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MONTEREY, CALIFORNIA

MODELING THE OPERATIONAL VALUE OF DATA FUSION ON ASW AND OTHER MISSIONS

by

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EXECUTIVE SUMMARY

The NAVAIR Mission Engineering and Analysis Department (MEAD, AIR-4.0M) conducts an annual cycle of engineering, engagement, and mission-level modeling and analysis to support program and technology investment decisions. The Minotaur mission system is being acquired by the Navy for integration on the P-8A Poseidon maritime patrol aircraft and MH-60R Seahawk maritime helicopter. Minotaur integrates sensors from Poseidon and Seahawk into a comprehensive, shared and networked picture. Minotaur offers significant increases in speed, accuracy, and memory capacity over legacy, largely manual, data fusion systems. However, the effects of Minotaur on mission effectiveness is unclear since, unlike a traditional kinetic effector (i.e., weapon), the impact of "better" data fusion on aircrew situation awareness (SA) is not readily captured within existing AIR-4.0M mission-level simulations using Naval Simulation System (NSS) and/or the Advanced Framework for Simulation, Integration, and Modeling (AFSIM).

The foundational hypothesis is that systems such as Minotaur add value by improving SA accuracy while reducing the amount of time to classify and identify contacts of interest. This improvement is expected to have a significant effect on surface targeting, self-preservation, and coordinated antisubmarine warfare (ASW) operations. Since Minotaur in particular does not fuse/correlate ASW sensors, it has less value there, but may still add some value, to be determined. The modeling and analytical approach developed in this study can be applied to such investigations.

The overarching goal of this study is to provide AIR-4.0M with insight into how Minotaur could or should be characterized in a mission-level analysis to include potential functions, metrics, the sufficiency of its current models, and indications if other models or approaches could or should be used.

The researchers used a logical approach based on a literature review, discussions with subject matter experts in the fusion, Poseidon, and Seahawk communities, and investigation of various modeling techniques. Since the sponsor uses NSS and AFSIM, particular emphasis was placed on those modeling tools.

On the surface, there was nothing unusual about the research objectives. Many decision makers need analytical tools and processes to assist with investment decisions. The research findings though, were broader and wider spread than expected:

- Understanding the value of fusion is not a challenge just for the maritime patrol and helicopter communities, but for the Navy as a whole. Different stakeholders have different expectations for fusion systems, and often the significant increases in fusion capability supported by networked platforms is either assumed away as easy, or completely ignored.
- Moreover, definitions of fusion and correlation are inconsistent across the Navy and within the modeling communities. For instance, NSS, Minotaur and the Joint Directors of Laboratories have three different definitions of fusion that are not consistent.
- Another finding was that the sponsor is interested now in the effects of fusion as derived from Minotaur. That was fine, but Minotaur provides capabilities that are not fusion related, but still very useful. Furthermore, there were other existing fusion capabilities in use in the Navy today that were not assumed to be available to these platforms.

In addressing the modeling challenge noted in the study purpose, it became clear that NSS offered a “good enough” solution that could be rapidly implemented with just a few additions to report models. This is accomplished by building a new “sensor” that includes capabilities for detection, classification, and identification, mirroring how fusion systems ingest differing sensors and create greater situation awareness. Because it is a straightforward matter to parameterize this “sensor’s” performance, many excursions of the baseline scenario would generate a look-up table for analysts to compare with exercise/experiment results. For instance, if an experiment demonstrated that Minotaur fusion increased contact identification to 95% at ranges out to 300nm (these numbers are notional) analysts could use the parametrized excursion equivalent to that performance, compare the operational metrics of that excursion to the non-Minotaur baseline, and thus be able to determine potential value added.

NSS use is not without concerns, though. NSS implements “fusion” by correlation of same sensors, not by the correlation of two or more separate and different sensors that Minotaur performs. Thus, the assumption of a “sensor” with the qualities modeled above representing fusion can be erroneous at times, for example, if a given contact of interest is not radiating, broadcasting Automatic Identification System (AIS), or is not in range of an active sensor. So, the NSS modeling approach is not 100% perfect. Again, that is why the researcher recommend parameterizing the probability values, so analysists can be as detailed as they need to be in their analyses.

The researchers believe that AFSIM offers alternative modeling approaches, but at a more foundational level than NSS. Where NSS has a number of functional representations of fusion processes pre-developed in the core software, AFSIM has a more open framework providing an opportunity to create more system-specific representations. However, this means that modeling processes of interest to this study requires more detailed design and implementation efforts, accompanied by necessary verification and validation procedures. This may be a more demanding (and costly) level of development than the sponsor can accommodate. Because of the numerous organizations using AFSIM, active participation in the AFSIM Users' Group could mitigate custom development costs if others have done modeling addressing some of the capabilities needed for study of operational value of data fusion *and* are willing to share their software.

Finally, the researchers observed that the field of fusion is about to explode as new ideas about data and knowledge representation explode across industry and eventually government. Fusing just two sensors used to be quite challenging. Now, new ingest and classification procedures mean that smart algorithms could be fusing dozens of different sources to tell a story. The researchers were reminded by a fusion subject matter expert, who has been at fusion efforts for 35 years, that "true fusion still really only happens in the mind."

The researchers believe that understanding the value of not just fusion, but leveraging the growing data avalanche delivered by Big Data, cloud computing, and machine learning, soon available to all platforms and the tactical edge, is crucial. The hype surrounding these emerging capabilities is huge, so careful consideration of the investments cannot be overstated. Therefore, the research team recommends research on modeling and analytics in the following areas:

- If the use of legacy models such as NSS continues, recommend that enhancements be made to account for multi-source fusion.
- Simulation frameworks like AFSIM, which give users greater manipulability (but also take longer to prepare), show promise for capturing the nuances of emerging

Big Data and fusion capabilities. More effort in modeling these techniques is warranted.

- While the corona virus disease 2019 (covid-19) restrictions and availability prevented in-depth exploration of the topic at the classified level, the researchers believe that a system-in-the-loop approach, using live, virtual, and constructive stimulation and simulation may yet still be a viable analytic approach. In this study, the sponsor tried hard to gain the researchers access to the platform simulators, but there was no availability.
- Advanced model-based systems engineering techniques, especially those enabled by System Modeling Language (SysML) 2.0, due out soon, would allow analysts to construct or reuse formal systems engineering models and associated parametric analyst tools that come with them. This has the power to integrate real systems engineering with modeling and analytical techniques to dive deep into potential investment decisions. Moreover, the naval services Digital/Systems Engineering Transformation Working Group is working on this capability today.

ABSTRACT

The NAVAIR Mission Engineering and Analysis Department (MEAD, AIR-4.0M) conducts an annual cycle of engineering, engagement, and mission-level modeling to support investment decisions. There is interest in data fusion systems, such as Minotaur. The Navy is integrating Minotaur onto the P-8A Poseidon maritime patrol aircraft and MH-60R Seahawk maritime helicopter. Minotaur integrates sensors from Poseidon and Seahawk into a comprehensive, shared, networked picture, offering increases in speed, accuracy, and memory capacity over legacy and manual data fusion systems. Fusion influences on mission effectiveness are unclear since existing AIR-4.0M simulations do not capture the impact of "better" data fusion. The purpose of this study is to describe a modeling, simulation, and analysis approach for quantifying the operational effectiveness of such systems. The working hypothesis is that fusion systems add value by improving situation awareness while reducing classification and identification times. The research team identified three options for modeling such fusion: exploit the Naval Simulation System (NSS), use the Advanced Framework for Simulation, Integration, and Modeling (AFSIM), or create and/or leverage a physics-based fusion modeling approach. For FY20, the researchers recommend that using NSS is the shortest path to create fusion value understanding, and modeling fusion as a "super" sensor with high probabilities of detection, classification, and identification at significant ranges is one way to approach this challenge. The researchers believe that this modeling challenge will continue to permeate many of the Navy's investment decisions in the future, so for the longer term AFSIM or a physics-based modeling approach will provide greater insight.

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I. INTRODUCTION

A. BACKGROUND

The Naval Air Systems Command (NAVAIR) Mission Engineering and Analysis Department (MEAD, AIR-4.0M) conducts an annual cycle of engineering, engagement and mission level modeling and analysis to program and technology investment decisions. The Minotaur mission system is being acquired by the Navy for integration on the P-8A Poseidon maritime patrol aircraft and MH-60R Seahawk maritime helicopter. Minotaur integrates sensors from Poseidon and Seahawk into a comprehensive, shared and networked picture. Minotaur offers significant increases in speed, accuracy and memory capacity over legacy, largely manual data fusion systems. However, the effects of Minotaur on mission effectiveness are unclear since, unlike a traditional kinetic effector (i.e., weapon), the impact of "better" data fusion on aircrew situation awareness (SA) is not readily captured within existing AIR-4.0M mission-level simulations using Naval Simulation System (NSS) and/or the Advanced Framework for Simulation, Integration and Modeling (AFSIM).

B. OBJECTIVES

The overarching goal of this study is to provide MEAD with insight into how Minotaur could or should be characterized in a mission-level analysis to include potential functions, metrics, the sufficiency of its current models, and indications if other models or approaches could or should be used. Minotaur has been modeled in prior intelligence, surveillance, and reconnaissance (ISR) studies by NAVAIR analysts. Early research indicates that NSS and AFSIM might both be capable of modeling either Minotaur explicitly, or at least the effects of Minotaur in the battlespace.

The objectives of our research are to shed light on operational and technical questions, in ways that benefit the topic sponsor and meet his challenging analytic agenda timeline. Questions include:

- What are the internal workflow processes that Minotaur effects on the airframes?
- What role does Minotaur have in the missions conducted by P-8A and MH-60R? How can Minotaur contribute to the ASW mission?
- What can Minotaur actually do today, versus what is envisioned and/or funded?

- What are Minotaur network topologies and bandwidth requirements? How do Office of the Deputy Chief of Naval Operations for Information Warfare (OPNAV N2N6) expectations of Minotaur capabilities and concept of operations (CONOPS) differ from those of the Navy's Director of Air Warfare (OPNAV N98)?
- What are the functional flows of Minotaur? Is it fusing or correlating data?
- What are the key metrics to measure Minotaur mission-level capability?
- Given that MEAD currently utilizes NSS and AFSIM simulations, which framework can best represent Minotaur capability? Are there other models that would be preferable to these?

C. APPROACH

To achieve the project objectives, the project team performed the following activities:

- Learn about Minotaur via meetings with subject matter experts. Obtain, or create if required, a functional flow understanding of Minotaur and its implementation on P-8A and MH-60R.
- Map the specific platform functional flows while using Minotaur. Consider an approach to capturing this information in a working group meeting with various crucial platform and Minotaur subject matter experts (SMEs). Leverage possible NAVAIR crew-in-the-loop simulator experiments.
- Develop potential use cases to highlight possible Minotaur value-added in a surface warfare mission and in an ASW mission. Utilize future year Mission Technical Baselines (i.e., scenarios) provided by MEAD.
- Develop Minotaur-related questions for Fleet users at the Fiscal Year 2020 ASW Naval Concepts Working Group (NCWG) tentatively scheduled for December 2019.
- Learn, review and analyze capabilities for modeling Minotaur that NSS, AFSIM, or other candidate simulation frameworks might provide. Discuss pros and cons of each with particular emphasis into how/if Minotaur can be represented to improve MEAD modeling and analysis.
- In coordination with the topic sponsor, develop metrics for what could be and needs to be measured about Minotaur performance in the above models.
- Based on the above, make recommendations to the topic sponsor on how to model Minotaur. Follow through with the topic sponsor to ensure the solution is executable.

The foundational hypothesis is that systems such as Minotaur add value by improving situation awareness (SA) accuracy while reducing the amount of time to classify and identify contacts of interest. This improvement is expected to have a significant effect on surface targeting, self-preservation, and coordinated ASW operations. Since Minotaur in particular does not fuse/correlate ASW sensors, it has less value there, may still add some value, to be determined.

NSS is in use by MEAD as a “good enough” simulation tool that is familiar to the software developers there. AFSIM requires more coding to produce desired effects for the specific study of interest—with more time and no corona virus disease (covid)-related restrictions on project performance, AFSIM or other approaches might prove better suited to address these research questions. We suggest two scenarios: (1) over-the-horizon (OTH) targeting, where the mission is to hold specific contacts of interest at risk by providing targeting information; and (2) a coordinated ASW operation where P-8, MH-60R, and surface ships are engaged in coordinated operations.

To determine the value, the idea is to hold Red force activities constant, and explore two excursions: ASW platforms without Minotaur, as they are today, as the baseline; and ASW platforms with Minotaur.

Fusion is a tricky word. Discussion with authors of the Joint Directors of Laboratories report on fusion suggests that while there are levels of fusion, real fusion occurs only at the human level. Various “fusion” tools provide suggestions, but the operators must understand the limitations of the various fusion processes so that they can trust the recommendations. Minotaur, then, is just another “fusion” tool. Discussions with real operators suggest that when Minotaur is working well, its algorithms are reliable.

Minotaur associates several inputs to the organic radar tracks on the platform. Some would argue that it does not *fuse* anything. We recommend avoiding discussions of fine-point distinctions. It’s like asking five people what they think autonomy is; you will get five different answers. Minotaur also provides additional data sources to ASW platforms through AIS and the intelligence broadcast. This includes some air track information, which we believe can make a difference for helping ASW platforms avoid enemy aircraft. Minotaur receives a variety of information even if the ASW platform is operating in emission control (EMCON), or partial EMCON.

The project team proposes that in the first, OTH scenario, that Red is deploying surface-to-surface missile shooters into a launch basket. The P-8 mission is to identify these shooters and share targeting information to the Surface Warfare and Strike

Commanders. Red employs decoys that broadcast emitters similar to the shooters, to confuse our picture.

