Validating a Digital Twin Taxonomy for Defense: Enhancing Interoperability in Simulation and Digital Engineering

Dr. Patrick I. Buckley
Northrop Grumman
Huntsville, AL
patrick.Buckley@ngc.com

Mr. Robert A. Proctor, Jr.
Real-Time Innovations, Inc. (RTI)
Sunnyvale, CA
robert.proctor@rti.com

ABSTRACT

As digital twins (DTs) become integral to defense modernization, ensuring their **interoperability, scalability, and reusability** remains a critical challenge. While frameworks such as the **Digital Twin System Interoperability Framework (DTSIF)** and the **Unified Data Reference Architecture (UDRA)** have established foundational guidelines, a standardized digital twin taxonomy remains underdeveloped. Without a common data model and classification structure, defense programs face integration complexity, data silos, and limited cross-platform applicability. This paper validates a digital twin taxonomy within a modeling and simulation environment, applying it across real-world defense programs to assess its effectiveness in digital engineering workflows.

Validation Process: The taxonomy is evaluated using quantitative and qualitative methods, including:

- **Interoperability Metrics:** Measuring alignment with DoD data strategies and **OMG Data Distribution Service (DDS)** standards to assess cross-system data exchange.
- **Composability & Reusability:** Evaluating reductions in integration effort and improved model reuse across **air, land, sea, and electronic warfare systems**.
- **Subject Matter Expert (SME) Assessments:** Gathering insights from digital engineering practitioners on usability and implementation feasibility.

Novelty of Approach: Unlike prior studies that focus on isolated implementations, this research validates a **standardized digital twin taxonomy across multiple defense platforms**, including the **Integrated Battle Command System (IBCS), Cooperative Engagement Capability (CEC), Aegis Combat System, and the Surface Electronic Warfare Improvement Program (SEWIP)**. This multi-domain validation bridges conceptual frameworks with operational defense applications, ensuring taxonomy-driven digital twin integration at enterprise scale.

Impact on DoD Strategy: The findings support DoD Data Strategy principles, reinforcing data-centric architectures, modular open system approaches (MOSA), and scalable digital engineering. By aligning with the Mission Architecture Style Guide (MASG), this research informs future DoD acquisition policies and promotes taxonomy-driven procurement strategies that enhance training, readiness, and system adaptability.

This research underscores the role of standardized DTs in enabling faster, more effective training and decision-making for multi-domain operations. A validated taxonomy strengthens simulation realism, operational agility, and system-of-systems integration, driving the future of digital twin adoption in defense.

ABOUT THE AUTHORS

Patrick I. Buckley, PhD is the IBCS Chief Architect at Northrop Grumman, where he provides technical leadership and direction of a team of enterprise and systems engineers developing the US Army's interoperable command and control system. He is a multi-time published author and co-author, senior member of IEEE, and President of the INCOSE Huntsville Regional Chapter. Current research interests include digital twins, digital thread, full digital lifecycle, and complex system of systems integration.

Robert A. Proctor, Jr. is a Staff Field Application Engineer for Real-Time Innovations. He has over 29 years of experience in A&D Embedded Software as a Software Engineer and Field Applications Engineer. Prior to his time as a Field Application Engineer, he developed and implemented real time embedded software at major Aerospace and Defense corporations. His roles have included developing software and system designs, mission-management, and display processing systems. Rob received his BS from Embry-Riddle Aeronautical University in Aerospace Studies and his MS from the University of South Florida in Engineering Management.

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MOTIVIATION FOR DIGITAL TWINS (DT) IN DEFENSE

As the Department of Defense (DoD) continues to embrace digital transformation, digital twins, virtual representations of real-world systems, behaviors, and environments, have emerged as foundational enablers for mission readiness, system lifecycle optimization, and training realism. Digital twins are no longer experimental tools; they are rapidly becoming critical assets in defense programs for synchronizing operational models, simulation assets, and live systems across a system's full lifecycle.

In the context of modeling, simulation, and training (MS&T), digital twins offer unprecedented capabilities: they enable mission rehearsal environments that mirror operational dynamics, support synthetic training constructs informed by real-time data, and foster tightly integrated feedback loops between system use and refinement. These benefits are particularly crucial in joint and multi-domain operations, where training environments must evolve rapidly to reflect system changes, threats, and operational complexity.

