Data-Driven Modeling and Simulation to Test the Internet of War Things

Jeremy Werner, Sandra Hobson, and Eric Demirjian
Office of the Secretary of Defense
Director, Operational Test and Evaluation (DOT&E)
Strategic Initiatives, Policy, and Emerging Technologies (SIPET)
2023-04-07

Abstract

The Director, Operational Test and Evaluation's Strategic Initiatives, Policy, and Emerging Technologies division (DOT&E SIPET) is shaping the test and evaluation (T&E) of future multi-domain warfighting. Our warfighters need an integrated view from the sea floor to space and through cyberspace to defeat our adversaries and safeguard our Nation. Comprehensive live testing of these capabilities is not possible due to environmental, fiscal, safety, classification, and ethical constraints, and so our evaluations will become more dependent on modeling and simulation (M&S) to test the efficacy and interoperability of our systems. In particular, testing and evaluating future capabilities will depend upon a data-driven enterprise M&S that is provided as a service to soldiers, sailors, airmen, guardians, and marines. This integrated, expansive, and digital M&S is on the edge of a new technology frontier with many outstanding questions, such as:

- How do we design our M&S and live tests to engender a "predict, live test, refine" feedback loop to improve M&S accuracy over systems' lifecycles?
- How do we field M&S as a service so that the skillset required to operate and understand its outputs mirrors the skills required of warfighters in the real world?
- How do we ensure integration across all warfighting domains and digital capabilities?
- How do we implement an environment with real-time analysis and accurate results for T&E and operational decisions?

This paper will explore these questions and walk-through applications of the Intelligence Community's Integrated Threat Analysis and Simulation Environment and the Defense Advanced Research Projects Agency's (DARPA) Distributed Experimentation Environment, with a view to outpacing our adversaries' capabilities.

Introduction

Using empirical observations to deduce and refine models has been a cornerstone of science, engineering, and technology for millennia. Tycho Brahe, for instance, made the most accurate astronomical observations of his time back in the 1500s, which Kepler then used to deduce his laws of planetary motion, which Newton in turn then used to deduce his three laws of motion and law of universal gravitation, and so on.

Speeding up to the present, we now have the advantage of real-time sensors and high throughput networks that can enable a tighter, faster, and ongoing coupling of real-world observations (i.e., data) to the models we build. For T&E of weapons systems, this entails maximizing the utility of the data we collect and minimizing the time required to analyze and convert data into valuable predictive knowledge about system performance. Moreover, once an adequate amount of live data has been collected to validate or deduce a model, we can then depend on said model to output accurate predictions without the need to collect more live data (just as we no longer need to replicate Tycho Brahe's observations of the night sky to predict the movements of planets). Any relevant additional data that becomes available from a system's operations can be used to further refine its model across that system's lifecycle (just as ongoing astronomical observations have helped to iteratively improve the accuracy of our planetary motion predictions even though Kepler's laws still generally hold), however.

From a warfighting perspective, this tighter, faster, and ongoing coupling of military operations to M&S environments offers an unparalleled battlefield advantage. It means that in the near-future, commanders will effectively have real-time feedback from the units under their command—and the entire theater of operations—which they can use to quickly and intelligently adopt tactics and inform operations in ways like never before.

Architecting M&S and live tests to engender a "predict, live test, refine" feedback loop to improve M&S accuracy over systems' lifecycles

In considering the architecture of M&S coupled to live test events—and actual operations—to engender a "predict, live test, refine" feedback loop to improve M&S accuracy over systems' lifecycles, we must address two different classes of models: *effects-based* and *physics-based*. Effects-based models are empirically deduced from real-world observations; they are built directly from data by design, and as such it is straightforward to update them as new data becomes available. Physics-based models on the other hand, are constructed from first principles of scientific law as expressed in equations and then converted to software code.

Kepler's laws of planetary motion, for instance, were directly deduced from Tycho Brahe's observations as an effects-based model, as were Newton's laws empirically deduced from Kepler's; albeit we now understand Newton's laws to be first principal and can in fact mathematically derive Kepler's laws from them—such is the powerful feedback loop of science, technology, and discovery!