Given that the modeling of such OTH missions is well-understood, the key difference is in how to model the effects of Minotaur. We propose doing that by inventing a new super Sensor *M* that has long detection range, very low error rate, and capabilities to identify surface contacts (we will provide guidance how to do that). Also needed are planned tactics for the P-8 based on various conditions, and a variable EMCON plan. A baseline P-8 takes a long time to sort out surface tracks, often needing to get close enough to visually identify a track. This leads to inefficient criss-cross searches, taking time and decreasing on-station time. Sensor *M* can be parametrized across several factors, such as range, probabilities of classification, identification, and detection, error rates, and abilities to maintain tracks, even if alternating EMCON. By parametrizing Sensor *M*, we can best match the actual Minotaur performance factors observed in various experiments and exercises. Unfortunately, since pandemic restrictions have reduced our access to classified workspaces and materials during the course of this study, we were unable to obtain actual performance numbers from various Center for Naval Analyses (CNA) reports.

Based on other discussions, we do not include MQ-4C Triton unmanned aerial vehicle (UAV) in this work. In our view, employment of a Minotaur-capable Triton can further enhance warfighting effectiveness in this OTH mission, but this can be explored in future work.

For the coordinated ASW scenario, we envision a similar Sensor *M*. We think the value of Minotaur is in rapidly correlating and identifying surface contacts, which we believe will allow the P-8 to more rapidly dismiss possible subsurface contacts. In the kinds of scenarios we anticipate, though, where surface traffic is expected to be more numerous, we believe this capability adds significant value.

D. ORGANIZATION OF THIS REPORT

Chapter I provides background information, including project objectives and approach. Chapter II describes the operational systems and processes that need to undergo evaluation. Chapter III describes modeling approaches and candidate simulations or simulation frameworks for use in performing evaluations of systems and processes.

Chapters IV and V describe scenarios for use in modeling and evaluating the performance of the systems and processes of interest, with suggestions for representations in NSS. Chapter VI provides a summary and recommendations for follow-on work. Appendix A provides a glossary of acronyms and abbreviations, followed by a list of references cited in the report.

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II. OPERATIONAL SYSTEMS AND PROCESSES

A. INTRODUCTION

This chapter provides background information on data fusion systems and processes to provide a foundation for subsequent discussion of modeling approaches.

B. DATA FUSION AND TRACK CORRELATION

The Joint Directors of Laboratories defines data fusion as “the process of utilising [*sic*] one or more data sources over time to assemble a representation of aspects of interest in an environment” (Lambert 2003, 69). The Naval Simulation System refers to data fusion as “any methodology designed to take information or observations collected about a force and process (fuse) this information over time for the purpose of generating time varying estimates of force size, force dispositions, unit identifications, unit readiness and damage states, and/or force intent” (Metron 2002, 178). Another system defines a “fused” track as one derived from the correlation of an AIS track to a surface track. The Minotaur User’s Manual provides its own perspective on what is considered as fusion for that system (Ticom Geomatics 2015). Which of these definitions is correct?

When one word has such a diversity of meanings, confusion and misunderstandings are likely. For this study, the researchers agree to avoid the term where possible. We recommend considering the functional capabilities that the operators desire for fusion operations. We take this step back, because such misunderstandings will become more prevalent in the future as the tactical data avalanche grows. With growing data, there will be demand for more “fusing” of the data, so that it becomes information, knowledge, or even wisdom. We start with basics.

In naval warfare, especially at the tactical level, the objective is to “shoot effectively first” (Hughes 1986). This is a simple phrase, with immense implications. Ideally, the Fleet desires to sense the enemy first, and engage him first with appropriate weapons, while operating in such a way as to avoid detection. The enemy gets a vote, so the tradeoffs begin.

One can use radar to detect contacts, but it is difficult to use radar to deliver contact identification. Modes such as ISAR and SAR can sometimes provide identification. However, these are active sensors so they give away both our location and identification to a wary enemy. Passive sensors reduce or eliminate exposing our position, but can be less reliable. Second parties could provide the sensing information, but now the Fleet needs to rely on communications and networking paths, also detectable. The enemy may also attempt to deceive our sensors by hiding within a dense fishing fleet, busy shipping lanes, jamming our sensors, or spoofing our communications.

What if we combined the information from sensors? If one has a surface radar contact, and we also hold an ESM line of bearing of a particular Red radar that passes exactly through that contact, and there are no other contracts nearby, one might reasonably assume that this contact is a Red warship of the class that uses that radar type. Even today, such fusion frequently is performed manually. In this example, Blue still used an active sensor, so was still detectable.

Consider two different platforms, using only ESM, hold the same Red radar. If they know each other's time and position, they could cue each other with an ESM fix, though this still requires some communications or network path so as to receive the other unit's time and position.

Now add a second party sensor, say something high overhead, which senses ESM. Because of its overhead look angle, it might portray a contact as an ellipse, not just a bearing. Through communications to the original Fleet platform(s), the original Fleet platform now has a pretty good idea where the Red contact is, and never was active, nor was it required to transmit communications or networking signals.

Extend this train of thought to multiple second-party sensors, some active, some decoys, and some passive, and imagine fusing all that information. It stands to reason that with the right algorithms, position, and time information, even if not precisely exact, one Fleet unit designated to shoot weapons might have a high-quality target picture, without ever doing anything to divulge his position or intent. Thus, able to "shoot effectively first."

It stands to reason that, given the right algorithms, the more data sources, the more likely it is that one can sort out Red forces against decoys, and other contacts. Combat identification becomes easier, and given enough information, it may be that the enemy's intent can be surmised. All while not exposing our intentions or position. This is not easy, so those investing in “fusion” in the future should consider their investments carefully.

Another challenge is that while more data can mean better fusion, often sensors owners do not share their data, for a variety of reasons, some good, most not. For instance, the intelligence community operates many high-quality sensors, but because of releasability issues or technical protection oversight, are unwilling to share their data routinely with those that might benefit operationally from that data. Recent changes are slowing changing this culture; but the intelligence community sometimes has legitimate reasons for not sharing data, due to protected sources and methods. Down-grading portions of the data requires complicated procedures and approvals, that are not tactically adroit.

Big Data, machine learning, and cloud computing, etc. offer new ways to merge and fuse even more data, in ways unimaginable just a few short years ago. However, as outlined above, just fusing two or three different sensors is complicated and fraught with errors. Adding many more data sources, be they sensors or social media, adds yet more complexity to the fusion process. Moreover, all the data needs to be represented in a way that algorithm writers can reason over the data. This is called knowledge representation, but is not done consistently well in the DOD (or anywhere) yet.

Adding all this data requires addressing what is called the five V’s characterizing Big Data: value, veracity, velocity, volume, and variety. It is the variety that helps fusion succeed, but data variety comes with the other four V’s, like it or not.

One technique to leveraging all this data is called machine learning, but those techniques have shortcomings as well. Among these challenges are not agreed upon ways to evaluate the worthiness and value of machine learning algorithms, the quality of data that goes into machine learning, and the quality of the outputs from the computational processes.

None of these challenges is unknown. A paper commissioned by N2N6 back in 2009 announced the arrival of an incoming data tsunami. The Navy was working Big Data solutions in 2011. Recently, the Navy hired a Chief Data Officer (CDO), but unfortunately, their background is in business, not military operations.

Another challenge of all this is that while industry faces all the challenges above, they have one focusing objective. Make money. The Navy's data objectives are more complicated, because often the Navy is not operating in wartime, where shoot effectively first would be a driving objective. Often, the Navy's mission is presence, which has multifaceted objectives, and thus multifaceted data needs.

Also, industry assumes enough processing and bandwidth resources, while the Navy can never make that assumption which implies two more critical factors related to fusion operations. First, the Navy needs to prioritize which data to fuse, and further, that prioritization changes all the time. Second, since industry does not have processing, storage, and bandwidth issues, the companies are not incentivized to solve these kinds of problems. Thus, the Navy will have to invest in those solutions, and cannot depend on industry to do so.

What will likely happen is that fusion tools that ostensibly add value, such as Minotaur, will be amended over time, despite the fact that systems like Minotaur were never engineered for such scaling and enhancements. There are organizational challenges as well. As an example, the Surveillance, Persistent Observation, and Target Recognition (SPOTR) effort is a computer vison tool, sponsored by the Office of Naval Research (ONR), which may be adopted in some form by Program Management Warfare (PMW)-120. Johns Hopkins University Applied Physics Laboratory builds Minotaur, which is sponsored in part by Program Management Activity (PMA)-290. What if it made sense to merge SPOTR and Minotaur, which seems like an obvious integration candidate to these researchers. Who is in charge of the integration? Installations? Test? Certification?

One final thought on all this. All of the above describes the fusion of data in real time. However, imagine a computer that not only tracks the data inputs from all sensors in real time, but can also look up past performances while it is doing the real time processing, and compare activity now to historical activities. That might be useful, right? But how does a platform reach back to such historical data? Or more importantly, does the Navy even keep such historical data? It turns out the answer is that yes, sometimes we do, but not comprehensively. For example, Aegis does not routinely save any of its data. P-8s save mission data, but only to the extent they have physical storage for it. When they need new tapes for flights, they just erase their oldest mission, and reuse the tape.

The potential power of fusion, Big Data, cloud, and knowledge representation is huge. If one uses all the available data, one can surmise that a very smart, scalable, Big Data apparatus, with high end fusion of all historic and current data, could tell us exactly where the enemy is and what their intent is. As highlighted above, though, while the various tools exist, or are emerging, the Navy has a long way to go to take decided advantage of these capabilities. Moreover, the enemy is aware of these capabilities as well, and is working diligently to achieve these capabilities themselves, as well as countermeasures to such capabilities.

C. FUSION PROCESSES

An established framework for discussing data fusion is the Joint Directors of Laboratories (JDL) data fusion model, shown in Figure 1. This model has evolved in the literature through a number of variations, but remains foundational to the field of study.

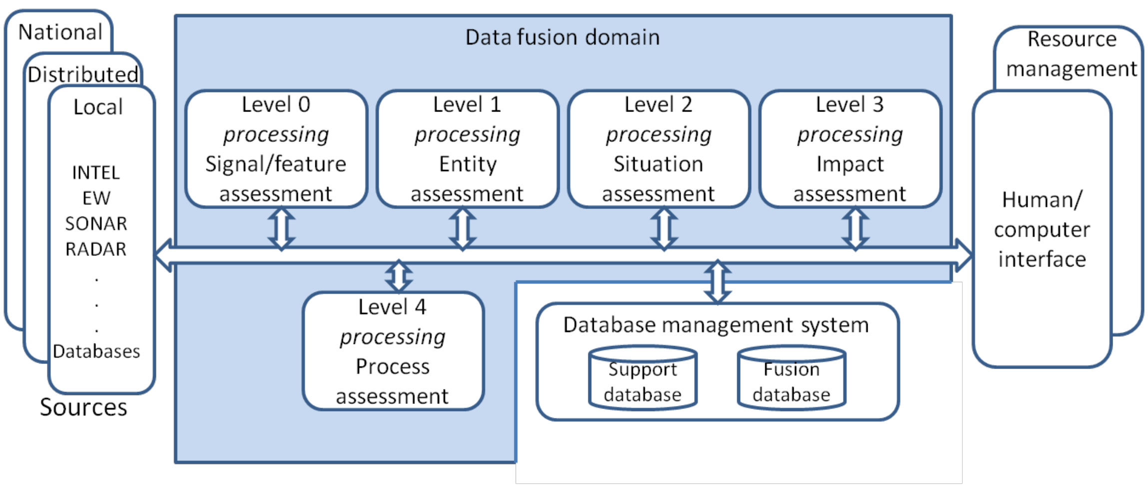

Figure 1. Joint Directors of Laboratories Data Fusion Model. Source: Steinberg and Bowman (2009, 52)

Kessler and White (2009, 24–25) define the levels of data fusion as follows:

Level 0: Source preprocessing/sub-object refinement. Preconditioning data to correct biases, perform spatial and temporal alignment, and standardize inputs.

Level 1: Object refinement. Association of data (including products of prior fusion) to estimate an object or entity’s position, kinematics, or attributes (including identity).

> Level 2: Situation refinement. Aggregation of objects/events to perform relational analysis and estimation of their relationships in the context of the operational environment (e.g., force structure, network participation, and dependencies).
>
> Level 3: Impact assessment: Projection of the current situation to perform event prediction, threat intent estimation, own force vulnerability, and consequence analysis. Routinely used as the basis for actionable information.
>
> Level 4: Process refinement. Evaluation of the ongoing fusion process to provide user advisories and adaptive fusion control or to request additional sensor/source data.

Blasch (2012) discusses an expanded data fusion model, shown in Figure 2, as developed by the Data Fusion Information Group (Blasch et al. 2006). This perspective adds a Level 5 (L5 in the diagram) for *user refinement*, described as: "adaptive determination of who queries information and who has access to information (e.g., information operations) and adaptive data retrieved and displayed to support cognitive decision making and actions (e.g., human computer interface)" (Blasch 2012, 45). It also adds a Level 6 (L6 in the diagram) for mission management, described as: "adaptive determination of spatial-temporal control of assets (e.g., airspace operations) and route planning and goal determination to support team decision making and actions (e.g., theater operations) over social, economic, and political constraints" (Blasch 2012, 45-46).