However, despite increasing adoption, digital twins in defense remain fragmented. Disparate programs develop digital representations in isolation, leading to integration friction, duplicated modeling effort, and reduced reuse. Without a common taxonomy, digital twins cannot be composed, reused, or federated effectively across simulation and mission systems. This challenge becomes especially acute when applying model-based systems engineering (MBSE) principles to training workflows, where consistency, fidelity, and modularity are essential.

Without such a validated taxonomy, digital twins will remain siloed experiments rather than enterprise assets. Establishing this common foundation is therefore critical to ensure that investments in digital engineering, MBSE, and MS&T scale beyond isolated demonstrations and into joint, operationally relevant ecosystems.

To advance from isolated use cases to a unified digital twin ecosystem, the DoD needs a shared, validated taxonomy that enables interoperability and composability. Such a taxonomy must not only align with architectural frameworks like MASG, UDRA, and DTSIF, but also support the practical integration of training and operational systems through standards such as OMG DDS. The work presented in this paper addresses this gap, focusing on validating a defense-relevant digital twin taxonomy within MS&T and digital engineering environments, using real-world defense programs as reference points.

In short, the promise of digital twins in defense cannot be fully realized without a shared foundation for classification and integration. A validated taxonomy provides this foundation, enabling digital twins to function not as isolated constructs, but as composable, interoperable assets that scale across programs, services, and missions. The remainder of this paper explores this taxonomy and its validation within defense-relevant digital engineering and MS&T contexts.