Let's return to the warfighter and the T&E of weapons systems. Consider the example of the real-world threat posed to warships by small boat raids. Warships may deploy large guns to defend against small boat raids, and it may be helpful to construct models that predict a warship's defensive capability against these threats. In this case, a modeler may consider two choices to characterize the gun and ammunition's capability to destroy small boats:

- Construct an effects-based model that uses statistical distributions deduced from live testing (e.g., gun slew time, targeting time, and firing time).
- Construct a physics-based model that uses first principles encoded in high fidelity software.

New live test data may be used to refine the effects-based model by simply updating the statistical distributions to include new test points. However, the correct method to update the physics-based model is less apparent, and opens up a set of questions that need to be addressed:

- Can a single tuning of the model's input parameters capture the results, particularly the stochastic variation characteristic of live testing and operations?
- If so, can this tuning be demonstrated to be stable over time (e.g., only change slightly when new live data becomes available)?
- If so, are the model's input parameters directly traceable to the live data? I.e., is there a clear and known relationship between the model's input parameters and the different data elements collected in live tests?

The answer to these questions, in turn, all need to be affirmative to demonstrate the physics-based model's capability to postdict, predict, and be easily understood and updated to account for new real-world observations and changes. Yet in doing so, it would seem that we have come full circle, effectively converting what started as a physics-based model to a "data-driven" effects-based one, which brings us to the conclusion of this section:

> *A model's capability to postdict, predict, and be easily understood and updated depends upon its demonstrated capability to capture the results and stochastic variation characteristic of live testing and operations, be stable in its tuning, and have input parameters that are directly traceable to live data. In this sense, a model becomes "data-driven." This is independent of whether a model is effects or physics-based; from this viewpoint the distinction between an effects-based and physics-based model useful for T&E is merely the use of an operations-oriented or physics-oriented set of input parameters and the corresponding live data underpinning them.*

Fielding M&S as a service so that the skillset required to operate it and understand its outputs mirrors the skills required of warfighters in the real world

Harnessing the full potential of M&S for both T&E and real-world military operations depend upon M&S accessibility, ease of use, and understandability. In short, realizing the full potential of M&S depends upon evolving the field from the current state wherein the model developer or other highly-trained technician is the typical user and interpreter, to one that provides actionable services directly to the warfighter as the end user[1]. This means the way a warfighter interacts with the M&S services must make use of the same skills they use to conduct military operations. To achieve this, the M&S services should provide:

- Infantry with a first-person digital interface for their tactical environment of teaming with their squad to locate, close with, and destroy the enemy by fire and maneuver.

---

[1] For our present purpose, we extend the common understanding of Software as a Service beyond cloud hosting to also include military operators as end users.

- Ship captains with a digital interface for their operational environment of navigation, ship health, situational awareness of potential threat contacts, as well as a view into the combat weapon system for ship self-defense and attacking enemy assets.
- Theater commanders with a digital interface for their strategic environment of viewing the status and locations of their forces across all-domains—from the sea floor to space and through cyberspace—as well as those of the enemies', so that our forces may be effectively directed to defeat them.

The similarity between the M&S services discussed above and contemporary video games is clear—be it first-person shooters like *Call of Duty* for infantry, *World of Warships* for ship captains, or *Hearts of Iron* for theater commanders. Indeed, the United States Army's video game series *America's Army* was developed primarily as an educational and recruitment tool but has since been used in various ways as a platform to train United States Army Soldiers.[2] The use of simulators to train the operators of military platforms is already prevalent and has had remarkable success as well.

> *Harnessing the full potential of M&S for T&E and real-world operations depends upon moving M&S capabilities from defense laboratories into the hands of our warfighters. As we move into the future, the processes of operating M&S and interpreting its output should be shifted from the technical practitioner to the warfighter. This will entail a substantial effort to integrate current "back-end" M&S capabilities into operator interfaces. Nevertheless, modern military-themed video games demonstrate a mature framework for providing such interfaces to their players that we can emulate.*

Ensuring integration across all warfighting domains and digital capabilities

Generating an M&S environment that is integrated across all warfighting domains and digital capabilities can be achieved by developing an open, high-level architecture for interoperability that overcomes the usability and integration challenges seen in many domain-specific tools. That is, this open architecture will provide the high-level, cross-domain interoperability layer, Application Programming Interfaces (API)[3], and connections to end user interfaces needed to integrate the DOD's many disjointed M&S tools into a single unified framework while allowing model builders to focus on the unique properties and physics of their specific domain.

