Digital Twins: Adding new dimensions to simulation and operational effectiveness?

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ABSTRACT

Within defense, digital twins are rapidly gaining ground as indispensable tools for enhancing capabilities in platform and concept development, experimentation, test and evaluation, and operational activities within today's intricate, multi-domain environment. With a growing need to compress training to skills deployment timescales, incorporating digital twins adds a new dimension to simulation systems by introducing a dynamic coupling between digital and physical assets. Using a digital data thread from physical military assets, the digital model and physical counterpart can be synchronized at a speed of relevance between simulation and physical domains, enabling timely analysis, insight and actions by military decision-makers using accurate, adaptive and responsive high resolution simulation environments.

This paper builds on research conducted by the NATO ACT (Allied Command Transformation) M&S (Modelling and Simulation) Future Technology Watch bi-annual activity which has identified digital twins, along with quantum computing, big data and AI as key technologies and disruptors of the M&S domain, requirements and solutions. The research investigates, proposes, designs and demonstrates approaches to digital twin integration into simulation systems within the context of aggregate level constructive simulation. By reducing the gap between simulated and real-world situations, digital twins make it possible to model battlefield scenarios, logistics, command structures and predict outcomes more precisely, evaluate various tactical, operational and strategic options and enhance the effectiveness, realism, responsiveness and adaption of constructive simulations, allowing for right-time, data-driven insights.

This paper reports on research conducted into the state of digital twins, concepts, frameworks and standards. It considers key challenges, technologies, best practices, and approaches to digital twin integration with simulation systems and next steps in their application to constructive simulation and enhanced mission effectiveness. This analysis is consolidated into a proof-of-concept system design and implemented as a modular, interoperable, standards-based systems architecture that demonstrates component encapsulation and seamless integration of a digital twin and simulation system.

ABOUT THE AUTHORS

Graham Long has over 30 years of experience in training and simulation. A synthetic environment specialist, he has an extensive background managing and developing visual systems, synthetic environments, their associated production pipelines, tools, and interoperability standards. His current role as Simulation Capabilities Product Line Architect incorporates digital twin technology and solutions development, including integration with M&S systems. Additionally, he is an active member of the NATO Science and Technology Organization M&S Group (NMSG).

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INTRODUCTION

Incorporating digital twins (DTs) into simulation systems offers the potential to enhance them with persistently connected models of physical assets, systems or processes that are bi-directionally exchanging data between digital and physical counterparts - adding a new, dynamic dimension to conventional M&S systems that typically comprise static models that do not remain connected to or evolve with the state of the physical asset they represent.

The NATO ACT (Allied Command Transformation) has identified digital twins, along with quantum computing, big data and AI as key disruptors of M&S (Modelling and Simulation). ACT is responsible for leading the transformation of NATO's military capabilities to meet current and future challenges, with a focus on developing concepts, doctrines, training and technologies to ensure NATO interoperability and effectiveness. NATO regards M&S as a core enabler for innovation, experimentation and capability development, as well as decision-making support. NATO ACT, together with the NATO Modelling and Simulation Group (NMSG), promotes the use of M&S to enhance multinational exercises and training, improve operational readiness and interoperability and facilitate research across member nations.

While NATO ACT engages with virtual, live and hybrid simulation, especially for exercises and interoperability, constructive simulations involving simulated people operating simulated systems (NATO, 2012) remain its primary domain and motivates ACT's curiosity regarding the benefits of integrating DTs into simulation systems.

CONSTRUCTIVE SIMULATION

NATO utilizes aggregate level constructive simulation (ALCS) for both operational and institutional functions. Operationally, it facilitates command post exercises by creating a synthetic battlespace for training at the operational and strategic levels. Institutionally, it supports analysis, experimentation, capability and concept development, informing long-range force design while enforcing M&S interoperability. Understanding the distinct roles of these simulations is essential for aligning resources and objectives in simulation-supported military activities, as well as for informing how they can exploit and benefit from the integration of DTs.

Training typically integrates constructive simulations into Computer-Assisted Exercises (CAX), where participants operate in synthetic environments driven by constructive simulation models, reinforcing doctrinal procedures, enhancing decision-making, and improving multinational coordination (NATO NCIA, 2016).