OVERVIEW OF EXISTING DIGITAL TWIN FRAMEWORKS

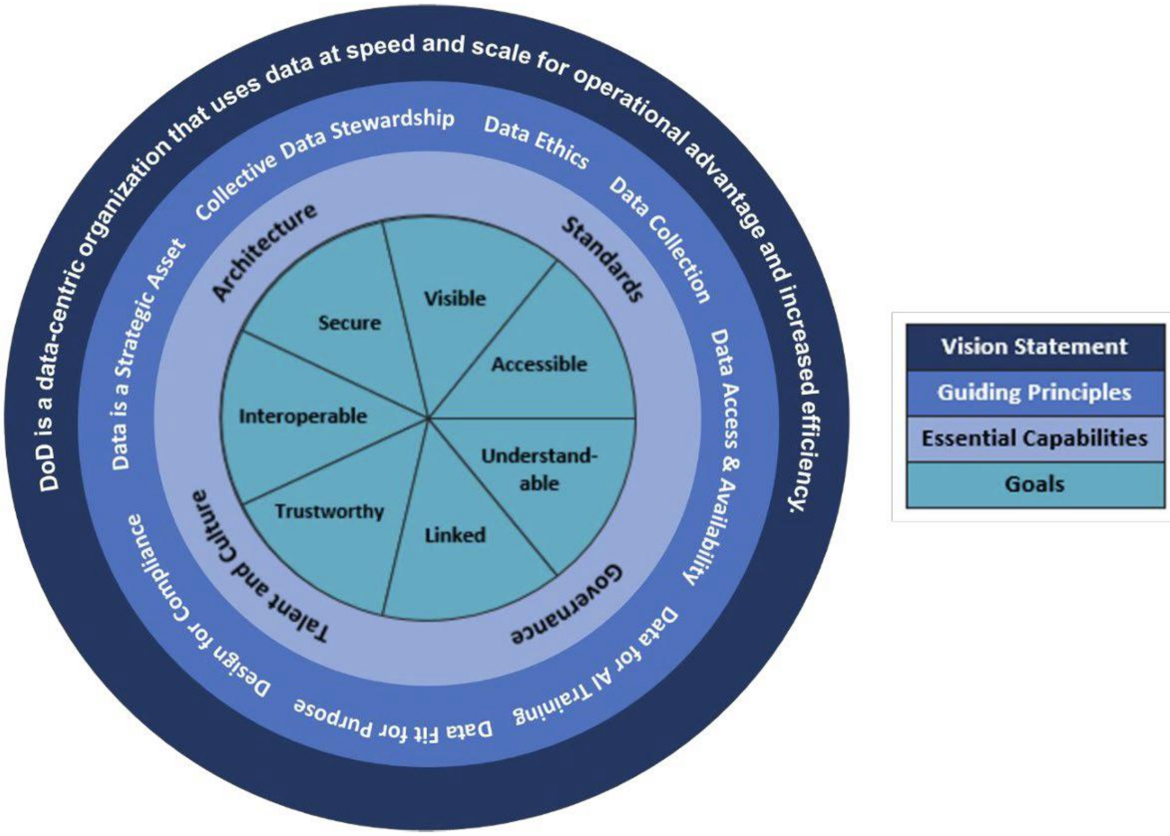

Figure 1: DoD Data Framework from DoD AD1112684

Over the past five years, the Department of Defense has taken deliberate steps to formalize its vision for digital twins and digital engineering. Among the most significant developments is the publication of **DoDI 5000.97 (2023)**, which establishes digital twin capabilities as a critical component of DoD acquisition, lifecycle sustainment, and training systems. The instruction defines digital twins as "integrated, authoritative representations of a system that are synchronized with the system through data and models," and mandates their use for decision-making, verification, and validation across the lifecycle of defense systems. Notably, DoDI 5000.97 emphasizes the need for digital twins to support **training and simulation** use cases, aligning closely with the MS&T mission.

Complementing this directive are architectural guidance documents such as the **Unified Data Reference Architecture (UDRA)**, the **Mission Architecture Style Guide (MASG)**, and the **Digital Twin System Interoperability Framework (DTSIF)**. While each offers unique perspectives—UDRA emphasizing data governance, MASG focusing on mission-driven interoperability, and DTSIF outlining levels of DT integration—none propose a unified taxonomy for categorizing and composing digital twins across simulation, training, and operational domains. As a result, program-specific digital twin efforts often remain siloed, with limited reuse or semantic consistency.

This lack of a shared taxonomy is particularly problematic in **Model-Based Systems Engineering (MBSE)** and **MS&T**, where simulation assets, software components, and real-world system representations must align at multiple fidelity levels and across domain boundaries. Programs such as the **Joint Simulation Environment (JSE)** and the **Simulator Common Architecture Requirements and Standards (SCARS)** initiative have made substantial strides in adopting modular, standards-based approaches. However, without a clear semantic structure for digital twins, integration remains effort-intensive, program-specific, and oftentimes cost prohibitive.

At the infrastructure level, **OMG's Data Distribution Service (DDS)** has emerged as a key middleware standard to enable **secure, real-time, and scalable** system-of-systems integration. Its use in defense programs demonstrates that

DDS provides the foundation for composable communication — but not yet composable data. This paper addresses that gap by validating a data-centric **digital twin taxonomy** that can extend the utility of DDS and MBSE into a fully modular and composable simulation architecture.

Finally, related literature on **systems integration taxonomies** underscores the need for cross-domain semantic alignment. Prior research has focused on modeling languages, metadata tagging, or simulation object models, but lacks the cross-program applicability and DoD alignment needed for digital twin deployment at scale. The taxonomy validated in this paper builds on this foundation, proposing a reusable and standards-aligned model for classifying digital twin entities in MS&T environments.