The technology and digital entertainment industries, for instance, are developing an array of related solutions that include open and extensible frameworks for building and running scalable

[2] Jean, Grace (February 2006), "Game Branches Out Into Real Combat Training," *National Defense Magazine*.
[3] Amazon, What is an API?, https://aws.amazon.com/what-is/api/#:~:text=API%20stands%20for%20Application%20Programming,other%20using%20requests%20and%20responses.

virtual 3D worlds that are enabled by Graphics Processing Units (GPU). At their core, these solutions are built upon robust, open digital data exchange layers and provide extensive features for describing the interactions between a multitude of agents and combining them into larger systems of systems. Additionally, they enable collaboration so that many users or developers can operate together simultaneously.

Many of DOD's M&S tools involve signal propagation and networks; here too these virtual 3D world-building technologies have been used by the telecommunications industry for integrating their radio frequency propagation models and network simulations to optimize the laydown of 5G cell towers in urban environments.

The DOD has likewise made substantial strides towards such a capability internally, as discussed in the following two examples:[4]

- Integrated Threat Analysis and Simulation Environment (ITASE)
- Distributed Experimentation Environment (DE2)

Integrated Threat Analysis and Simulation Environment (ITASE)

Figure 1 highlights the Integrated Threat Analysis and Simulation Environment (ITASE) developed and used by the Intelligence Community. Validated threat models and scenarios can be integrated into ITASE to enable assessments from the engineering to the kill web multi-domain mission level including land, air, sea, space, cyber, and electronic attack.

ITASE provides open, interoperable interfaces and has been successfully integrated into distributed live test range data streams, as well as simulation environments of US capabilities, such as One Semi-Automated Forces (oneSAF), Next Generation Threat System (NGTS), and Advanced Framework for Simulation (AFSIM).

ITASE has been successfully used for mission planning and includes integrations with the actual mission data packages for post mission analysis.

[4] Thomas Simms, *Advancing Gaming Exercising, Modeling and Simulation Capabilities*, House Report 117-118, pages 46 and 47, accompanying H.R. 4350, the National Defense Authorization Act for Fiscal Year 2022, Oct 2022, https://ac.cto.mil/wp-content/uploads/2022/12/Advancing-Gaming-Exercising-Modeling-and-Simulation-GEMS-Capabilities.pdf