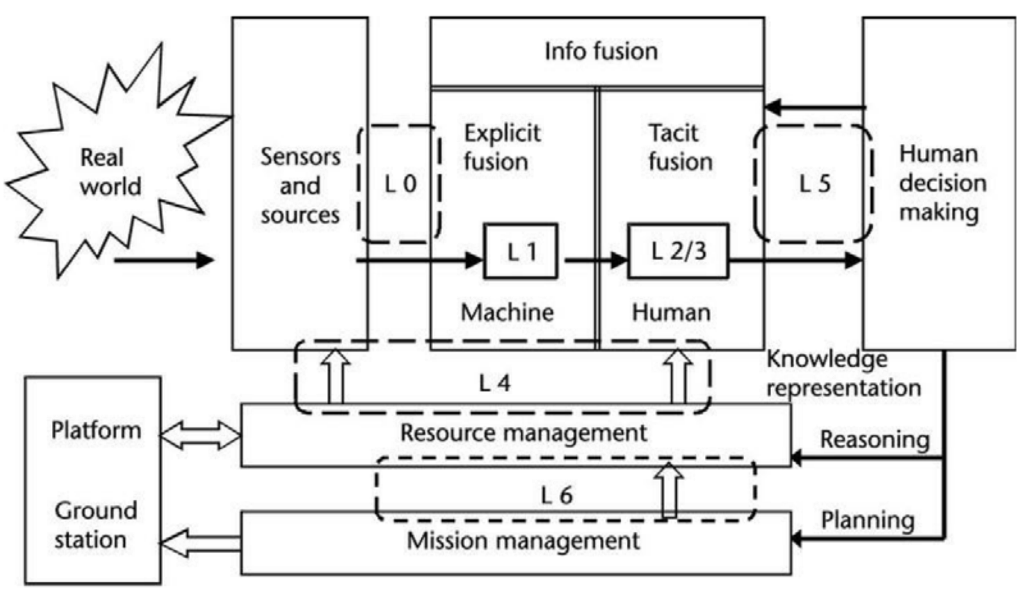

Figure 2. Data Fusion Information Group Model. Source: Blasch (2012, 46)

Figure 3 depicts the Information Fusion Situation Assessment model, further elaborating on the human aspects of the overall process (comprehension, projection, reasoning). There is a complex interplay between the machine processing of information and the human interpretation and reasoning on information obtained from that processing as well as tacitly held through training, situation awareness, and even intuition. To make things more complex, the human "mental state" can be affected by physiological and psychological factors (fatigue, stress, etc.). The performance of the system as a whole involves the sensors, computational processors, human-machine interface design, *and* the human operator(s).

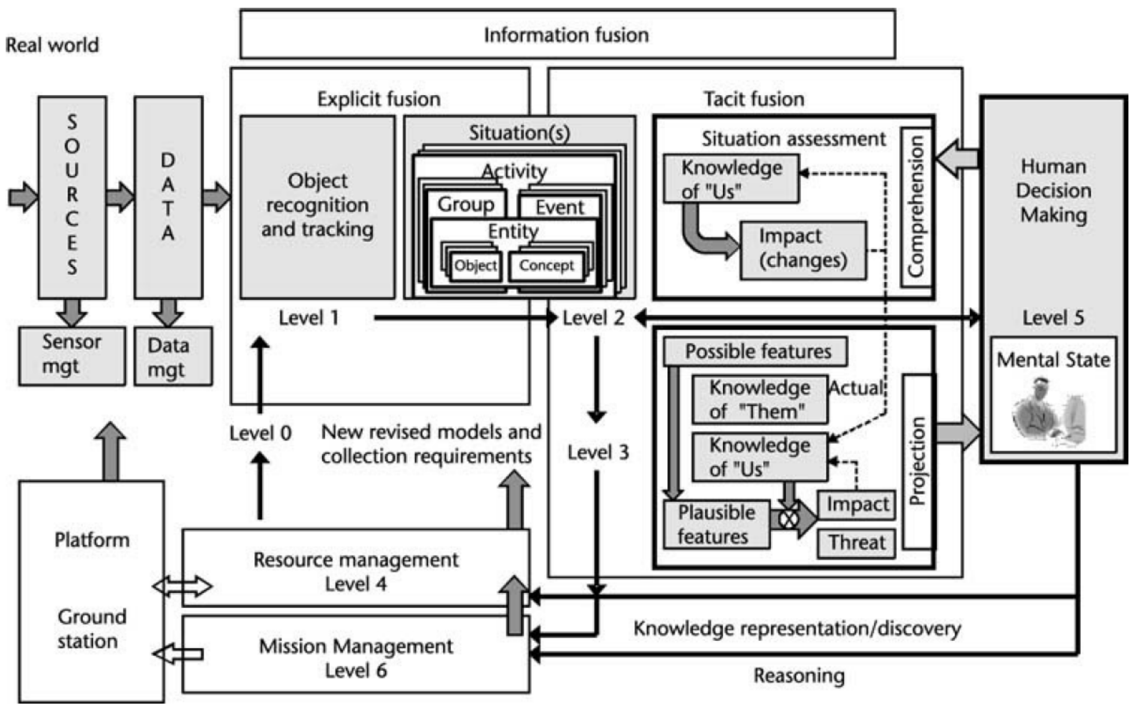

Figure 3. Information Fusion Situation Assessment Model. Source: Blasch (2012, 54)

The overall process today involves both the automated side and the human side. There are major questions whether the process could ever be *fully* automated, particularly if the decision-making ultimately results in weapon launch. Of importance here is the recognition that data fusion involves both machine processes and human processes. Measuring the influence of a data fusion system on warfighting effectiveness needs to consider both the machinery of information collection and processing as well as the cognitive and decision-making actions of the human. This has bearing on the way the system is represented and analyzed, as we discuss further in Section III.

D. WARFARE MISSIONS

This research focused on the capabilities of the Minotaur system, which improves the quality of surface tracks by correlating AIS or ESM information to those tracks. Minotaur supports both surface and anti-submarine warfare. The basic steps of those warfare areas, as related to the P-8 or MH-60R platforms, are described in the following paragraphs.

Figure 3 provides a general flow of a surface warfare targeting mission involving the P-8 and sensor inputs available to Minotaur processing and operators of the Minotaur system. Minotaur's capabilities do not change the process flow, but if properly employed, they reduce the time required to execute several of the steps. This may result in a significant tactical advantage. For example, Minotaur receives AIS information and correlates that information to known surface tracks. By doing so, Minotaur reduces the time needed to classify and identify any surface track.

Legend: AIS-automatic identification system; COI-contact of interest; Cus-course; EMCON-emission control; ESM-electronic support measures; FOC-furthest-on-circle; HF-high frequency; ID-identification; IR-infra-red; L16-Link-16; MCC-Maritime Component Commander; NAS-Naval Air Station; SAR-synthetic aperture radar; SATCOM-satellite communications; SPD-speed; SSR-surface search radar; TSC-Tactical Support Center; TTG-threat task group; Wx-Weather

Figure 4. General Surface Warfare Targeting Mission Flow using Sensors related to P-8 and Minotaur (notional scenario).

Figure 4 illustrates a general functional flow in acoustic data processing, a key element of anti-submarine warfare. Notice the emphasis within the process on offboard contacts. Minotaur, for the same reasons as above, helps anti-submarine operators to classify and identify more rapidly most of the offboard contacts, enabling the crew to focus on those contacts that are not known.

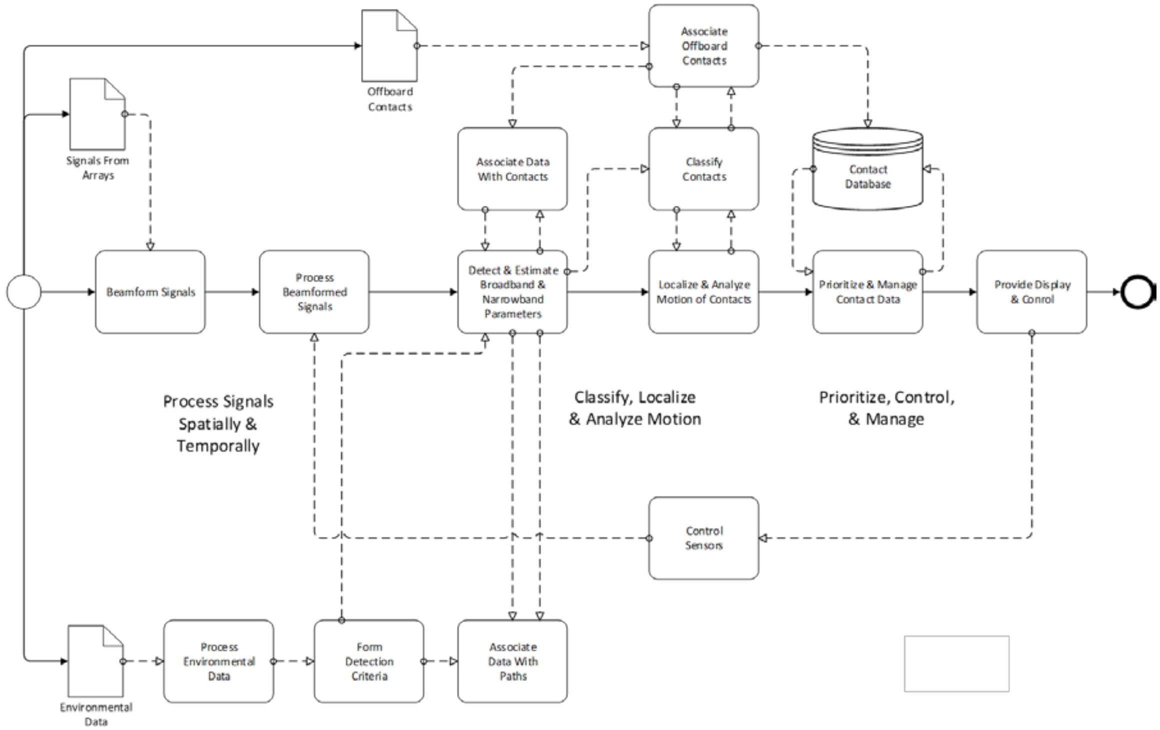

Figure 5. Functional Flow for Acoustic Contact Processing

E. METRICS

There are numerous possible metrics of interest in a multi-source data fusion environment. For example, Llinas (2009) defines measure of performance as measurements of “the ability of the fusion process as an information process to transform signal energy either emitted by or reflected from a target, to infer the location, attributes, or identify of the target” (p 656). He identifies the following set of measures of performance (MOPs) applicable to multisensor fusion system performance (all taken from (Llinas 2009, 656)):

- Detection probability—probability of detecting entities as a function of range, signal-to-noise ratio, and so on

- False alarm rate—rate at which noisy or spurious signals are incorrectly identified as valid targets
- Location estimate accuracy—the accuracy with which the position of an entity is determined
- Identification probability—probability of correctly identifying an entity as a target
- Identification range—the range between a sensing system and target at which the probability of correct identification exceeds an established threshold
- Time from transmission to detect—time delay between a signal emitted by a target (or by an active sensor) and the detection by a fusion system
- Target classification accuracy—ability of a sensor suite and fusion system to correctly identify a target as a member of a general (or particular) class or category

Llinas defines a measure of effectiveness (MOE) of a multisensory fusion system as "a measure of the ability of a fusion system to assist in completion of an operational mission" (p 656), identifying the following measures of effectiveness (all taken from (Llinas 2009, 656-657)):

- Target nomination rate—the rate at which the system identifies and nominates targets for consideration by weapon systems
- Timeliness of information—timeline of availability of information to support command decisions
- Warning time—time provided to warn a user of impending danger or enemy activity
- Target leakage—percentage of enemy units or targets that evade detection
- Countermeasure immunity—ability of a fusion system to avoid degradation by enemy countermeasures

In support of this study, MEAD personnel provided the following set of possible metrics for consideration (several are stated in the context of Minotaur explicitly):

- Operational Function: Intelligence and Command and Control (note that specifics can be further defined based upon system capability; e.g. time to localize with system *xx*. Also, to determine impacts of organic and inorganic sensor inputs.)
    - Time required for platform identification (PID)
    - Time required for combat identification (CID)
    - Type of sensor used to obtain contact (list)
    - Number of organic systems used for contact generation (count)
    - Number of inorganic systems used for contact generation (count)

- Percent of inorganic systems in communication with own Minotaur (ratio)
- Percent of time inorganic systems are able to communicate with own Minotaur
- Number and type of data points used (organically/inorganically) to obtain contact generation (and classify/identify/localize/track) (count/list)
- Time to transmit and receive data points (appropriate time)
- Time to integrate inorganic information for contact generation (and classify/identify/localize/track)
- Time to pass/receive information to Master Minotaur System (appropriate time)
- Percent of time inorganic units are contributing to Minotaur System (ratio)
- Percent of time Minotaur is providing command with updates (ratio)
- Percent of time that contact has continuous sensor observation (ratio)
- Time to obtain contact (appropriate time)
- Number of unresolved ambiguities in tactical picture (count)
- Time to indicate unique contact (appropriate time)
- Distance required for multiple contacts in close proximity to be separated (yards)
- Number of contacts with dual tracks (count)
- Methods to obtain contact (list)
- Time to classify contact (appropriate time)
- Percent of contacts correctly classified (ratio)
- Time to identify contact (appropriate time)
- Percent of contacts accurately identified (ratio)
- Able to locate/localize contact (Y/N)
- Time to localize target (appropriate time)
- Number of contacts able to be located (count)
- Percent of contacts accurately located (ratio)
- Error in location of contacts (yards)
- Number of contacts that are able to be tracked (count)
- Percent of contacts that are able to be tracked (ratio)
- Percent accuracy of contacts tracked (ratio)
- Error of contacts tracked (yards)
- Time to update position (appropriate time)

- Time to update track (appropriate time)
- Number of breaks in track (count)
- Time from identification to external receipt of information (appropriate time)
- Able to collect autonomously (Y/N)
- Percent of targets accurately identified through autonomous collection (ratio)
- Percent of targets accurately located through autonomous collection (ratio)
- Percent of collection requirements fulfilled by reconnaissance/surveillance assets (ratio)
- Percent of time able to respond to collection requirements (appropriate time)
- Percent of contact cues converted into contact detections (ratio)
- Time to recognize contact from contact cues (appropriate time)
- Percent of contacts tracked in the contact, identification, engagement area (CIEA) (ratio)
- Percent of targets tracked in the CIEA (ratio)
- Number of means to acquire intelligence requirements (count)
- Number of intelligence requirements that can be filled for mission (count)
- Percent of intelligence requirements filled by system (ratio)
- Time to respond to emergent tasking (appropriate time)
- Percent of time conducting search plan (ratio)
- Percent of area coverage in OA (ratio)
- Rate of area coverage in OA (area/time)
- Ability to transmit updated cuing information (Y/N)
- Time to successfully transmit information (appropriate time)
- Percent of reported information that is graded as high reliability (or good enough for targeting) (ratio)
- Percent of information that can be handed off for seamless mission transition (ratio)
- Percent of information that can be relayed to tactical units (ratio)
- Percent of correct messages transmitted (ratio)
- Percent of correct messages received (ratio)
- Percent of enemy actions of warning provided (ratio)

