) Sense: this is the detection phase with the first track created by an E-2D
2) Make Sense: this phase fuses information form the F/A-18 sensors as well as the E-2D ESM sensors to provide an improved, shared situational awareness picture with ID information
3) Act: the real-time mission manager initiatives an automated strike assignment once the ID and kinematic information is sufficiently accurate

The time duration for each of these phases is assessed for both of the following two cases:

1) Without Autonomy: F/A-18s have a prescribed make sense orbit that has been preconfigured with designed geometry, but without knowledge of exact inbound threat vector
2) With Autonomy: an autorouter utilizes the real-time situational awareness information to autonomously create dynamic waypoints for the FA/18s in order to optimized sensing geometries

A scenario lasts approximately 15 minutes to progress through the three phases until a strike assignment is designated. The following results were obtained after ten runs each, with and without autonomy. Figure 5 shows the average variance of time to complete the 4 scenario steps between static and dynamic routing.

Figure 6 show the results of those simulation runs. The results in Figure 6 show not only an overall reduction in killchain processing by 34%. Additionally, each of the stages showed individual reductions in duration using autonomy. Both Sense and Act saw reductions of 20% and 16% respectively. However, it was the Make Sense stage that showed the largest gains using autonomy, of nearly 73%.

While these results are only preliminary and representative (using the notional scenario described in Section 2.2.1 and notional sensors), this approach demonstrates the feasibility and benefit of modeling complex JADC2 scenarios at the tactical data level, in order to assess and trade AI/ML algorithms and their ability to support mission effectiveness.

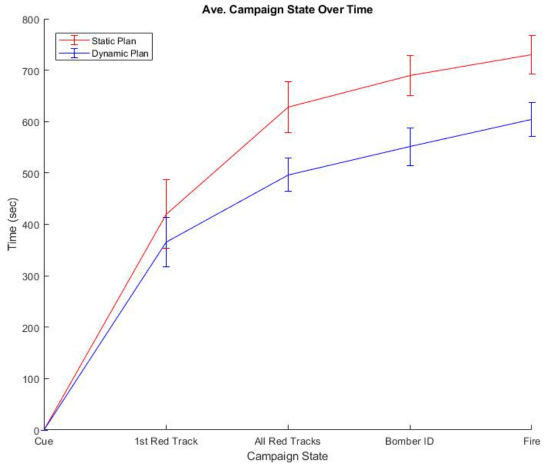

Figure 5. Average Scenario step time and variance comparing static and dynamic replanning.

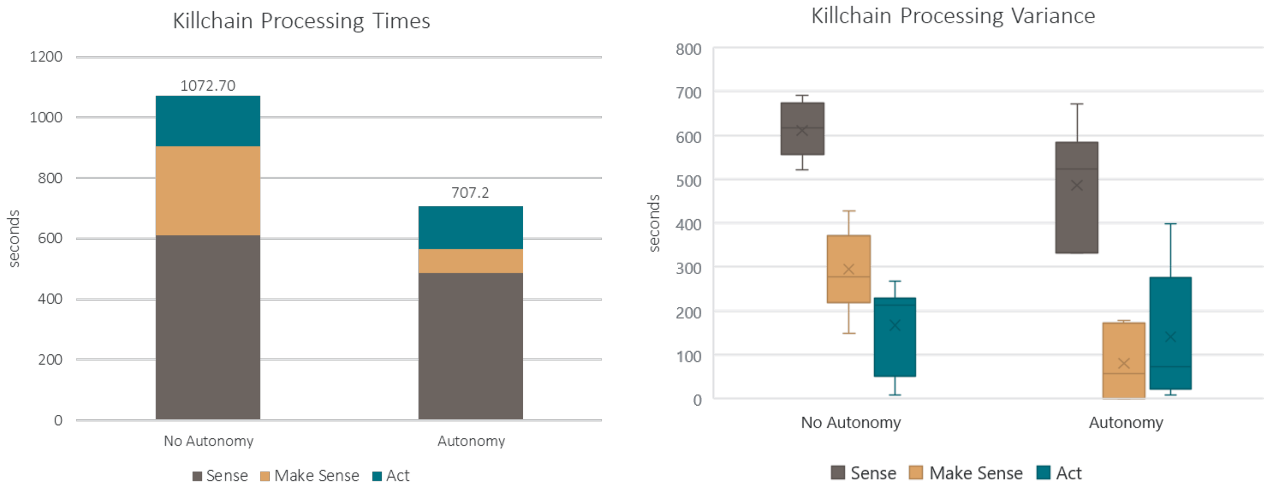

Figure 6. Killchain processing times and variance showing a 34% overall timeline improvement utilizing autonomy

SUMMARY/FUTURE WORK

JADO poses unique challenges to the US Defense community, requiring not only the development of new capabilities, but also, crucially, the effective and robust composition of these capabilities into agile Systems of Systems, capability of executing kill chains at speed and scale against highly capable peer threats. The US Department of Defense has articulated a strategy for providing command and control of these kill chains through JADC2, which enables joint and all domain forces to “Sense, Make Sense, and Act” in the challenging JADO environment.