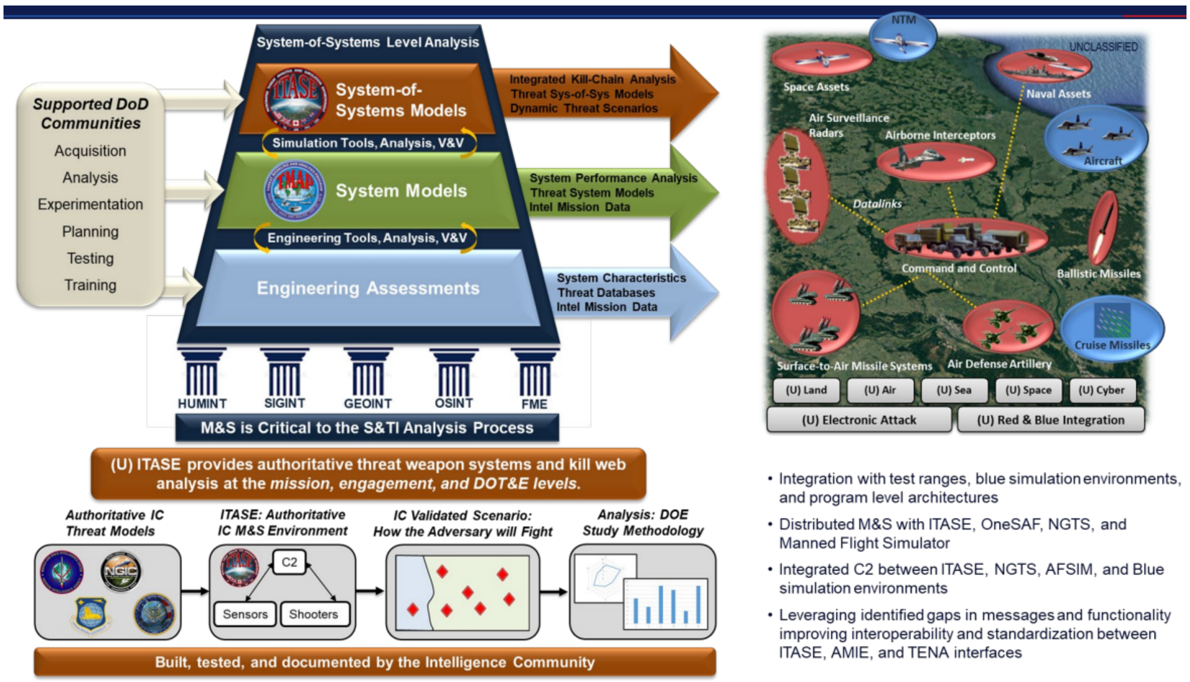
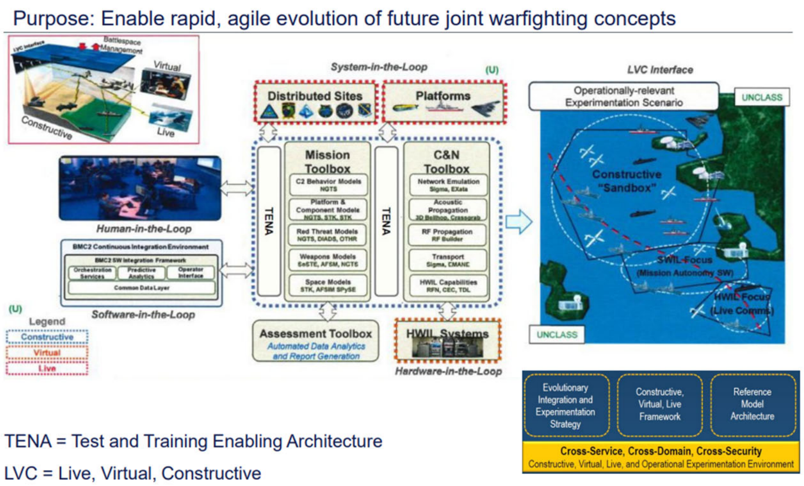


Figure 1: Integrated Threat Analysis and Simulation Environment (ITASE)

Distributed Experimentation Environment (DE2)

DARPA has developed the Distributed Experimentation Environment (DE2) to enable the rapid and agile evolution of future joint warfighting concepts, as highlighted in Figure 2. Continuous refinement of models and simulation against live data can be achieved in DE2 through live, virtual, and constructive experimentation that engenders a “live test, refine, predict” feedback loop.

DE2 provides a continuous integration environment that is built on top of an interoperable common data layer and can include tactical software and hardware-in-the-loop. It is also distributed, having integrations into many sites and platforms as well as being cross-service and cross-domain, while supporting multilevel security environments.



Live, virtual, constructive experimentation enables continuous refinement of models and simulation against live data – engendering a "Live test-refine-predict" feedback loop.

Figure 2: Distributed Experimentation Environment

> *Generating an M&S environment that is integrated across all warfighting domains depends upon embracing an open architecture interoperability layer to integrate the DOD's many disjoint M&S tools into a single unified framework while allowing model builders to focus on the unique properties and physics of their specific domain. The commercial industry is rapidly maturing closely related open technologies for building and running virtual 3D worlds that we can either copy or directly adopt. These open technologies further enable the fielding of digital twins that are synchronized with the real world. They have also been used in military-adjacent applications such as optimizing 5G cell tower laydowns. The military application of these commercially available technologies is currently being investigated by several DOD organizations, including the United States Army 5th Special Forces Group (operational support), Carnegie Mellon University's Software Engineering Institute (R&D), and DOT&E (T&E). The DOD has also made substantial strides towards such a capability internally, as evidenced by the Intelligence Community's ITASE, DARPA's DE2, and the data interoperability layer they each provide.*

Implementing an environment with real-time analysis and accurate results for T&E and operational decisions

A large-scale industrial computing infrastructure must be deployed across the T&E enterprise to enable credible data-driven decision making on both the complexity level and rapid timescale of future joint warfighting operations. In other words, the collection, analysis, and high-level aggregation of test data must be networked, automated, and integrated with the unified M&S environment envisioned earlier in this article—all the way from the tactical edge to the C-suite.