- Percent of failed attacks on targets that are attributed to incorrect enemy location data (ratio)
  - Percent of unintended attacks on non-targets that are attributed to incorrect enemy location data (ratio)
  - Number of contacts that require re-identification (count)
  - Percent of time lost on mission to re-identify contact (ratio)
  - Percent of targets verified before next targeting cycle (ratio)
  - Percent of contacts with conflicting designation assignments (count)
  - Ability to provide visual information (Y/N)
  - Ability to verify target (Y/N)
- Operational Function: Fires
  - Conduct Battle Damage Assessment (BDA) (Y/N)
  - Conduct munitions effects assessment (Y/N)
  - Recommend re-attack recommendations (Y/N)
- Operational Function: Maneuver
  - Able to identify Target/Team (Y/N)
  - Percent of correctly identified Target/Team (ratio)
  - Time Force delayed due to inadequate reconnaissance/surveillance. (appropriate time: hours, min, sec, etc.)
  - Are Target/Team locations accurate (Y/N)
  - Error of Target/Team location (yards)
  - Percent of Target/Team locations not accurate (ratio)
  - Ability to confirm civilized and natural environment (Y/N)
  - Error of environment locations (yards)
  - Percent of environment locations not accurate (ratio)
  - Time to complete reconnaissance/surveillance (appropriate time)
  - Observe conditions that produce variations in capability (day/night, sun angle, enemy type, counter-detection methods, etc.)
- Human Interface
  - Operator-hours that Minotaur autonomous mode provide on mission (appropriate time)
  - Percent of operator-hours that Minotaur autonomous mode provides on mission (ratio)
  - Maximum number of simultaneous sensors active at one time (count)

- Measures of operator-perceived workload, drain, and stress (observation and interview)
- Number of performance errors over time (count)
- Number of accidents from poor performance (count)

Silbert and Rea (2019) identify a set of performance metrics for what they call multi-target data fusion systems—systems that perform multi-source, multi-target tracking through a “complex process of tracking and identifying one or more targets given a sequence of measurements from one or more sensors or sources” (Silbert and Rea 2019, 4). Later discussion in this report recommends a small number of metrics for initial calculation from simulation runs.

The challenge in this work is in determining the contribution of a specific system (e.g., Minotaur) to overall warfighting effectiveness in the context of a particular force structure, configuration of platform and force sensors and fusion processors, operating against a particular enemy force with its set of systems, and within a particular operational and environmental set of conditions. Given the ability to represent all of these aspects in simulation (a very challenging problem in its own right), it is theoretically possible to hold all conditions the same, varying only the single data fusion system of interest.

F. SUMMARY

There is significant literature and knowledge of operational systems to provide a solid base of understanding of current design practices. It is harder to obtain detailed understanding of the performance of a particular system, and even harder to obtain the contribution of a multisensor data fusion system in a complex system-of-systems configuration on a platform or across a force against a variety of hostile, friendly, and neutral forces and under a variety of operational and environmental conditions.

III. MODELING APPROACHES

A. INTRODUCTION

To assess the performance of multisensor fusion processes, Llinas (2009) identifies testbeds, simulations, and standard data sets as tools for evaluation. The various approaches involve a “cost versus quality/fidelity trade-off” as depicted in Figure 6. This perspective was first conceived by Przemieniecki (1990) at a time when computer simulations and interactive games were not as advanced as they are today. Even so, the general concepts remain applicable.

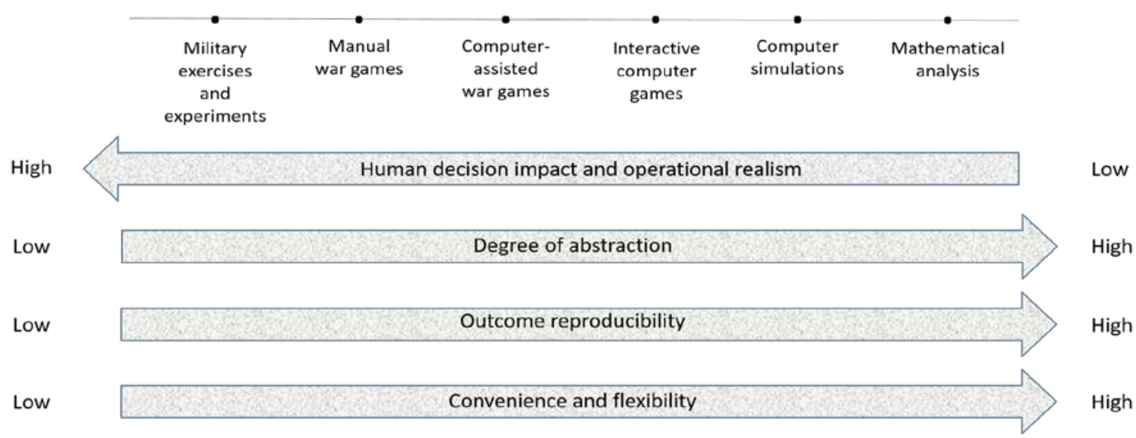

Figure 6. Modeling Techniques and Trade-offs. Adapted from Llinas (2009, 664).

In this chapter, the research team elaborates a number of modeling approaches to examine pros and cons, and to guide the effort toward practical recommendations.

B. MODELING APPROACHES

As Figure 6 illustrated, there are multiple approaches to modeling operational systems (data fusion, in this case), with multiple trade-offs and expectations. That figure did not convey the cost consideration, possibly because that can depend so greatly on the desired level of detail and fidelity for a particular purpose. The following subparagraphs provide additional considerations and tradeoffs when deciding on a method for measuring the operational value of data fusion systems.

1. Real-world Evaluation through Live Experimentation

The most realistic approach, short of employment and measurement in actual operations, is conducting live experimentation of the relevant platforms and systems (far left side of the spectrum in Figure 6). This is difficult and costly to plan, execute, and control. Live experimentation may involve only a single execution of the situations and conditions in a scenario or a very minimal number of replications for analysis. Since there are very few replications (often even just one), it is impossible to exercise the platforms/systems/operators under a wide variety of environmental and threat conditions. Although the Navy has conducted some limited live experiments with Minotaur, the research team had very limited access to classified results due to COVID-19 travel and site visit restrictions. And while experimentation in live operations is considered costly, it may be far less expensive and time-consuming than detailed simulation development. Nonetheless, the limitations persist—the variety of conditions under which the system of systems is evaluated is very minimal.

2. Integrating the System or Process under Evaluation into a Test Environment

If the system cannot be executed in an actual environment, the next approach is to employ the actual system but placed in an experimental setting (such as a test harness) using synthetic or real-world (recorded) sensor feeds and communications. This environment provides the opportunity to include actual operators in conduct of experiments. However, again it is difficult to vary scenarios and conditions, especially when using recorded stimuli. Also, it is difficult to evaluate the synergies or complications introduced by multiple systems interacting together to develop the operational picture, since those systems may not be present in the test environment. One advantage of this approach, though, is the ability to execute the actual system computational processes against a known set of stimuli (real or synthetic).

An additional consideration in the use of a test environment is the ability to substitute components readily. As described by Llinas (2009):

> Over the past several years, the defense community has built up a degree of testbed capability for studying various components of the DF [data fusion] process. In general, these testbeds have been associated with a particular program and its range of problems, and—except in one or two instances—the testbeds have permitted *parametric-level* experimentation but not *algorithm-level* one. That is, these testbeds, as software systems, were built from *point* designs for a given application wherein normal control parameters could be altered to study attendant effects, but these testbeds could not (at least easily) permit replacement of such components

> as a tracking algorithm. … One important consequence of building testbeds that permit algorithm-level test and replacement is of course that such testbeds provide a consistent basis for system evolution over time, and in principle such testbeds, in certain cases, could be shared by a community of researcher-developers. (Llinas 2009, 662)

Such environments exist for studying Minotaur, but the sponsor was unable to obtain access to those resources during the period of performance of this study. It is not known to what extent the existing environments enable parametric-level or algorithm-level experimentation, as described by Llinas above.

3. Evaluation in a Simulated Environment

Clearly, simulation only approximates the real-world. It is difficult, if not impossible, to replicate human and computational processes. Moreover, it is difficult to impossible to replicate the physical environment within which the scenario is executed. This is *not* to say those processes and environments cannot be characterized in some statistical way that captures, statistically, a very high portion of the sources of error and uncertainty in the real-world conditions. Even so, it can be very difficult, if not impossible, to conduct the data collection necessary to create such characterizations. The analyst must be well aware of what the missing sources of uncertainly are and what effect they exert on the outcomes of automated and human processes under various conditions. On the other hand, simulation provides a fully controlled environment supporting statistical analysis using various techniques (e.g., design of experiments, data farming). Simulation also provides flexibility in representing a variety of scenarios and conditions that cannot be obtained in real-world settings. The cost trade-offs mentioned earlier make use of an existing simulation product, such as NSS, highly attractive. If modelers and analysts can use the product to represent and execute much of what is needed, then the costs become limited to license fees (if any), cost of training users, and cost of developing the scenario for data collection. The tradeoff, of course, arises if additional capabilities much be developed to improve the capabilities of the product to meet the study requirements. Depending on the nature of the required change, this could become cost-prohibitive (although generally still less than developing a new simulation from scratch).

4. Hybrid Simulation

A hybrid simulation approach combines the synthetic environment with actual computational software; i.e., employing the actual computational processes of the system(s) under evaluation, with recognition of challenges in presenting the processes with sufficiently realistic stimuli. Development of a virtual environment can immerse human operators into a visually and operationally compelling “world” where they operate a simulated presentation of the actual hardware and user interactions. Analysts can then study user employment of the system and resulting benefits/difficulties. As with the other options, cost to develop the hybrid simulation environment depends on the level of detail and fidelity in the representations required to achieve sufficient realism. This approach requires careful experimental control to support analysis, but has the advantage of executing the actual processes of interest.

5. Evaluating the Human Component in the Processes

Incorporating the human element into simulation of the fusion process requires either human-in-the-loop experimentation or synthetic representation of the human in the simulation model. In either case, a thorough task analysis of the operator actions and decision-making needs to be performed to fully understand what would constitute optimal human performance, at least with respect to the “as-delivered” functionality of the human-system interface. Use of a virtual environment as mentioned in the previous subsection provides an opportunity to vary the actual user interface design to explore potential improvements to operation of the system supporting the human decision-making. The earlier discussion of difficulties and limitations of human-in-the-loop experimentation still apply.

Another option is simulation of the human operators, to include user interface actions and human cognitive processes. Methodologies such as cognitive task analysis would provide the foundation for representation of the human interactions with the system and how those interactions change the human’s perception of the battlespace and influence decision-making. An approach to a detailed representation of the human element in the data fusion process is to use cognitive architectures such as Soar (https://soar.eecs.umich.edu/) or ACT-R (http://act-r.psy.cmu.edu/). NPS and Metron have done work in the past integrating Soar with NSS, so that presents an interesting possibility for future modeling (e.g., see https://nps.edu/web/cag/-/applying-the-soar-architecture-to-model-cognitive-functions-in-a-kill-cha-1).

It is interesting to note that in a discussion of "grand challenges of information fusion," Lambert (2003) describes a *system* challenge as "the desire for a unified framework for SDF [system data fusion], a framework that can account for interactions between people, interactions between machines, and interactions between people and machines" (p 219). In short, Lambert states the question as "How should we manage data fusion systems formed from combinations of people and machines?" (Lambert 2003, 219) Clearly, this remains a challenge to modeling and analysis of data fusion systems. Even so, simulation is an important tool for exploring this complexity.

C. CANDIDATE SIMULATION FRAMEWORKS / SIMULATION SYSTEMS

Two simulation frameworks that are immediately available to MEAD modelers are the Naval Simulation System (NSS) and the Advanced Framework for Simulation, Integration, and Modeling (AFSIM). While other simulation tools may be useful in studies of the operational value of data fusion, project scope limited the investigation to NSS and AFSIM, with the primary focus on NSS.

1. Naval Simulation System (NSS)

NSS is a mission-level simulation providing significant detail in representation of capabilities and performance of platforms, sensors, communications, and weapon systems. Principal focus areas include command and control decision-making and data processing architectures across the platforms and command centers represented in a scenario.

For purposes of this study, a key area of interest is representation of data fusion in NSS. From the NSS Analyst Guide:

> NSS provides for comprehensive data fusion system representation capabilities in four resolution levels described below: (A) ground truth; (B) dead-reckoning with perfect correlation; (C) dead-reckoning with imperfect correlation; and (D) Kalman Filter state estimation with imperfect correlation. … Levels B, C, and D fusion are accessible through three object classes: simple fusion processor, perishable ID fusion processor, and correlation fusion processor. (Metron 2002, 193)

Figure 7 illustrates the basic structure of information processing in a platform represented in NSS. Information (Contacts) from sensors (onboard or offboard) or communications, possibly directly shunted or passed to other platforms through communications capabilities, can enter a pre-fusion processing node. Here, such processing as initial identification (contact identifier generation) or unfused contact filtering can occur. The pre-processed data are then passed, possibly again with some or all of the information shunted to other platforms, to a fusion node. NSS offers several built-in fusion processes that can be selected for this node, such as fusion by signature, by perishable identifier, by correlation, or by Kalman filter. Of course, the suitability of these specific processes depends on the system being modeled. Finally, in the architecture shown, information from the fusion node can pass to a post-fusion processing node for further operations on the data, such as a classification generator, identification generator, or area of uncertainty refinement. The data processing architecture can include queuing nodes on all inputs or on selected inputs that can introduce delays in the flow of information, possibly to represent limited capacities, specialized processing, or even human interactions with the data. Modelers can create very complex data processing architectures using the components available in NSS

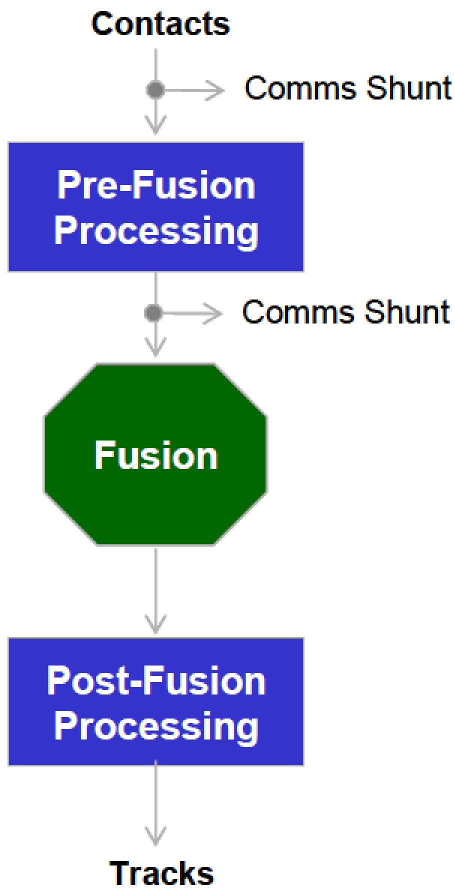

Figure 7. Fusion Processing Nodes in NSS Platform Models. Source: NSS 2002.