In contrast, constructive simulations for analysis are designed to evaluate decisions, explore and test future concepts, such as Multi-Domain Operations, and inform capability development through Computer-Assisted Wargaming (CAW) and Concept Development and Experimentation (CD&E), allowing thorough analysis of Courses of Action (COAs) (Bruvoll et al., 2015), and evaluation of emerging technologies and operational constructs before implementation into required capability (Pavlov, 2021).

Some simulations, such as those used in the Coalition Warrior Interoperability eXercise (CWIX), serve both training and analytical purposes, assessing interoperability between command and control (C2) systems while providing realistic training contexts and helping to validate technical standards and human processes (Pullen, Erickson, & Ruth, 2024).

DIGITAL TWINS AND AGGREGATE LEVEL CONSTRUCTIVE SIMULATION

The integration of DTs into ALCS represents a significant advancement in enhancing the realism and relevance of simulation-based exercises, analytical activities and events, aiming to bridge the long-standing gap between live operational data and the abstract models typically used for campaign-level training and analysis.

In contrast to CAX and CAW, which rely on traditional data-driven models and scripted, statistically derived behaviors, a DT introduces a continuously updated, physics and data-driven representation of a real system, or multiple systems, into the simulation loop. Dynamically connecting real-world conditions and abstract simulation entities allows planners and analysts to examine complex interdependencies and emergent behaviors with greater precision. This approach can enhance the force-on-force model fidelity without compromising the scale needed for theatre-level decision support (U.S. DoD, 2018).

Integrating Digital Twins and Simulation Systems

When considering the integration of DTs with simulation systems, a strong foundation built on shared definitions, clearly defined system boundaries, synchronized bidirectional communication, real-time data integration, consistent data semantics, and interoperable architectures is required. Without these fundamentals, any two systems struggle to interoperate seamlessly. Therefore, integration solutions must address these critical foundational elements to ensure DTs function as integral components of a coherent simulation architecture.

Modern M&S systems have a heritage stretching from digital computing and USAF flight simulators in the 1950's, through the introduction of distributed simulation in the 1970's, to current immersive systems, incorporating AI, big data and extended reality. There are thousands of deployed and operational systems, spanning multi-domain, live, virtual, and constructive simulation, supported and enabled with established M&S standards covering topics from architecture, interoperability and data to synthetic environments. This proven, established, highly mature level of M&S solutions contrasts with the relatively immature state of DTs.

Despite increasing adoption across various domains, the DT concept suffers from significant definitional ambiguity. At its core, a DT is "an integrated data-driven virtual representation of real-world entities and processes, with synchronized interaction at a specified frequency and fidelity" (McKee, 2023). However, surveys have consistently highlighted numerous definitions (at least 37) (Awasthi et al. 2024) revealing conceptual ambiguity driven by domain and use-case needs. This complicates integration into broader M&S systems, which has motivated the NMSG to propose its own definition of a DT as *'a validated virtual model of a physical entity or process, with the capability to be seamlessly connected throughout its lifecycle, enabling simulation, performance optimization, and informed decision-making.'*

Definitional ambiguity reflects not only semantic problems but practical uncertainty regarding what constitutes the scope and boundary of a digital twin. Articulating the temporal, functional and spatial scope is essential to ensuring interoperability and composability within system-of-systems frameworks (Liu et al., 2018). In particular, when federating DTs across domains, a lack of boundaries hampers trust, repeatability, referential integrity, and the ability to manage data flows across M&S pipelines and control systems.

Kritzinger et al. (2018) propose a taxonomy to support clear delineation of DTs by distinguishing between digital models (static, offline), digital shadows (automated, unidirectional updates), and DTs (fully automated, bidirectional) based on data-flow characteristics. Without such precision, it becomes unclear which aspects of a system are simulated, their update frequency, or the fidelity required for meaningful decision support. Explicit boundary definition not only guides system-of-systems integration of DTs with simulation platforms but also informs performance trade-offs (Kritzinger et al., 2018), clarifies fidelity requirements and enables component reuse.