Figure 3 provides both a technical (cyan) and notional operational view (orange) of this enterprise data and analysis environment, involving:

- *At the edge:* Raw streaming data from the platform, onboard data reduction, and distributed raw binary data stores.
- *Across the enterprise:* Data post-processing into open, machine-readable formats (e.g., the DOD-developed *Cloud Hybrid Edge-to-Enterprise Evaluation and Test Analysis Suite* (*CHEETAS*)[5]-provided data interoperability layer); integration into data-backed M&S; "online" system performance analyses using an open, general-purpose automated data analysis environment (e.g., the DOD-developed *Automaton*[6] data analysis platform); and ad hoc "offline" manual analyst-performed experimentation and development.
- *At the C-suite: Advana*[7] for big data-aggregated advanced analytics using a data mart[8] composed of high-level system performance analysis artificacts .

---

[5] https://dataworks.testscience.org/wp-content/uploads/sites/18/formidable/23/T1_Powell_2022-03-24-KM-and-CHEETAS-for-ICOTE-Powell.pptx

[6] The Automaton general-purpose data intelligence platform abstracts data analysis out to a high level and automates many routine analysis tasks while being highly extensible and configurable - enabling complex algorithms to elucidate mission-level effects. Automaton was developed for the DOD by Johns Hopkins University Applied Physics Laboratory to support an ongoing military mission and perform statistically rigorous analyses that use Bayesian-inference-based Artificial Intelligence to elucidate mission-level effects. Automaton has unfettered Government Purpose Rights and is freely available. A full capabilities description and prerecorded demo are available at the following links:

- https://www.trmc.osd.mil/wiki/download/attachments/184156180/automaton_letter_2022-08-22.docx?api=v2
- https://www.trmc.osd.mil/wiki/download/attachments/184156180/automaton_briefing_and_demo_2021-07-30.mp4?api=v2