It is possible to insert actual system-of-interest fusion algorithms into the data processing flow by creating Pearl scripts encoding the algorithms and integrating those into NSS, without having to modify core NSS software. Further study is needed to determine if the incoming data flows can meet all the input requirements of the actual fusion algorithms in a system like Minotaur.

It is possible to create new processing nodes in NSS and to associate customized software logic; e.g., from the NSS Analyst Guide:

> The incorporation of new data fusion algorithm capabilities into NSS can be reasonably straightforward. There are two main interfaces between a candidate new fusion algorithm and NSS sensor and commander objects as follows. First, NSS sensors will need to satisfy the information assumptions of the fusion algorithm in terms of the content of the assumed sensor observations plus the reported errors. Currently NSS sensors report 2D (latitude and longitude) location, altitude/depth, velocity, classification, identification, and target damage state. Changes to NSS

> sensor representations would be required for a fusion algorithm expecting different (content or format) observation types. Secondly, NSS commanders process the outputs of the fusion algorithm which currently in NSS is again 2D (latitude and longitude) location, velocity, classification, identification, and target damage state. For fusion algorithms producing different track state information, NSS commander logic would have to be suitably modified. (Metron 2002, 186-187)

There is also the possibility of interfacing to external data fusion software through the High Level Architecture standard (IEEE 2010):

> Future NSS data fusion requirements in the areas of 3D ballistic tracking, nonlinear undersea warfare tracking, or other advanced fusion algorithm employments can be satisfied by federating operational tracker software with NSS using the NSS High Level Architecture (HLA) interface. Such federation of NSS with data fusion software would eliminate the need to port complex algorithm code directly into NSS (which nevertheless is also an option). (Metron 2002, 187)

However, lacking access to the real-world computational algorithms, the researchers did not attempt to incorporate any real-world system algorithms into the platform and system representations during this study. This remains an open area for follow-on work.

Chapters IV and V of this report provide considerable details on the use of NSS to represent the scenarios under study.

2. Advanced Framework for Simulation, Integration, and Modeling (AFSIM)

AFSIM is a multi-domain simulation framework providing a flexible architecture for representing platforms, sensors, systems, weapons, and processes. Figure 8 shows the principal components of the AFSIM architecture. The architecture provides basic building blocks for constructing agent-based simulations of interest to the user community. Developers encode agent behaviors using a specialized scripting language, providing significant flexibility in what can be represented. Whereas users are largely confined to the built-in capabilities of a simulation like NSS, AFSIM provides flexibility to represent any aspect of warfighting of interest to the user, at whatever level of detail needed to meet user requirements. Of course, with greater flexibility comes potentially greater costs, in that the user must create the functionality desired for a particular purpose. Today, there are several hundred organizations using AFSIM, so the *opportunity* for sharing code and capabilities is high. For example, the Air Force Research Laboratory (AFRL) is working on a multi-target tracker simulation using AFSIM. That organization has indicated a willingness to share the model with other organizations in the AFSIM Users' Group, which could greatly reduce the effort required by others to recreate the capability. On the other hand, the software would need to be examined carefully to determine to what extent it addresses a user's particular study objectives or to determine if it could be readily adapted to for this intended purpose.

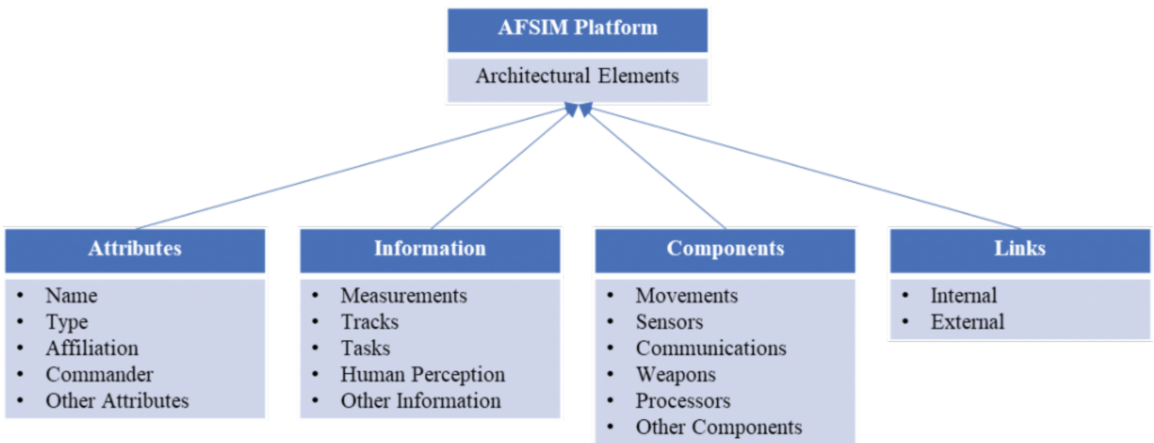

Figure 8. AFSIM Architectural Elements. Source: West and Birkmire 2020.

Platform models in AFSIM can have components for various processors and track managers, including several correlation methods. The processors can include fusion centers similar to NSS. There are a number of predefined processor types in AFSIM. Most importantly, the code implementations of those types are open to the users, allowing for reuse and modification for specific purposes. Compared to NSS, the AFSIM architecture provides a more generalized means of interfacing external software (such as the data fusion processes from an actual system) to a simulated scenario through dynamic linked libraries.

Addressing the current problem through a more bottom-up development approach in AFSIM opens the door to consideration of innovative techniques for conceptualizing the modeling requirements, especially those hard-to-quantify aspects of the operational space. For example, Pugsley (2017) describes a model development process (MDP) to address what he calls “external, seemingly-intangible, non-quantifiable” factors and effects:

> Hard-to-quantify factors and effects have represented a significant challenge, and rather than addressing these challenges, they have for the most part been largely ignored by model developers. And, while ignoring the irrelevant aspects of the real world is paramount to the success of any MDP, in an era of unprecedented cross boundary and cross domain interoperability, the determination of the line between relevant and irrelevant must be more closely scrutinized. By moving away from considering hard-to-quantify factors and external force multipliers as nonquantifiable, and rather describing such effects as External, Seemingly Intangible/Non- Quantifiable (ESINQ), a more accurate representation of these effects can be captured by model developers, one which addresses the possibility of quantifying the impacts of these effects in the referent, while highlighting the difficulty in doing so. (Pugsley 2017, xxi)

Because of the explicit modeling of data fusion processing (as well as explicit communications and command and control decision-making) available in NSS, we have approached the problem more directly in that simulation. However, whereas NSS provides these capabilities, not all of this functional infrastructure may be available readily in an AFSIM model of the operational and tactical environment. Of course, if we do not attempt to include the human operators in the simulation environment, neither as human-in-the-loop execution of the simulation nor as simulated humans, then both the representation of the operations of interest in NSS and the likely approach to representation of the operations of interest in AFSIM will not provide a full representation of the data fusion process. In that event, Pugsley’s approach may be a way to formulate and account for the effects of the human operators in the overall process. This could simplify the AFSIM development effort without sacrificing important conceptual components of the operational environment.

D. SUMMARY

As an available simulation system, NSS provides a foundation for the study of the operational value of data fusion. Chapter IV of this report describes the proposed scenario for such study and provides a preliminary approach to representation of the scenario and key aspects of the data fusion process using NSS. Project scope and other restrictions did not permit a detailed analysis of the effort required to represent the scenario and data fusion processes in AFSIM, although it is clear that other organizations are exploring similar questions using that framework. Other simulations, such as the Extended Air Defense Simulation (EADSIM), Executable Architecture Management System (ExAMS), or Next-Generation Threat Simulation (NGTS), may benefit the study of the operational value of data fusion. Moreover, process modeling tools such as the commercial ExtendSim product (https://extendsim.com/), may enable a detailed representation and examination of the data and functional flows of sensor information through the data fusion architecture. It was not possible to examine these and other simulations or modeling approaches during this study, but could prove valuable in follow-on research.

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IV. SURFACE WARFARE SCENARIO AND EXPERIMENTAL APPROACH

A. INTRODUCTION

Evaluation of system performance has to occur in some operational context. Silbert and Rea (2019) state it this way:

> This means a multi-target data fusion (MTDF) system needs to be tested over time as the situation evolves. These evolving situations are usually referred to as scenarios or vignettes. Thus, the performance of a MTDF system is quantified for a particular scenario. (Silbert and Rea 2019, 5)

This chapter describes a notional scenario and alternative vignettes containing operational elements considered important for simulating data fusion systems and for evaluating the operational impact of such systems on warfighting effectiveness. The discussion provides a suggested approach for representing the scenario in NSS.

B. BASE SCENARIO AND EXCURSIONS

[NOTE: Comments in *italics* include reasoning, suggestions and thoughts about fusion and modeling.]

[NOTE: There are lines that are ~~struck through~~; they are left in the discussion, because at some point their guidance might prove useful.]

This scenario is designed to answer one key question: Does airborne fusion enable the P-8 platform to improve its contribution to the surface warfare (SUW) mission?

The approach is to model two excursions of the exact same scenario. In the first excursion, one P-8 baseline uses existing sensors and fusion is accomplished by the crew. In the second excursion, an updated P-8 with advanced fusion capabilities and additional offboard sensor input executes the identical mission, but most of the fusion is automated.

The mission is to patrol an assigned area, then detect, identify and classify all surface contacts, with an emphasis on Red Combatants, and report location to the Surface Warfare (SUW) Commander (SUWC). The SUWC needs accurate locations for the Red Combatants, and must understand what other contacts, even if neutral, are nearby the Red Combatant. SUWC also needs to know where Red Decoys exist.

The two excursions will be compared in several ways:

- How long does it take to find the Red combatants?

- Can the P-8 maintain track of the Red combatants?
- How accurate are the track report positions compared to ground truth, since SUWC might use these reports for a targeting solution.
- To complicate matters, Red will likely deploy vessels to act as Red Combatant decoys. Will the P-8 be able to deduce which are real and which are decoys?
- ~~To further complicate matters, Red may deploy fighters with a mission to engage and destroy the P-8. The P-8 will need to use a combination of offboard reporting and onboard capabilities to avoid the Red fighter. This may necessitate departing the patrol area early, thus reducing the time the Red combatants are tracked. We put this off as not necessary. May be worth looking into later.~~
- How much time in EMCON can the P-8 spend? We hypothesize that increasing time in EMCON makes targeting the air platform more difficult, if that was Red's intent. We realize that detecting and reporting contacts often requires emitting various sensors. We believe that the fusion capabilities we have modeled make staying in EMCON longer easier to do, and that this adds survivability to the mission.

1. Scenario Geography

Blue Airbase: 34-10 N, 119-11W NAS Point Mugu

Blue P-8 patrol area, NE corner: 30N, 118W NW corner: 29N, 128W SW corner 16N, 124W SE corner 18N, 110W

Red Naval Base: 23-02N, 110-03 W Naval Station Los Cabos

~~Red Air Base 23-25N, 109-38W~~

Red LB#1 (where LB = launch basket) 25-26N, 116-117W

Red LB#2 22-23N, 115-116W

Red LB#3 20-21N, 118-119W

Red LB#4 18-19N, 121-122W

Red LB#5 16-17N, 118-119W

Red LB#6 15-16N, 111-113W

Red LB#7 19-20N, 113-114W

~~Red Air Barrier~~ 21-30N, 109-112W

White Canal route: 15N, 111W to 20N, 122W

White Coastal route: 14N, 110W to 29N, 119W

2. Scenario Order of Battle

<u>Blue</u>

1 x P-8A: With airborne surface search radar, ESM, synthetic aperture radar, optical sensor. Fusion capabilities limited. P-8A can certainly fuse all sensors, but takes time, and often done manually. Can receive ESM from offboard sources via Link or radio report.

1 x P-8M (for "Modified"): Second excursion, with airborne surface search radar, ESM, synthetic aperture radar, AIS, ship measuring sensor, optical sensor. Fusion is more automated. ESM and AIS fused with surface radar picture automatically. Offboard ESM is also automatically fused with surface radar picture.

Red

3 x Red combatants (should be representative), standard sensors (see signature discussion for Red combatants)

3 x Red decoys (should be smaller size than Red combatants; see signature discussion)

~~1 x squadron of Red fighters with 8 fighters not required yet~~

White

7 x 4-boat groups of fishing boats

10 x single larger fishing boats

80 x merchants

- 35 merchants transit the Canal route
- 35 merchants transit the Coastal route
- Last 10 merchants can fill in other areas

3. Scenario Command and Control

Red

Red Group Commander

Red SUWC

~~Red Air Defense Commander not required yet~~

Blue

Blue Group Commander

Blue SUWC

Blue Air Defense Commander not required yet

4. Scenario Motion Plans

The P-8 will fly during daytime. P-8 flies transit to patrol area, 440 Knots true. Patrol speed: use whatever is in the database. Transit altitude 30K feet. Patrol altitude 10000 feet. Then, random search is fine, with the tactics table. We believe that there may be other ways to do the search, and this would take a little work in the model. We recommend using whatever approach allows the P-8 to have maximal coverage of the region.