Over the past decade, DTs have evolved from static models toward multi-dimensional, cyber-physical ecosystems, extending from three dimensions - the physical, virtual, and connection elements - to five (Tao et al., 2017) that incorporate services and data modules (Figure 1), and subsequently to six dimensions (Ren et al., 2024). The digital thread, a continuous, bidirectional information flow, is at the heart of the DT ecosystem, forming the communication backbone, enabling operational synchronization and traceability (McKee, 2023; Dihan et al., 2024), and allowing DTs to function as system-of-systems. Without a robust digital thread, DTs lose closed loop feedback and cannot maintain fidelity or integrate with simulation and decision support ecosystems. True DTs enable bidirectional data flow, and simulation systems must, therefore, support both data ingestion from twins and operational controls.

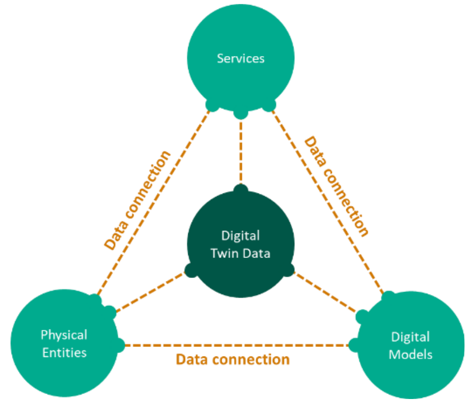

Figure 1 Five-dimensional DT model

To formalize such complex constructs, several organizations have proposed reference architectures. The Digital Twin Consortium's Platform Stack Architectural Framework outlines modular layers, from data ingestion and integration to modelling and applications, with an emphasis on scalability and composability (McKee, 2023). Similarly, NIST (National Institute of Standards and Technology) and ISO (International Organization for Standards) have introduced ISO 23247 for manufacturing, defining ontology, interoperability and assurance dimensions, while other initiatives, such as the Industrial Internet Consortium (IIC) and International Electrotechnical Commission (IEC), address standards for data models, connectivity, and verification. These architectures can guide system-of-systems integration, enabling M&S platforms to interface cleanly without reengineering entire ecosystems.

Despite these efforts, DT-related standardization remains fragmented. While industry bodies recognize the need for shared ontologies and semantic interoperability (e.g., OPC-UA (Open Platform Communications Unified Architecture), AAS (Asset Administration Shell), IoT (Internet of Things) protocols), no globally accepted DT standard exists. The DTC and IIC have orchestrated ecosystem-wide frameworks, yet global standard bodies have not ratified a consistent reference model (McKee, 2023; IIC, 2015). Domain and vendor-specific standards, data schemas, communication patterns, and model-description protocols proliferate, resulting in fragmented tool chains and friction that complicates integration into heterogeneous M&S environments.

The implications for modelling and simulation are significant. Without agreed definitions, bounded twin instantiations, bidirectional interoperability, layered reference architectures, and shared standards, DTs may remain isolated assets rather than integrated components. For M&S systems to leverage the potential capability twins offer, an integrated system solution must address these foundational issues.

DT & M&S INTEGRATION ARCHITECTURE

Integration challenges and requirements

Moving beyond these fundamental, foundational system issues, the specific goal of integrating DTs into ALCS raises several longstanding challenges that any solution architecture must consider.

Multi-Resolution Modeling (MRM) and Consistency

Firstly, military simulations often require representing the same battlefield or scenario at multiple resolutions - perhaps incorporating high-resolution models for individual vehicles and coarse aggregate models for battalion movements. Ensuring that these multi-resolution models remain mutually consistent is a core challenge. Systems must manage the aggregation and disaggregation of units without introducing errors and maintain data and temporal consistency.

Data Aggregation and Model Fidelity

There is a trade-off between model fidelity (resolution and accuracy) and performance. Aggregate simulations sacrifice some detail for scalability, whereas DTs often embody high fidelity models. Architectures must allow data aggregation from detailed twins up to higher levels and disaggregation from high-level commands down to detailed actions. Transitions between aggregate units and their detailed components must be seamless, enabling higher resolutions where needed without unduly compromising accuracy at the aggregate level.

Real-Time Performance vs. Analytical Rigor

Training simulations demand low latency, real-time performance and interactivity to enable trainees to interact with the simulation live. In analysis uses, speed and interactivity are less important than fidelity and repeatability, and simulations can be run slower or faster than real-time. A comprehensive solution must be able to provide timely responses and smooth integration of live players or operational systems for training, while allowing high-detail modeling and possibly asynchronous or accelerated time progression for analysis.