Advanced algorithms for AI, Machine Learning, and Autonomy are critical enablers for the reliable and robust execution of this “Sense, Make Sense, Act” loop in the face of the uncertainties posed by adaptive threats and contested electromagnetic environments, but their effective employment requires analysis of tradeoffs at the system of systems, mission, and information content level. We have presented in this paper initial work on a System of Systems Digital Testbed that combines modeling and simulation, model-based system engineering (MBSE) tools, and representation of information exchange among advanced algorithms to support these analyses. Initial results, presented in this paper for a notional JADO scenario, demonstrate that we can assess the mission benefit of the use of advanced algorithms (e.g. Autonomy in support of more rapid sense-making).

Future work will focus on three areas of development:

- All-domain modeling: We plan to extend to provide support for modeling scenarios that span all domains of interest. Current work in progress will expand modeling of a robust space layer for sensing and communications. We plan to improve modeling of maritime scenarios through existing simulation tools, and incorporation additional simulation components to support modeling of space kill chain elements.
- Enhanced network layer: We plan to enhance the EMANE network modeling tool to further expand our abilities to model communications through the kill chain. This will include incorporation of additional message formats such as Link-16, OTH Gold (OTH-G), and Cursor on Target (COT), and will allow for analysis and trades of using different message formatting to represent information.
- Scalability to large scale trade study execution: We plan to extend the testbed to add capabilities for automated execution of large scale trade studies evaluating multiple dimensions of system of systems architecture and algorithm configuration. We are modifying the testbed to support faster than real time analysis to further support this. We will couple this with enhanced capabilities for metrics collection, analysis, and visualization.

REFERENCES

[1] "Summary of the Joint All-Domain Command & Control (JADC2) Strategy," US Department of Defense publication, (March 2022).

[2] Christian Brose, "The Kill Chain: Defending America in the Future of High-Tech," Hachette Books, (April 21, 2020).

[3] Todd Harrison, "Battle Networks and the Future Force," Center for Strategic and International Studies published report, (August 5, 2021).

[4] Ravi Ravichandran, Chee-Yee Chong, Robert E. Smith, "Artificial Intelligence and Machine Learning: A Perspective on Integrated Systems Opportunities and Challenges for Multi-Domain Operations," Proceedings of SPIE Conference on AI/ML for Multi-Domain Operations, (April 2021).

[5] Michael B. Martell, et al, "Graph-based Framework for Tracking Objects and Groups," Proceedings of the National Symposium on Sensor and Data Fusion (NSSDF), Gaithersburg, MD, October (2017).

[6] Michael K. Schneider, et al, "Context-Sensitive, Distributed, Multi-Domain Adaptive Option Generation," Proceedings of SPIE Conference on AI/ML for Multi-Domain Operations, (April 2021).

[7] Todd South, "Soldiers will test Army's new robotic combat vehicle in 2022," Army Times, December 21, (2021).

[8] Ashley John, "Army announces contract awards for OMFV Concept Design Phase," US Army release, (2021).

[9] "Air Launched Effects (ALE)," United States Army PEO Aviation release, (August 21, 2020). https://www.army.mil/article/238407/air_launched_effects_ale

[10] Col. Timothy D. West, Brian Birkmire, "AFSIM: The Air Force Research Laboratory's Approach to Making M&S Ubiquitous in the Weapon System Concept Development Process," Cybersecurity and Information Systems Information Analysis Center Journal, Volume 7, Issue 3, (Winter 2020).

[11] "Mission Engineering Guide," Office of the Deputy Director for Engineering, US Department of Defense, (November 2020).

[12] Bryan Clark, Dan Patt, Harrison Schramm, "Mosaic Warfare: Exploiting Artificial Intelligence and Autonomous Systems to Implement Decision-Centric Operations," Center for Strategic and Budgetary Analysis (CSBA) publication, (2020).