Red combatants depart port at time 0, and go to their patrol areas in a complex motion plan:

Red Combat #1 LB6, LB7, LB3, LB2

Red Combat #2 LB4, LB3, LB5, LB6

Red Combat #3 LB1, LB7, LB4, LB5

Red Decoy #1 LB3, LB2, LB1, LB4

Red Decoy #2 LB6, LB5, LB4, LB1

Red Decoy #3 LB7, LB3, LB5, LB6

Transit at same speed of transit as combatants, 15 knots. Patrol areas at 10 knots, for ten hours. Combatants operate in EMCON on patrol; intermittent (half) EMCON in transit.

For a classified scenario, might want to check with Intelligence SMEs to make sure this plan is realistic enough.

Merchant ships, according to Wikipedia, travel 16-25 knots. On each route, have half go one direction, and vice versa.

Fishing boats: Have the seven groups of four fishing boat fleets (FG) operate within 200NM of coast:

FG#1: near LB#1

FG#2: just east of LB#2

FG#3: in LB#7

FG#4: just east of LB#7, north of LB#6

FG#5: just east of LB#2

FG#6: just south of LB#7, North of LB#6

FG#7: southeast of LB#6

Ten independent fishing boats: Place in P-8 patrol area on random search, at five knots.

Depending on actual classified scenario, might need to either increase or decrease White shipping and fishing to reflect realistic observations.

5. Sensors and Signatures

Red combatants and decoys have five signatures (several of these are not electromagnetic *signatures* per se, but it is convenient to conceptualize them in this way, and is directly supported by NSS representations): inherent radar return signature, ESM line of bearing (LOB), SAR "Blob" signature, ship length signature, and optical signature. *We believe that in the future, especially as Red uses decoys and deception, sensing a variety of phenomenology and features will help reduce the effectiveness of decoys and deceptions. Increasing the number of sensors used, though, adds to crew workload, unless much of it can be fused. Thus, we believe that fusion adds value in a deception/decoy rich environment.*

- The ESM LOB signature is on when not in EMCON, off otherwise. If detected, it gives identification and classification to the receiving sensor of Red Combatant, even if really is a Red Decoy.
- The SAR Blob signature is always on. In the tactics, there are various times when Blue may choose to use its blobology sensor. If it uses the blobology sensor it will return correct classification and identification. This signature has a range that is a factor of the radar search range. Refer to P-8 details for that. *We say this because on the old ISAR radar on the P-3, the blob range, because it used more energy, was shorter by some xx% than the max radar range.*
- The Ship Length signature is always on. If Blue chooses to use that sensor, it returns correct classification and identification of Red Combatant or Red Decoy. *The Minotaur User's Manual and other sources all discuss ship length sensor in detail. Recommend checking with the Fleet or Weapons School if this capability really works.*
- Only Red combatant or decoy have ESM LOB signature, blobology signature, and ship length signature. *As NSS instructors suggest, keep it simple. Yes, we could add blobology and ship length signatures to merchants, but we believe this needlessly complicates things. There are other scenarios, though, where this might be useful (e.g., when the combatant wants to be "seen" as a merchant).*
- Red has an optical signature. There is a small chance, adjusted in sensor performance, that none of the other sensors will determine classification and identification. Optical sensor will generate correct classification and identification but restricted to optical sensor range.

Merchant shipping will have standard radar return signature, ESM LOB signature, and an AIS signature.

Fishing boats have standard radar return, ESM LOB, and optical signatures.

P-8 uses six sensors: airborne surface search radar; ESM receiver; SAR "blobology"; ship length; and optical.

P-8M: airborne surface search radar, ESM receiver, AIS, radar-derived ship length, SAR blobology, and optical. *Note the P-8 does not need any special signatures. If one intends to explore air defense, evasion, and escape analytic questions, then signatures need to be added to make that possible. In the future, this may be useful.*

6. Scenario EMCON Plan and Tactics

P-8 Baseline: Transit in EMCON. In patrol area, general idea is to turn on surface-search radar (SSR), then go to EMCON and leverage other sources to localize and identify the contacts of interest (COIs):

(1) Given a radar picture, take closest contact. Go EMCON and check for ESM.

a. If ESM line of bearing (LOB) correlates with track, and if ESM bearing is radar associated with merchant (their radar is always on), then report contact to SUWC and fly towards next closest track repeating step (1). Note that reporting, depending on comm plan, may violate EMCON. In our modeling we did so, because the SUWC wants to update the COP.

b. If ESM LOB is associated with fishing boat, then report contact to SUWC and fly towards next closest contact, repeating step (1).

c. If ESM LOB is associated with Red Combatant COI, then use SAR blobology sensor (this means leaving EMCON to operate radar).

i. If blobology confirms Red combatant, then report contact to SUWC and fly towards next closest contact, repeating step (1).

ii. If blobology confirms COI is too small to be Red combatant, then report contact to SUWC as Red Decoy and fly towards next closest contact, repeating step (1).

iii. If blobology is inconclusive, then close with the contact to optical range and use optical sensor.

[1] If optical sensor confirms Red combatant, then report contact to SUWC and fly towards next closest contact, repeating step (1).

[2] If optical sensor confirms merchant or fishing boat, then report contact to SUWC and fly towards next closest contact, repeating step (1).

[3] If optical sensor confirms Red Decoy, then report contact to SUWC and fly towards next closest contact, repeating step (1).

d. If there is no ESM LOB, then use SAR blobology sensor.

i. If blobology confirms Red combatant, then report contact to SUWC and fly towards next closest contact, repeating step (1).

ii. If blobology is inconclusive, then close to optical range and use optical sensor.

[1] If optical sensor confirms Red combatant, then report contact to SUWC and fly towards next closest contact, repeating step (1).

[2] If optical sensor confirms merchant or fishing boat, then report contact to SUWC and fly towards next closest contact, repeating step (1).

[3] If optical sensor confirms Red Decoy, then report contact to SUWC and fly towards next closest contact, repeating step (1).

P-8M. Transit in EMCON. On patrol, the main idea is to operate in EMCON as much as possible, using mainly AIS and ESM to identify and classify tracks.

(1) Arrive in patrol area. Use surface search radar to establish picture. Compare AIS picture and radar picture, and dismiss all tracks reporting AIS (we should set it up that the AIS sensor reports directly to the SUWC as well, so SUWC already has AIS tracks). This should reduce the number of tracks to a small number. Return to EMCON. The easy way to model it is not to process the AIS tracks at all, so only the Combatant tracks are of interest. This assumes away this logic for eliminating AIS tracks, but loses the AIS picture. It's a trade-off. The modeler could create a new fusion processor that does the distance comparison and setting them the same, if that would be appropriate, and then add that into the processing architecture. Again, the importance of modeling AIS explicitly depends on operational input from the wing or Weapons School. As modelers often paraphrase Einstein, keep the model as simple as possible, but no simpler.

a. Focus on nearest remaining track. If ESM LOB exists and is associated with merchant or fishing boat (their radar is always on), then report contact to SUWC and fly towards next closest contact, repeating step (1).

b. If ESM LOB is associated with Red Combatant, then use Sensor M ship length sensor (this necessitates turning radar back on).

i. If ship length confirms Red combatant (equals plus/minus 40 feet whatever the data base has for the length of that ship), then report contact to SUWC and fly towards next closest contact, repeating step (1).

ii. If ship length confirms Red Decoy (less than 300 feet), then report contact to SUWC and fly towards next closest contact, repeating step (1).

c. If ESM LOB does not exist or is inconclusive, then use SAR blobology sensor (this means leaving EMCON to operate radar).

i. If blobology confirms Red Combatant, then report contact to SUWC and fly towards next closest contact, repeating step (1).

ii. If blobology is inconclusive, then close the contact to optical range and use optical sensor (return to EMCON).

[1] If optical sensor confirms Red combatant, then report contact to SUWC and fly towards next closest contact, repeating step (1).

[2] If optical sensor confirms merchant or fishing boat, then report contact to SUWC and fly towards next closest contact, repeating step (1).

[3] If optical sensor confirms Red Decoy, then report contact to SUWC and fly towards next closest contact, repeating step (1).

White merchants. Transit and radiate their merchant surface search radar (and AIS “signature” in P-8M excursion).

Fishing boats in groups. One radiates all the time. The others are within five miles.

Independent fishing boats. Radiate surface search randomly but at least 60% of the time.

~~**Red Air Fighter**. EMCON during transit, radiates air search radar while on station (barrier) (no need to represent this yet).~~

Red Surface Combatant (and decoys). There are three real combatants (~440 feet), and three decoys. The decoys are shorter in length (~200 feet). The real surface combatants execute EMCON when in their patrol area, but radiate while in transit. The decoys use a random EMCON schedule, half on, half off.

C. SUGGESTIONS FOR REPRESENTATION OF THE SUW SCENARIO IN NSS

Modeling fusion functions in NSS is possible, but for many reasons was seldom employed in most analyses. What follows are ideas on how to model fusion functions in NSS. This material is intended to supplement the NSS Analyst’s Guide, in the context of investigating the operational value of data fusion systems such as Minotaur.

In this case, we are considering airborne platforms with limited, but still useful, fusion functionality. While the modeling approach may change slightly for different scenarios, these techniques should get the analyst started. NSS does not explicitly model advanced fusion, but does model correlation. It also has a data processing set of filters which can be used to represent the effects of fusion. Care must be taken, because fusion works for a very narrowly defined set of assumptions, so one needs to study the particular fusion engine and understand the assumptions and constraints before trying these techniques. We also recommend discussion with actual users vice PowerPoint slides and/or user manuals because reality is often different than program office intentions.

Each portion of the discussion is intended to show a step-by-step process for modeling considerations. This supplement is intended for modelers familiar with basic NSS modeling. We assume the basic scenario set-up described earlier in this section.

1. Sensors and Signatures

Consider again the sensors onboard the P-8 identified earlier:

- Airborne Surface Search Radar. We see no required modifications of this sensor. Model as you usually do.
- AIS. For an AIS sensor set up a special sensor detector that detects special signal type 1 (or, can type in a name for the custom signature). Put the special signature type 1 only on the AIS-enabled ships. Use cylindrical volume of large diameter and Pd=1. Have it detect classification, identification, location, CUS, and SPD ("super" sensor). Have no processing queue for AIS. Could have Pd = 0, then cued Pd = 1; i.e., pick up on a sensor, then cue AIS: sensor hit first, tactic to cue AIS sensor, then cued Pd, which would fuse with the radar track.
- ESM Receiver. Set up ESM as a spot sensor, have it send an elongated ellipse which simulates a line of bearing.
- SAR Blobology. Assume operators do interpretation. In the queue, register the ID after getting through the queue; define the sensor to have the capability to generate the ID, but not processed, so it needs to go through a pre-fusion node (contact processor) to pull out the ID.
- Ship Length. To set up ship length sensor, create a special sensor associated with special "ship-length" signature. Make probability of detection = 0 for uncued. Once radar cues target, then make probability of detection for the cued sensor = 1. Make range of special sensor equal that of the radar. Add small delay in special sensor prefusion queue to account for slight operator check, remembering that 30 seconds might be a long time! Only install special signature on Red Combatants and Red Decoys. Again, this is a good one to check with Fleet or Weapons School.

  One way to build a sensor is to make the sensor provide unprocessed data (i.e., normal radar, no ID), then determine id or mistaken id extracted through processing queue, model that result as a queue in the data architecture, then send that to contact processing fusion in data architecture, then to local fusion or to SUWC fusion. The special sensor only grabs ID information (Pd = 1, using same range as the radar).

* Optical. We see no required modifications of this sensor. Model as you usually do.

For the P-8 sensors, differentiate the confidence level for each sensor, such that confidence on optical > length > blobology > ESM > radar track.

2. Data Processing Architecture

NSS provides the ability to construct a data processing architecture. Since fusion requires the consideration of how two or more data sources might help one another, organizing a data architecture is important if one wants to model fusion-like functions. The NSS Analyst Guide has considerable, detailed descriptions available on this. In the past, METRON suggested that most user analysts have gone with the default settings, so not many users are familiar with these options. Because that manual must cover every possibility, by the time one gets done reading the section, it is still not obvious what to do. We will attempt to do so here. Start with Figure 9.

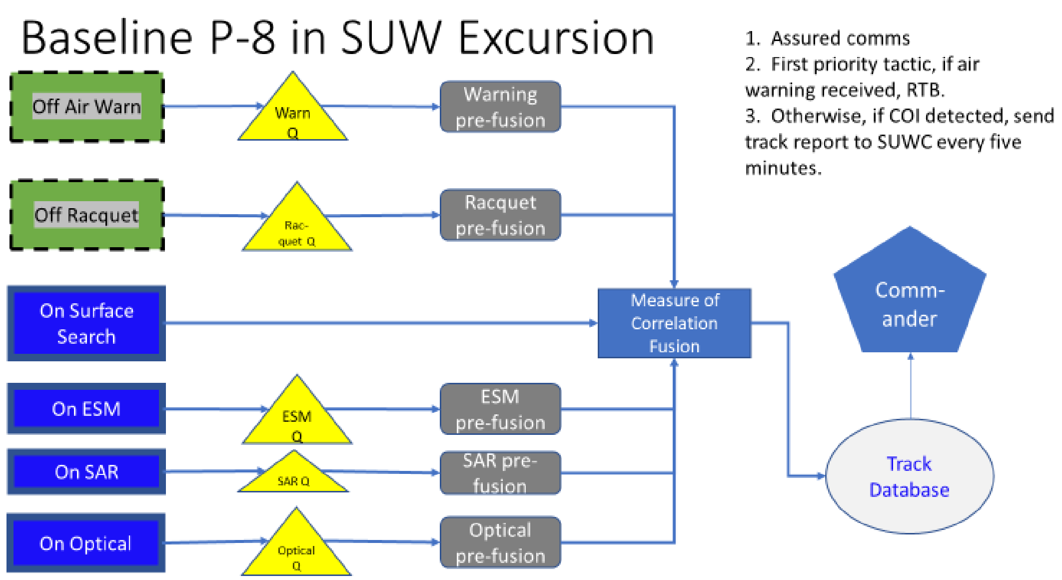

Figure 9. Example Data Processing Architecture in NSS

The basic flow is data source to queue to pre-fusion to fusion (really correlation, as discussed below) to track database to messaging Commander(s) which follows reality at a high level. Complications occur easily because of the different data sources and their potential dissimilar paths. Not pictured is that at any point whatever kind of data is available at the end of any process, that data can be shunted via any communications path to other entities. This may be important if two or more platforms have fusion functions that can collaborate (such as Minotaur Grid).