Bi-Directional Data Flow and Control

The bi-directional data flow of DTs requires clear interfaces for both inbound data, from systems or sensors, and outbound data, to systems or actuators, often requiring filtering or abstraction layers to protect real-world operations, while ensuring that real-time data and feedback loops do not introduce latency that may distort training objectives.

Data Security and Trustworthiness

These bi-directional links between DTs and live systems introduce vulnerabilities, raising security issues and necessitating robust synchronization, particularly as DTs may represent critical assets attractive to adversarial cyberattacks. Traditional reliance on "air-gapped" networks or system-high segregation is cumbersome in coalition contexts where data of varying classifications must coexist. A modern security framework, such as a Zero Trust Architecture, is required to secure data in transit and at rest, authenticate and encrypt all data exchanges, and enforce strict access controls (Thales Group, 2021). These measures also support the trustworthiness of DT models, providing stakeholder confidence in the accuracy and reliability of DT outputs.

Interoperability and Distributed Architecture

Interoperability is essential, requiring the integration of diverse simulation components, including DTs, into a cohesive environment. Federated architectures support this through standard interoperability protocols, such as the High-Level Architecture (HLA) or similar protocols like DIS (Distributed Interactive Simulation). These standards enable the integration of new DT components with minimal modifications to existing legacy systems. Established data distribution standards, such as the Data Distribution Service (DDS), can also facilitate real-time publish and subscribe of data to the simulation. Ensuring semantic interoperability, where systems consistently interpret shared data, and the use of common ontologies or data models to align DT data with the simulation's data model is crucial to achieve interoperability among heterogeneous DTs and HLA federations (Li et al., 2021).

In summary, an architectural design must address multi-resolution integration, fidelity management, performance versus detail trade-offs, interoperability across systems, security and trust, and live data integration.

Proof of Concept Integration Architecture

As a critical first step in meeting the challenges of integrating DTs into a simulation system, a proof-of-concept (PoC), interoperable architecture was designed and implemented as the foundation for further evolution and capability development. The PoC design demonstrates a practical approach to the encapsulation of simulation components, including DTs, enabling system orchestration and composition, and the seamless integration of DTs in place of or in addition to existing simulation components.

Figure 2 AOEDT

The DT PoC solution is based on the Thales Air and Space Operational Environment Digital Twin (AOEDT) (Figure 2), which combines a synthetic environment, constructive and virtual simulation components, digital models, shadows and DTs to provide offline and online, high fidelity decision aiding, optimization and control capabilities.

An Unmanned Aerial System (UAS) DT consisting of a small quadcopter drone (Figure 3), and its digital counterpart comprised of a flight dynamics model, drone flight controller, and ground control station was integrated into the AOEDT system. The UAS DT incorporates an artificial intelligence (AI) flight dynamics and battery model trained from physical UAS telemetry data. Evolutions of the UAS DT were integrated into the simulation system as the performance of the AI flight model improved through the training process.

The digital thread between the physical and digital UAS consists of flight telemetry data streamed via the MAVLink communication protocol to the Elasticsearch, Logstash, and Kibana (ELK) stack analytics platform, and also supports sending control and mission data to the physical drone.

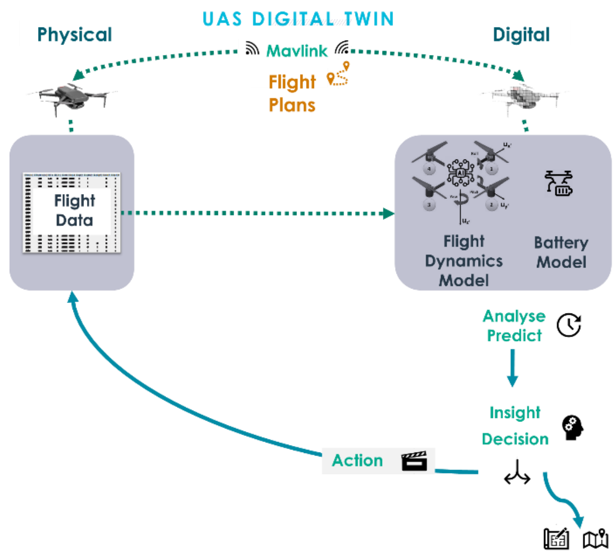

Figure 3 UAS Digital Twin

PoC System Architecture

The AOEDT system (Figure 4) employs a standards based, HLA Evolved (IEEE 1516-2010) distributed simulation architecture designed to provide an open, versatile, adaptable system framework to compose solutions from synthetic environment and simulation components, digital models, shadows, and twins, data and analytics services in a federated, interoperable simulation environment.