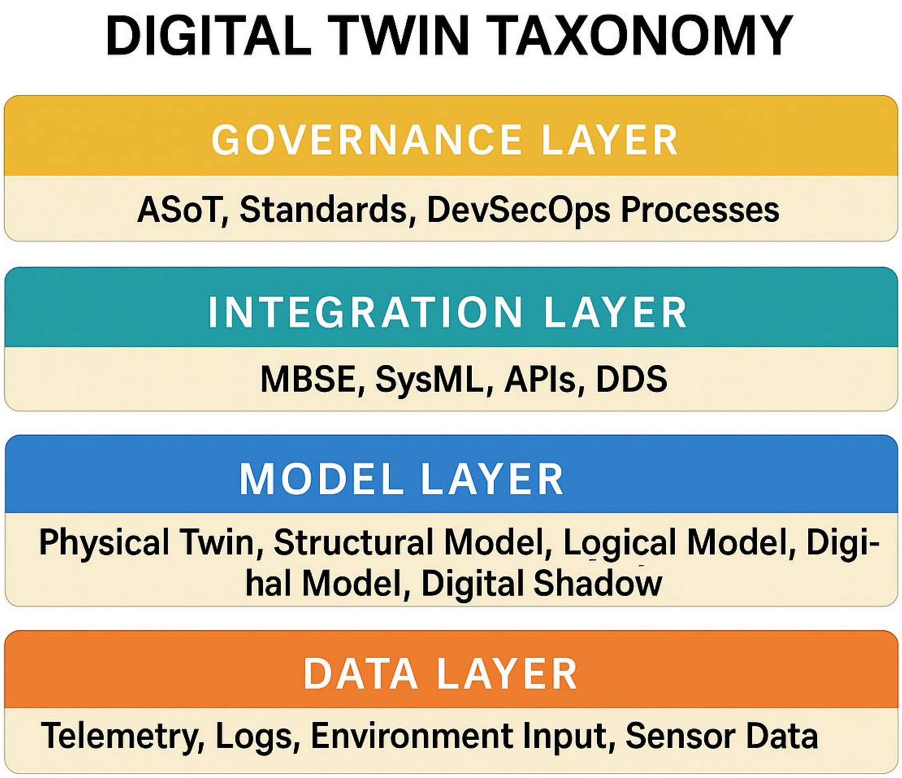

Table 1: Key DoD Frameworks and Directives Supporting Digital Twin Adoption

Framework / Directive	Primary Focus	Relevance to Digital Twins	Implications for MS&T
DoDI 5000.97 (2023)	Acquisition, Lifecycle Support	Mandates digital twin use for verification, sustainment, and decision-making	Establishes DTs as core to training, test, and simulation lifecycle
Unified Data Reference Architecture (UDRA)	Data governance and reuse	Standardizes interfaces and semantics for authoritative data sources	Enables federated data access for live/simulated system training
Digital Twin System Interoperability Framework (DTSIF)	Levels of DT maturity and integration	Classifies DT implementations across fidelity and integration axes	Aligns virtual training assets with operational systems

Mission Architecture Style Guide (MASG)	Operational and system architecture patterns	Promotes reusable architectural approaches for modular, composable systems	Encourages model-based, simulation-aligned system integration
MOSA Mandates (NAVSEA, PEO STRI, etc.)	Modularity and open standards	Requires DTs to be composable and interoperable	Drives standards adoption in simulation frameworks
SCARS / JSE Programs	Simulator standardization, joint training realism	Implement open architectures that support modular simulation assets	Serve as proving grounds for taxonomy-driven DT reuse

PROPOSED VALIDATION APPROACH FOR A DEFENSE-BASED TAXONOMY FOR DIGITAL TWINS

Motivation for Validation

While Buckley and Proctor (2024) proposed a structured taxonomy for defense digital twins (DTs), adoption of any such framework requires validation against real-world use cases. Validation ensures that the taxonomy meaningfully supports interoperability, composability, and lifecycle integration across defense acquisition, simulation, and operational contexts.

Validation Objectives

To assess the applicability and usefulness of the proposed taxonomy, the following objectives guide this validation effort:

- Evaluate how well the taxonomy supports **semantic alignment** across models used in MBSE, M&S, and system-of-systems contexts.
- Assess whether taxonomy elements improve **cross-platform reusability** and **composability** for DT components.
- Determine how well the taxonomy maps to **authoritative standards** such as UDRA, DoDI 5000.97, and the DoD Data Strategy.

Validation Environment

To remain grounded in the practical realities of defense simulation and digital engineering, the validation process uses both qualitative and quantitative measures drawn from:

- Digital engineering platforms (e.g., SysML/Cameo, Ansys, MathWorks, DDS tools).
- Representative real-world defense programs with multi-domain interoperability needs, such as:
  - **US Army IBCS**: An air and missile defense system with a strong MBSE underpinning and MS&T integration.
  - **US Navy CEC**: A sensor netting system anchored in MBSE and LVC to design, analyze, and validate the network architecture.
  - **US Navy SEWIP**: An initiative for embedded advanced electronic warfare capabilities validated in complex contested environments.

Validation Methodology

The methodology consists of four layers of assessment:

- **Semantic Interoperability Testing**:
  - Use a digital engineering environment (SysML + DDS + MS&T) to model the same asset in different fidelity levels and scopes based on need an lifecycle phase (component, system, SoS).