Here are a couple of ideas on how to use this construct. On the upper left, there is a data source called *off air WARN*, standing for offboard airborne warning. This would be a voice call of a potential air threat. This data enters a waiting queue. Since it was voice report, the receiver would write this data down, then perhaps enter it into the mission system. This takes time. She might also have to announce to the rest of the crew this information, since not all crewmembers might have been monitoring that circuit. In the pre-fusion box, the system would then capture the data entry and display it in the mission system, where the mission commander can understand the report and make tactical decisions. Depending on the mission system, this information may be fused with other reports or be fused with ESM signals that correspond to an air threat.

NSS provides the opportunity to adjust the amount of time it takes to do these functions. In a strong fusion system, once the voice data is input, it may take just seconds for the mission system to recommend action and correlate with other sensors. On many of today's platforms, this is still handled manually, and the fusion may take minutes. From a mission analysis point of view, one can see that these time differences can add up, and that the data processing architecture is a good place to reflect these manual versus automated differences in time. As mentioned previously, systems that provide fusion work within a certain range of constraints, and it is possible for fusion systems to make inferences that are incorrect. It is important for modelers to work closely with those familiar with these fusion systems to ascertain performance variabilities, and see if additional modeling techniques may be needed.

Consider *On SAR* as a separate data source example. *On SAR* stands for onboard (organic) synthetic aperture radar. SAR is used one contact at a time, because it uses a different radar mode. Thus, there is a waiting cue for any particular track to be checked with SAR. Once SAR is applied to a track, it also takes a time to integrate the return into something that can be deciphered. Currently, using SAR to identify or classify a target is more of an art form than science, but it can work. Note that the queue adds time to the process, then so does the pre-fusion process of SAR. Also, one should account for the artistry of SAR by using known probabilities of identification/classification from authorized sources.

One final example is *On Surface Search*. We just mean the on-board surface search radar. Note there is no queue or pre-fusion step, because the radar returns location. The “fusion” box is actually a correlation function. It considers the repeating contacts and generates a track with course and speed. The radar does not generate classification or identification, but the other sources can contribute that information within the fusion function. The output of this effort is the track database. Rule sets can be established to share that information with Commanders and other platforms as the mission demands. If the platform is in EMCON, then no information is shared, no matter the quality of their newly fused track database.

Notice that it is not difficult to add another data source, say SIGINT, to this architecture. The devil is in the details of understanding what such a sensor may provide to the platform, and how that information can be used to improve the overall picture. One can also assume that perhaps the SIGINT source is at a different classification level, thus complicating the data processing architecture. The above assumes all the sources are at the same classification level. Cross-domain security modeling would take further research effort.

A key point, though, is that all of the representations developed in NSS for this study use NSS pre-fusion and fusion nodes *as currently available* in the simulation system. As a proof-of-concept, the processing algorithms available in NSS may be considered representative of the algorithms used in real systems, but are certainly not equivalent to the algorithms used in any particular system, such as Minotaur. Scenario Definition and Execution in NSS. As mentioned earlier, lacking access to the real-world computational algorithms for Minotaur, the researchers did not attempt to incorporate its algorithms into the system representations. This remains an open area for follow-on work.

Much of the SUW scenario has been defined in NSS as an example set-up and proof-of-concept execution for MEAD NSS modelers. Figure 10 shows the operation area for the SUW scenario, with platforms in motion approximately 48 minutes into the scenario execution. The P-8 (call sign BLUE TRACKER) is enroute to its patrol area and forming tracks from detections of surface platforms (in this case, merchant vessels).

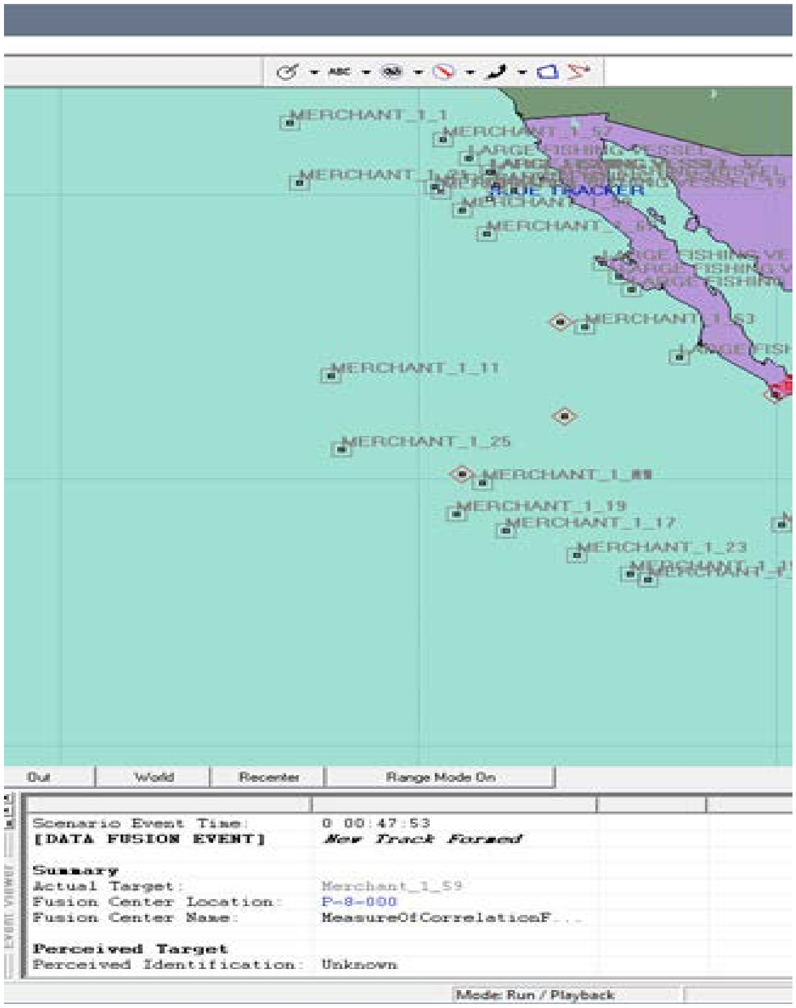

Figure 10. Baseline SUW Scenario Execution in NSS

D. METRICS

The following is an initial set of metrics for investigating the operational value of data fusion in the suggested scenario:

- Average time to detect and ID Red Combatant #1, Red Combatant#2, and Red Combatant#3.
- Average time to detect and ID Red Decoy #1, Red Decoy #2, and Red Decoy #3.
- For P-8 flight, every 15 minutes compare P-8 surface picture to ground truth. There are 70 total contacts in the scenario. What is percentage held by the P-8? For contacts held, what is average error distance from ground truth?

- Number of contact reports P-8 makes to SUWC during flight for merchants, fishing boats, Red Combatants, and Red Decoys. From contact reports, average AOU.
- Average time P-8 radiates air surface search radar? Maybe it makes a difference which mode it is in, general surface search versus blobology mode.

E. EXPERIMENTAL DESIGN

As proposed, the experimental design is straightforward. Rather than an experimental design involving numerous independent variables, the approach is to vary only the data processing architecture onboard the P-8. Running the model many times will generate output distributions for the selected metrics, and statistical tests can be performed to determine if the output measurements are likely from the same distributions or different distributions (the working hypothesis for the study asserts the distributions would be different). If no statistical difference is indicated, then it is possible that the new data fusion capabilities truly have no measurable effect on the warfighting outcome, OR that the modeling to that point has not yet truly distinguished the differences between the baseline architecture and the new architecture. At that point, further work would be needed to ensure that critical differences have been represented in the modeling.

Future work also can consider alternative designs where analysts begin to vary parameters defining the data processing architecture in order to find areas of the design space that provide the best overall performance of the system-of-systems. Such parameters then inform future system improvements, or enable rapid evaluation of overall effectiveness when isolated performance parameters are improved through new algorithm design or other modifications to the fusion processes.

F. SUMMARY

The research team has described a study approach for investigating the operational value of data fusion. The team has implemented much of the scenario elements in NSS as a proof of concept and example for MEAD modelers, although further work to refine and test the scenario is needed.

V. ANTI-SUBMARINE WARFARE SCENARIO

A. INTRODUCTION

The previous section discussed evaluation of operational value of data fusion in a SUW scenario (baseline and excursion). In this chapter, we describe a scenario for performing a similar analysis but in the context of an ASW scenario.

B. ASW BASE SCENARIO AND EXCURSIONS

[NOTE: Comments in *italics* include reasoning, suggestions and thoughts about fusion and modeling.]

[NOTE: There are lines that are ~~crossed out~~; they are left in the discussion, because at some point their guidance might prove useful.]

This second scenario is designed to answer one question: Does airborne fusion enable the P-8 and MH-60R ASW platforms to improve their contribution to the anti-submarine warfare (ASW) mission?

The approach is to model two excursions of the exact same scenario. In the first excursion (baseline), one P-8 and MH-60R baseline aircraft use existing sensors. Fusion is accomplished by the crew. In the second excursion, an updated P-8 and MH-60R with advanced fusion capabilities and additional offboard sensor input execute the identical mission, but most of the fusion is automatic. Per discussion with MH-60R operators, this advanced airborne fusion also enables the MH-60R to contribute ESM information. Normally when an MH-60R conducts an ASW mission, they are too busy to manually collect and fuse ESM information.

In this scenario, the P-8 has an ASW operating area, and is supplemented by the MH-60R when available. The mission is to search an assigned area, then detect, classify, and attack all Red submarines and report same to the ASW Commander (ASWC; they may call it Undersea SWC now, but we are old). The ASWC needs accurate locations for the Red submarines, Red combatants, any decoy ships/submarines, and all White shipping.

The NPS researchers built much of the first scenario in NSS as an example and proof-of-concept for MEAD modelers. We were not able to do so for this scenario, so there is less detail in this description.

The two excursions will be compared in several ways:

- How long does it take to find the Red submarines and combatants?
- Can the P-8 and the MH-60R detect, classify and attack the Red submarines?
- How accurate are the surface track reports positions compared to ground truth, since ASWC wants to attack submarines, not surface vessels.
- To complicate matters, Red will likely deploy a UUV to act as a Red submarine decoy. Will the P-8 and/or MH-60R be able to deduce which are real and which are decoys?
- To further complicate matters, Red may deploy fighters with a mission to engage and destroy the P-8 or MH-60R. The P-8 will need to use a combination of offboard reporting and onboard capabilities to avoid the Red fighter. This may necessitate departing the patrol area early, thus reducing the time the Red combatants are tracked. We put this off as not necessary. May be worth looking into later.
- How much time in EMCON can the P-8 spend? We hypothesize that increasing time in EMCON makes targeting the air platform more difficult, if that was Red's intent. We realize that detecting and reporting contacts often requires emitting various sensors. We believe that the fusion capabilities we have modeled make staying in EMCON longer easier to do, and that this adds survivability to the mission. We realize that on an ASW mission, this may not be a useful metric, since ASW does normally require emissions.

1. Scenario Geography

Design the geography such that the P-8 and MH-60R can interact in coordinated ASW. The scenario is designed to look at activity over the course of one P-8 on station, because the intent is to see if fusion helps in a particular mission. Campaign analyses might require an extended time frame. Trying to keep this simple for now. There will be two merchant routes, the coastal route and the canal route.

2. Scenario Order of Battle

Blue

1 x P-8A

With airborne acoustic, surface search radar, ESM, SAR, and optical sensor. Fusion capabilities are limited. P-8A can certainly fuse all sensors, but takes time, and often done manually. Can receive ESM from offboard sources via Link or radio report.

1 x MH-60R

With acoustic, surface search radar, ESM, and optical sensor. Can fuse sensors manually, if time is available.

1 x P-8M (for modified)

Second Excursion, with airborne surface search radar, ESM, SAR, AIS, ship length sensor, optical sensor. Fusion is more automated. ESM and AIS fused with surface radar picture automatically. Offboard ESM is also automatically fused with surface radar picture.

1 x MH-60R-M

With acoustic, surface search radar, ESM, and optical sensor. Fusion is more automated. ESM and AIS fused with surface radar picture automatically. Offboard ESM is also automatically fused with surface radar picture.

1 x DDG

With active and passive acoustics, surface search and air search radar, ESM, and optical sensors. In this scenario, DDG is not equipped with fusion capabilities, but we recommend adding it in another scenario.

Red

1 x Red SSGN, standard sensors/ see signature discussion for Red submarines.

2 x Red SSN, standard sensors/ see signature discussion for Red submarines.

1 x submarine decoy UUV, fake acoustic signature, plus its own acoustic signature. Because its autonomy system requires frequent updates, UUV comes to comms depth approximately once every six hours, though a bit randomized. It stays at comms depth ten minutes +/- 3 minutes. UUV carries no weapons, so is not a threat, just a distractor.

3 x Red DDGs. These will be located outside the P-8 patrol area far enough away to not threaten the P-8 and MH-60R, but detectable by the P-8 and MH-60R on ESM at times.

~~1 x squadron of Red fighters with 8 fighters not required yet~~

White

4 x 4 boat groups of fishing boats

5 x single bigger fishing boats

40 x merchants

17 merchants transit the Canal route

17 merchants transit the Coastal route

Last 6 merchants can fill in other areas

3. Scenario Command and Control

Red

Red Group Commander

Red SUWC

Red USWC

~~Red Air Defense Commander not required yet~~

Blue

Blue Group Commander

Blue SUWC

Blue ASWC

~~Blue Air Defense Commander not required yet~~

4. Scenario Motion Plans

Blue P-8 will fly Day 1, hour 0. Fly the P-8 during daytime. P-8 flies transit to patrol area, 440 Knots true. ASW patrol speed uses whatever is in the database. Transit altitude 30K feet. Patrol altitude as required by ASW mission. Blue MH-60Rs are on station continuously in support of the P-8. That implies some relieving plan.