[7] https://www.acq.osd.mil/asda/ae/ada/data-analytics.html

[8] https://en.wikipedia.org/wiki/Data_mart

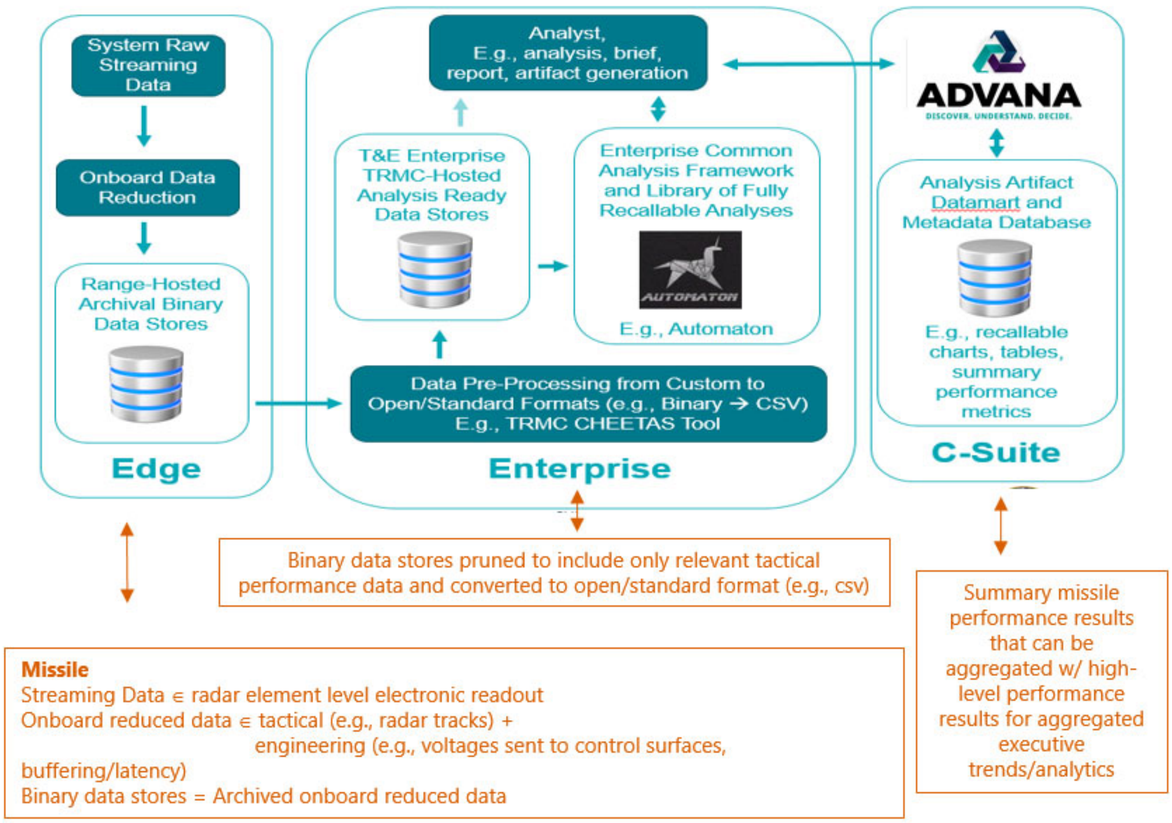


Figure 3: Technical (cyan) and notional operational (orange) views of the future common T&E enterprise data and analysis environment.

The rigor behind the automated data and analysis infrastructure described above will enable not only faster analysis, but also the complex and multi-tiered analysis necessary to glean high-level and synergistic mission effects. For example, live data collected in simpler scenarios will be "remixed" and fused with M&S to create "digital arenas" for evaluating more complex warfighting scenarios and their related emergent behaviors by using a variety of advanced analysis techniques including artificial intelligence and Bayesian networks.

Let's return to our small boat-raid defense example and expand it into a full chokepoint scenario. Suppose that the adversary deploys an array of weapons and platforms—e.g., mines, torpedo-armed submarines, and missile batteries—to deny the warship passage and let's further suppose that the warship is now escorted by small boat-shooting fighter jets and submarine-hunting attack submarines. In our data remixing and digital arena concept, live test data and threat models of the various weapons and platforms are fused together in a virtual environment to enable an integrated analysis of this more complex warfighting scenario.

Several initiatives are underway to build and deploy the industrial computing infrastructure needed to perform the credible data-driven T&E of future joint warfighting *operations. The unified M&S environment envisioned earlier in this article will be integrated into this data and analysis environment. Current enabling tools include the DOD-developed CHEETAS and general-purpose Automaton data analysis platforms as well as the Advana advanced analytics platform. Automated analyses will be put into production all the way from the tactical edge to the C-suite. We will glean the high-level and synergistic mission effects characteristic of future joint warfighting operations, as well as the emergent behaviors they entail, by remixing data and fusing it with M&S to create "digital arenas". In this way, we will evaluate these complex warfighting scenarios using a broad collection of advanced analysis techniques including artificial intelligence and Bayesian networks.*

Conclusion

DOT&E understands that our warfighters need an integrated view from the sea floor to space and through cyberspace to defeat our adversaries and safeguard our Nation. DOT&E's SIPET division—Strategic Initiatives, Policy, and Emerging Technologies—is shaping the T&E of future multi-domain warfighting. The T&E of these future capabilities will depend upon a data-driven enterprise M&S environment that is integrated into live tests and data feeds and provided as a service to our soldiers, sailors, airmen, guardians, and marines. This article has described DOT&E's vision for such an environment while delving into many of the challenges it presents:

- Architecting M&S and live tests to engender a "predict, live test, refine" feedback loop to improve M&S accuracy over systems' lifecycles
- Ensuring integration across all warfighting domains and digital capabilities
- Fielding M&S as a service so that the skillset required to operate it and understand its outputs mirrors the skills required of warfighters in the real world
- Implementing an environment with real-time analysis and accurate results for T&E and operational decisions

The appraisal of these challenges was real-world solutions focused and centered around rapidly maturing technologies, advanced methods, and real-world use cases pertinent to the T&E of future joint warfighting concepts. DOT&E and our partners have several R&D projects underway that are advancing our T&E capabilities and positioning us to meet the challenge–with many more on the way. We have released our S&T strategy to the public (https://www.dote.osd.mil/News/News-Display/Article/3118739/dote-strategy-update-2022/) and will follow up with the release of our detailed implementation plan in the coming months.

We will do our part by transforming T&E to enable delivery of the world's most advanced warfighting capabilities at the speed of need. We seek your proposals to collaborate with us.