  - Examine whether the taxonomy provides the right interconnections to define, discover, and federate these models via DDS-based messaging.
- **Composability and Reusability Metrics**:
  - Quantify reductions in integration effort when applying standardized tags, QoS settings, and roles from the taxonomy across simulations in the Joint Simulation Environment (JSE) and joint multi-domain testbeds.
  - Use DDS discovery logs to measure successful reuse across branch-specific simulations.
  - Use SysML libraries and profiles to extend the SysML standard as needed and maximize reusability.
- **SME Interviews and Use Case Mapping**:
  - Conduct structured interviews with DE professionals and acquisition engineers to determine usability, gaps, and alignment with MOSA.
  - Map the taxonomy elements to existing UDRA use cases and determine alignment or divergence.
- **Toolchain Integration**:
  - Integrate the taxonomy into a model-based engineering tool (e.g., Dassault Systemés Cameo Enterprise Architecture) using a profile/stereotype approach.
  - Use RTI tools or other DDS implementations to test round-trip data model and runtime alignment.
  - Use integration tools (e.g., Ansys Model Center) to dynamically link MS&T and SysML environments at the needed fidelity.

Table 2: Validation Layers for a Defense-Based Digital Twin Taxonomy

Validation Layer	Description
Semantic Interoperability Testing	Validates alignment of model fidelity, scope, and DDS representation. Focuses on consistency of data definitions across system layers and domains.
Composability & Reusability Metrics	Measures reduction in integration effort and increased reuse across simulation platforms. Leverages QoS alignment, tagging, and DDS discovery metrics.
SME Interviews & Use Case Mapping	Gathers practitioner insights to evaluate usability, MOSA alignment, and gaps. Maps taxonomy to real-world UDRA and MASG-aligned workflows.
Toolchain Integration	Tests implementation in SysML tools, MS&T systems, and DDS-based runtime systems. Confirms round-trip traceability from model to execution.

Case Studies Across Real-World Programs

US Army Integrated Battle Command System (IBCS)

IBCS is the U.S. Army's next-generation air and missile defense command-and-control system designed to integrate sensors and effectors across multiple platforms and services into a integrated fire control network. By decoupling sensors from shooters and enabling real-time data sharing across joint forces, IBCS provides a flexible, scalable, and resilient architecture significantly improving situational awareness, target tracking, and engagement coordination at all echelons. It supports joint all-domain operations by allowing disparate systems, such as the PATRIOT weapon system and Sentinel, to interoperate cohesively under a common command structure. Through its use of open architecture, modular design, and integration of MBSE and MS&T environments, IBCS enables rapid integration, testing, validation, and adaptation to evolving threats and mission needs.

Through a series of interconnected contractor- and government-run test beds leveraging common digital simulation tools, the IBCS system is capable of rapid upgrades to fielded systems limiting obsolescence risk and expediting the delivery of capabilities to the warfighter. Additionally, the IBCS modular architecture allows for the rapid insertion of emerging technologies such as developing weapons technologies, artificial intelligence, high-power computing, and emerging communications pathways. This modularity is regularly validated across the IBCS test beds supporting joint experimentation and major initiatives across the DoD, such as Project Convergence and Valiant Shield.

US Navy Cooperative Engagement Capability (CEC)
CEC is a networked sensor fusion system allowing U.S. Navy ships, aircraft, and select allied platforms to share real-time sensor data, creating a unified, composite track picture across the battlespace. By distributing fire control–quality data among multiple platforms, CEC significantly enhances situational awareness, extends engagement ranges, and supports integrated air and missile defense (IAMD) operations. It allows dispersed units to operate as a coordinated force, improving response times and increasing the effectiveness of defensive and offensive operations. CEC is a critical enabler of naval and joint force interoperability and plays a foundational role in the development of the Navy's distributed maritime operations and Joint All-Domain Command and Control (JADC2) initiatives.

The Navy's CEC LVC training and development environment seamlessly integrates live platforms with virtual simulators and computer-generated targets through the Navy Continuous Training Environment, enabling realistic, large-scale sensor-netting and engagement scenarios without the cost, risk, or tactical exposure of live-fire events. The self-healing capability of the CEC network ensures operational effectiveness through the Quality of Service capabilities offered by the OMG DDS standard. The integrated LVC environment regularly tests and verifies the flexibility and agility of the integrated network.