Red submarines will be operating in same area as the ASW search area. SSN objective is to detect, classify, and attack Blue DDG. Red SSGN has a launch basket for longer range missile strikes against targets not in the scenario. Thus, the SSGN will make every effort to stay quiet and hidden. The SSN has one comms window per 24-hour period. The SSN will also come to periscope depth if it thinks it is going to attack the DDG. The SSGN does not need to surface to shoot its missiles, but it will come up at least once every four hours to comms depth to get targeting updates. Expect the Red submarines, to the greatest extent possible, to leverage shipping lanes and fishing boats to mask their movements.

Merchant ships, according to Wikipedia, travel 16-25 knots. On each route, have half go one direction, half the other.

Fishing boats: Have the seven groups of four fishing boat Fleets (FG) operate within the ASW operating area.

Ten independent fishing boats: Place in P-8 ASW patrol area on random search, at five knots.

Depending on actual classified scenario, might need to either increase or decrease White shipping and fishing to reflect realistic observations.

5. Scenario Sensors and Signatures

Red combatants in this scenario have one signature, air search radar. Red Submarines have a passive acoustic signature, a signature associated with returns from active acoustic pinging, a surface search radar that is detectable, and a periscope/mast signature detectable by surface search radar and optically. For simplicity, the Red combatant air search radar is always on.

The decoy Red submarine UUV has both a fake passive acoustic signature, similar to the SSN or SSGN, depending on a schedule, a real passive acoustic signature based on its actual propulsion system that is usually masked by the fake signature, a signature associated with returns from active acoustic pinging, a surface search radar that is detectable, and a periscope/mast signature detectable by surface search radar and optically. The Red submarine and submarine decoy passive acoustic signature and returns from active acoustic are always on. Depending on what intelligence advises, the fake passive emitter on the decoy may not be 100% reliable, and that should be accounted for if it is significantly less. Obviously, the submarine and UUV surface search sensors only work when the vessels come to communications or periscope depth. Also, Blue's surface search and optical sensors only detect in the same circumstances.

We believe that in the future, especially as Red uses decoys and deception, sensing a variety of phenomenology and features will help reduce the effectiveness of decoys and deceptions. Increasing the number of sensors used, though, adds to crew workload, unless much of it can be fused! Thus, we believe that fusion adds value in a deception/decoy rich environment.

Merchant shipping will have standard radar return signature, ESM LOB signature, an AIS signature, and an acoustic signature.

Fishing boats have standard radar return, ESM LOB, and optical signatures, plus an acoustic signature.

P-8 uses six sensors: passive and active acoustic sensors; airborne surface search radar; ESM receiver; and optical.

P-8M: passive and active acoustic sensors; airborne surface search radar; AIS; ESM receiver; and optical.

NOTE: the P-8 does not need any special signatures. If one intends to explore air defense, evasion, and escape analytic questions, then those signatures need to be added to make that possible. In the future this may be useful.

MH-60R (and -M): acoustic passive and active sensors; airborne surface search radar; AIS (for MH-60R-M only); ESM receiver; and optical.

6. Scenario EMCON Plan and Tactics

White merchants. Transit and radiate their merchant surface search radar (and AIS "signature" in P-8M excursion).

Fishing boats in groups. One radiates all the time. The others are within five miles.

Independent fishing boats. Radiate surface search randomly but at least 60% of the time.

~~**Red Air Fighter**. EMCON during transit, radiates air search radar while on station (barrier) (but no need to represent this yet).~~

C. METRICS

The following is an initial set of metrics for investigating the operational value of data fusion in the suggested scenario:

- Average time to detect, classify, and attack Red SSN and SSGN and Red UUV decoy.
- For P-8 flight, every 15 minutes compare P-8 and MH-60R surface picture to ground truth. There are 61 total contacts in the scenario. What is percentage held by the P-8? For contacts held, what is average error distance from ground truth? Does advanced fusion improve the surface picture? Did this help with the submarine detect, classify, and attack metrics?
- Number of contact reports P-8 makes to ASWC during flight for merchants, fishing boats, Red SSN, Rd SSGN, Red combatants, and Red Decoys. From contact reports, average AOU.
- Average time P-8 radiates air surface search radar.

D. SUGGESTIONS FOR REPRESENTATION OF THE ASW SCENARIO IN NSS

With respect to sensors and signatures for representing the ASW scenario in NSS, consider again the sensors onboard the P-8 and MH-64R identified earlier:

P-8 (and -M) sensors:

- Passive and active acoustic sensors. *We see no required modifications of these sensors. Model as you usually do.*
- Airborne Surface Search Radar. *We see no required modifications of this sensor. Model as you usually do.*
- AIS (for P-8M only). For an AIS sensor set up a special sensor detector that detects special signal type 1 (or, can type in a name for the custom signature). Put the special signature type 1 only on the AIS-enabled ships. Use cylindrical volume of large diameter and Pd=1. Have it detect classification, identification, location, CUS, and SPD ("super" sensor). Have no processing queue for AIS. Could have Pd = 0, then cued Pd = 1; i.e., pick up on a sensor, then cue AIS: sensor hit first, tactic to cue AIS sensor, then cued Pd, which would fuse with the radar track.
- ESM Receiver. Set up ESM as a spot sensor, have it send an elongated ellipse which simulates a line of bearing.

  One way to build a sensor is to make the sensor provide unprocessed data (i.e., normal radar, no ID), then determine id or mistaken id extracted through processing queue, model that result as a queue in the data architecture, then send that to contact processing fusion in data architecture, then to local fusion or to SUWC fusion. The special sensor only grabs ID information (Pd = 1, using same range as the radar).
- Optical. *We see no required modifications of this sensor. Model as you usually do.*

For the P-8 sensors, differentiate the confidence level for each sensor, such that confidence on optical > AIS > ESM > radar track.

MH-60R (and -M):

- Acoustic passive and active sensors. *We see no required modifications of these sensors. Model as you usually do.*
- Airborne Surface Search Radar. *We see no required modifications of this sensor. Model as you usually do.*
- AIS (for MH-60R-M only). For an AIS sensor set up a special sensor detector that detects special signal type 1 (or, can type in a name for the custom signature). Put the special signature type 1 only on the AIS-enabled ships. Use cylindrical volume of large diameter and Pd=1. Have it detect classification, identification, location, CUS, and SPD ("super" sensor). Have no processing queue for AIS. Could have Pd = 0, then cued Pd = 1; i.e., pick up on a sensor, then cue AIS:

sensor hit first, tactic to cue AIS sensor, then cued Pd, which would fuse with the radar track.

- ESM Receiver. Set up ESM as a spot sensor, have it send an elongated ellipse which simulates a line of bearing.

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- Optical. *We see no required modifications of this sensor. Model as you usually do.*

E. SUMMARY

The foundational hypothesis in this study is that data fusion systems such as Minotaur add value by improving SA accuracy while reducing the amount of time to classify and identify contacts of interest. This improvement is expected to have a significant effect on surface targeting, self-preservation, and coordinated ASW operations. Since Minotaur in particular does not fuse/correlate ASW sensors, it has less value there, but may still add some value, to be determined by additional modeling and analysis. The modeling and analytical approach developed in this study can be applied to such investigations.

VI. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

A. CONCLUSONS

On the surface, there was nothing unusual about the research objectives. Many decision makers need analytical tools and processes to assist with investment decisions. The research findings though, were broader and wider spread than expected:

- Understanding the value of fusion is not a challenge just for the maritime patrol and helicopter communities, but for the Navy as a whole. Different stakeholders have different expectations for fusion systems, and often the significant increases in fusion capability supported by networked platforms is either assumed away as easy, or completely ignored.
- Moreover, definitions of fusion and correlation are inconsistent across the Navy and within the modeling communities. For instance, NSS, Minotaur and the Joint Directors of Laboratories have three different definitions of fusion that are not consistent.
- Another finding was that the sponsor is interested now in the effects of fusion as derived from Minotaur. That was fine, but Minotaur provides capabilities that are not fusion related, but still very useful. Furthermore, there were other existing fusion capabilities in use in the Navy today that were not assumed to be available to these platforms.

In addressing the modeling challenge noted in the study purpose, it became clear that NSS offered a "good enough" solution that could be rapidly implemented with just a few additions to report models. This is accomplished by building a new "sensor" that includes capabilities for detection, classification, and identification, mirroring how fusion systems ingest differing sensors and create greater situation awareness. Because it is a straightforward matter to parameterize performance of this "sensor," many excursions of the baseline scenario would generate a look-up table for analysts to compare to exercise/experiment results. For instance, if an experiment demonstrated that Minotaur fusion increased contact identification to 95% at ranges out to 300nm (these numbers are notional) analysts could use the parametrized excursion equivalent to that performance, compare the operational metrics of that excursion to the non-Minotaur baseline, and thus be able to determine potential value added.

NSS use is not without concerns, though. NSS implements "fusion" by correlation of same sensors, not by the correlation of two or more separate and different sensors that

Minotaur performs. Thus, the assumption of a "sensor" with the qualities modeled above representing fusion can be erroneous at times; e.g., if a given contact of interest is not radiating, broadcasting AIS, or is not in range of an active sensor. So, the NSS modeling approach is not 100% perfect. Again, that is why the researchers recommend parameterizing the probability values, so analysts can be as detailed as they need to be in their analyses.

The researchers believe that AFSIM offers alternative modeling approaches, but at a more foundational level than NSS. Where NSS has a number of functional representations of fusion processes pre-developed in the core software, AFSIM has a more open framework providing an opportunity to create more system-specific representations. However, this means that modeling processes of interest to this study requires more detailed design and implementation efforts, accompanied by necessary verification and validation procedures. This may be a more demanding (and costly) level of development than the sponsor can accommodate. Because of the numerous organizations using AFSIM, active participation in the AFSIM Users' Group could mitigate custom development costs if others have done modeling addressing some of the capabilities needed for study of operational value of data fusion *and* are willing to share their software.

Finally, the researchers observed that the field of fusion is about to explode as new ideas about data and knowledge representation explode across industry and eventually government. Fusing just two sensors used to be quite challenging. Now, new ingest procedures mean that smart algorithms could be fusing dozens of different sources to tell a story. The researchers were reminded by a fusion subject matter expert, who has been at fusion efforts for 35 years, that "true fusion still really only happens in the mind."

B. RECOMMENDATIONS FOR FUTURE WORK

The researchers believe that understanding the value of not just fusion, but leveraging the growing data avalanche delivered by Big Data, cloud computing, and machine learning, soon available to all platforms and the tactical edge, is crucial. The hype surrounding these emerging capabilities is huge, so careful consideration of the investments cannot be overstated. Therefore, the research team recommends research on modeling and analytics in the following areas:

- If the use of legacy models such as NSS continues, recommend that enhancements be made to account for multi-source fusion.
- Simulation frameworks like AFSIM, which give users greater manipulability (but also take longer to prepare), show promise for capturing the nuances of emerging Big Data and fusion capabilities. More effort in modeling these techniques is warranted.
- While COVID-19 restrictions and availability prevented in-depth exploration of the topic at the classified level, the researchers believe that a system-in-the-loop approach, using live, virtual, and constructive stimulation and simulation may yet still be a viable analytic approach. In this study, the sponsor tried hard to gain the researchers access to the platform simulators, but there was no availability.

Furthermore, we recommend NAVAIR explore a few other considerations using this approach, other platforms and emerging AI techniques:

- SPOTR is an ONR-developed computer vision tool that can detect, classify, and identify tracks from images, including those taken from commercial satellites in space. It would be a tremendous complement to the P-8 and Triton. Additionally, SPOTR added to overhead images, then fed to P-8s or Tritons on station, would make them even more responsive. The science behind SPOTR is applicable to more than image phenomenology, but also to other kinds of phenomenology, whether blobs, or even acoustic signatures. While MAVEN gets the press, SPOTR has already put computer vision out of business at SSC-P and NRL. SPOTR is already used at the warfighting numbered fleet, albeit in a slightly different way, since 2017, and also at the 24th Air Intelligence Squadron in Ramstein in support of three COCOMs. While they have ongoing discussion with PMA-290, nothing seems to happen. Perhaps some rigorous modeling might change their minds.
- While not a requirement for this study, recommend modeling Triton and Fire Scout with fusion and computer vision.
- SIGINT is just another sensor, while understanding the need to model separately, recommend considering incorporating SIGINT into broader sensor fusion modeling.

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APPENDIX A. GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AFSIM	Advanced Framework for Simulation, Integration, and Modeling
AIS	Automatic Identification System
ASW	anti-submarine warfare
ASWC	Anti-Submarine Warfare Commander
CNA	Center for Naval Analyses
CONOPS	concept of operations
COVID	corona virus disease
DF	data fusion
EADSIM	Extended Air Defense Simulation
EMCON	emission control
ESINQ	external, seemingly-intangible, non-quantifiable
ESM	electronic support measures
ExAMS	Executable Architecture Management System
ISR	intelligence, surveillance, and reconnaissance
JDL	Joint Directors of Laboratories
MDP	model development process
MEAD	Mission Engineering and Analysis Department
N2/N6	Office of the Deputy Chief of Naval Operations for Information Warfare
N98	Director of Air Warfare
NAVAIR	Naval Air Systems Command
NCWG	Naval Concepts Working Group
NGTS	Next Generation Threat System
NOLH	nearly orthogonal Latin hypercube
NPS	Naval Postgraduate School
NSS	Naval Simulation System
OPNAV	Office of the Chief of Naval Operations
OTH	over-the-horizon
PMA	Program Management Activity
PMW	Program Management Warfare
SA	situation awareness
SAR	synthetic aperture radar
SME	subject-matter expert
SPOTR	surveillance, persistent observation, and target recognition
SSGN	nuclear-powered guided missile submarine
SSN	nuclear-powered general-purpose attack submarine
SUW	surface warfare
SUWC	Surface Warfare Commander
SysML	System Modeling Language
UAV	unmanned aerial vehicle
UUV	unmanned underwater vehicle

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