US Navy Surface Electronic Warfare Improvement Program (SEWIP)
SEWIP is a spiral-development initiative to incrementally upgrade the legacy AN/SLQ-32 "Slick-32" electronic warfare suite across increasingly capable blocked configurations. Block 1 provides improved interfaces, specific emitter ID, and high-gain/sensitivity. Block 2 enables enhanced detection, classification, and situational awareness with new antennas, processing, and combat system integration. Block 3 will deliver advanced electronic attack with AESA arrays and soft-kill coordination. Using a common hardware specification at each block ensures a stable baseline for these critical upgrades in a tightly controlled manner. SEWIP uses the DDS real-time publish and subscribe protocol ensuring timeliness and reliability of real-time data across the architecture.

The SEWIP LVC capabilities provide a robust test and evaluation environment integrating live platforms, virtual systems, and constructive threats to simulate complex electromagnetic warfare scenarios. This LVC testbed enables realistic and repeatable validation of SEWIP's incremental upgrades anchored in MBSE architectures. Through the use of advanced modeling, digital twins, and real-time system integration, the testbed ensures each SEWIP upgrade meets operational performance goals while reducing cost, risk, and development timelines. It supports both system-level verification and fleet-level mission rehearsal, making it a key enabler of accelerated capability deployment and continuous system evolution.

Preliminary Results & Observations – IBCS
Semantic Validation
The IBCS architecture requirements drove the design to be real-time and modular, real-time due to fire control and mission support and modular for rapid technology insertion. The software architecture uses modules which are deployed at distributed nodes through an RTPS interface. Engineers model the software interfaces in SysML for integration and check out with low-fidelity simulations driving by the RTI Connext tool suite. Test engineers validate network requirements prior to release of interface specifications every three-week sprint in accordance with the Scaled Agile Framework (SAFe). Validation rules within Cameo Enterprise Architecture ensure semantic validity and proper style regardless of which develop implements the change. Once the interfaces are checked out, they are pushed to the truck for inclusion in the build process. The RTI Connext tool suite performs further semantic and syntactic validation during the generation of the middleware software. Finally, systems engineers trace the data model to the physical software model where low-fidelity simulations ensure the software modules properly process the complex data transmitted or received across the DDS interface.

Composability and Reusability Metrics
One of the key metrics tracked in SAFe is velocity. Velocity is a measure of the amount of work a development team completes within a sprint. This metric varies from team to team; however, it can serve as a corollary to the composability and reuse of the software being architected and developed. For example, if a feature under development requires specific functionality and through analysis it has discovered this functionality resides elsewhere in the software architecture, systems engineers can lift and shift that functionality from one software

module to another eliminating rework. In this example, the interface specification supporting the functionality can also be reused reducing retesting and thus schedule. Designing the IBCS architecture for composability and reuse results in more complex work done more quickly allowing development teams to increase their velocity over time.

Additionally, the IBCS team traces enterprise-level architectures to system and subsystem level models through the use of the Unified Architecture Framework (UAF) and SysML. UAF allows solutions architects to specify how IBCS participates in the US Army's Integrated Air and Missile Defense system of systems architecture documenting capabilities and requirements as specified by the user community. System engineers decompose UAF models to IBCS system and subsystem components providing full traceability and visibility to all stakeholders. Reuse of UAF libraries across the enterprise reduces the need to model the same things repetitively and development across a shared ecosystem provides the visibility required throughout the full lifecycle. Engineers generate artifacts directly from the models, including interface specifications, architectural diagrams, and technical data packages with the digital architectures serving as the source of truth for the entire program.

SME Review and Use Case Mapping

As mentioned above, traceability between UAF and SysML allows for tracing of user-defined use cases and ensures IBCS meets all requirements. Subject matter experts not only review the content within the architectures but are active participants in the modeling itself. Within the SAFe construct, collaboration is critical to ensure IBCS meets the needs of the warfighter through regular interchanges with all stakeholders. Their inputs serve as guidance during the maturation of the IBCS digital architecture and serves as a forcing function to update any deficiencies in the MS&T tooling and processes. This interaction has led to a 100% success rate during live fire exercises throughout the life of the IBCS program and has set the stage for all major program milestones.

Toolchain Integration

One of the challenges with digital engineering is the integration of tools and the sharing of data across those tools particularly in an program spanning security domains. Making data visible, accessible, understandable, linked, trustworthy, interoperable, and secure (VAULTIS) is a major tenant of the US Army UDRA. At program initiation, IBCS took these guiding principles into consideration through the entirety of the program's lifecycle. Data sharing between all stakeholders, while not without its challenges, has been paramount especially during the design, implementation, MS&T, and fielding. The Joint Analysis Teams (JAT) are the lynchpin in this process. Data collected at various sights supporting various events is reduced, federated, and analyzed using a common set of tools. Once reviewed, the JAT provides data and results of the analysis to all stakeholder for incorporation into the integrated tool chain. This expedites the remediation of issues and provides opportunities for technology insertion. The secure interoperable data pathway is all built on open standards such as DDS and Distributed Interactive Simulation (DIS).

ANALYSIS AND DISCUSSION: IMPLICATIONS OF TAXONOMY VALIDATION

The validation process demonstrates a standardized digital twin taxonomy meaningfully advances interoperability, simulation composability, and integration across digital engineering toolchains. Across the testbed domains, key benefits emerged:

Accelerated Integration and Interoperability

By applying the taxonomy to Joint All-Domain systems such as IBCS and CEC, validation showed reduced integration complexity when combining assets modeled in disparate toolchains. DDS discovery logs and topic structures reflected reduced configuration overhead, especially when layered with UDRA-aligned schema.

Improved Reusability Across M&S Environments

The taxonomy's categorical structuring enabled reuse of subsystem models and simulation artifacts across air, land, sea, and EW domains. For example, radar sensor models defined in SEWIP could be adapted for use in JSE without restructuring their DDS data contracts or model stereotypes.

Integration with Digital Engineering Toolchains

The integration of the taxonomy into SysML2 tooling (e.g., Cameo with DDS plug-ins) showed that models could be annotated with composability-relevant metadata, enabling traceability from architecture to simulation runtime. This supports model-centric configuration control and scenario reuse across program phases.

Support for DevSecOps and CI/CD Pipelines
Validation further showed the taxonomy could support model-driven pipelines by tagging digital twin components for automated deployment and integration checks. This helps position digital twins not as one-off builds, but as evolving assets within continuous integration pipelines.

Alignment with DoD Strategy and MASG
Finally, the taxonomy demonstrated direct alignment with DoDI 5000.97, MASG, and the DoD Data Strategy. Through its use of modular descriptors, data tagging, and runtime mappings, it supports data-centric acquisition principles and mission architecture compatibility.

A compelling validation of the taxonomy can be observed in IBCS. IBCS exemplifies how a standards-based, data-centric architecture enables interoperability across heterogeneous sensors and effectors, including Patriot, Sentinel, and emerging capabilities such as THAAD. By aligning with open standards like OMG DDS, IBCS has demonstrated measurable improvements in integration velocity—reducing timelines for bringing new sensors online from months to weeks. Within the taxonomy framework, IBCS highlights the value of composable digital twin elements across system, platform, and engagement layers, providing an operational proof point that the taxonomy's categories map directly onto real-world requirements for agility, resilience, and mission effectiveness.

CONCLUSION AND FUTURE WORK

As the US DoD continues to evolve toward a fully data-centric enterprise, digital twins are becoming central to lifecycle acquisition, mission rehearsal, and synthetic training environments. However, the lack of a standardized taxonomy has hindered their full potential—complicating integration, limiting reuse, and introducing barriers to composability across services and domains.

This paper validated a defense-oriented digital twin taxonomy through a structured methodology grounded in modeling, simulation, and digital engineering environments. By applying the taxonomy across real-world platforms—such as IBCS, CEC, SEWIP, and JSE—and using tools like Cameo and DDS-based messaging, the study demonstrated tangible benefits: improved model interoperability, reduced integration effort, increased simulation reusability, and tighter alignment with DoD architecture and data strategies.

Importantly, this work underscores that data-centric interoperability is not a future aspiration—it is achievable today with open standards like OMG DDS, model-based engineering tools, and a taxonomy that reflects both technical and mission-centric dimensions of digital twins.

Future work will expand on this validation effort by formalizing metrics for composability, integrating the taxonomy into DevSecOps toolchains, and refining SysML 2.0 domain overlays for operational simulation use cases. Further research should explore taxonomy extensions for AI-enabled DTs and cross-domain security enforcement, particularly in LVC/MS&T systems requiring MLS compliance.

Ultimately, a validated, domain-spanning digital twin taxonomy offers a pathway to operational agility, improved readiness, and faster, more informed decision-making—exactly what's needed for the DoD's next generation of mission-critical systems.

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