The AOEDT system employs the industry standard SISO-STD-001.1-2015 Real-time Platform Reference (RPR) FOM and the HLA compliant MAK High-Performance Runtime Infrastructure RTI (MAK Technologies). This imposes the requirement on all federates that join the AEODT federation, including DTs, to adhere to the RPR FOM standard, which serves to encapsulate their internal data structures and expose only necessary attributes and interactions.

The baseline AOEDT system was configured with a set of simulation federates consisting of a 3D real-time visualization of the operational area and entities, a test UAS DT, the ASCOT7 Computer-Generated Entity (CGE) platform, and ADS-B data.

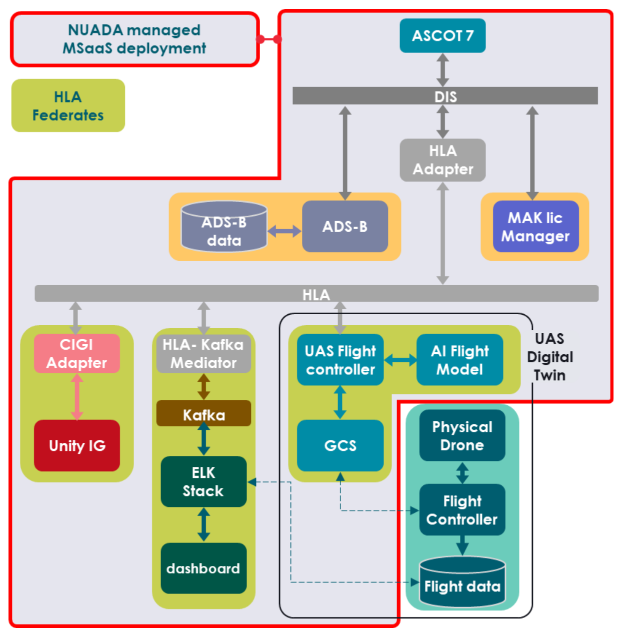

Figure 4 AOEDT System Architecture

Adapters and mediators facilitate federate communication and integration, acting as intermediaries to manage and optimize interactions and ensure seamless data exchange, synchronization and compatibility between heterogeneous federates. An HLA adapter bridges HLA to the ASCOT7 and ADS-B DIS IEEE 1278 components, to the Image Generator through a CIGI (Common Image Generator Interface) adapter and integrates the ELK stack federate through an HLA to Kafka mediator.

PoC System Composition

The proof-of-concept implementation employs a Modelling and Simulation as a Service (MSaaS) approach to simulation component encapsulation, composition and seamless integration of the UAS DT into the simulation system. The MSaaS solution was implemented using the Thales NUADA product – an agile MSaaS tool for creating and efficiently managing simulation federations where multiple simulation resources need to be assembled in different configurations at different times. NUADA maintains a catalogue of reusable simulation assets – the physical devices, systems, applications, services, scenarios and data files required to build a federation - and provides the framework to compose these with their dependencies into an asset plan, and deploy them as an event.

For the proof-of-concept, the AOEDT HLA architecture was adopted as the predefined system design pattern, forming a managed, interoperable baseline, allowing repeatable composition, and swapping of assets. The inherent features of HLA enable and support encapsulation of distributed simulation components, including the UAS DT, ensuring that each federate operates independently and interacts with other components in a controlled manner, promoting modularity, interoperability, and reusability.

The AOEDT baseline architecture was configured as an asset plan and deployed as an event to create a configured, managed virtual network connecting physical assets and virtual machines running the baseline components in an HLA federation. From this baseline, the UAS DT and the ELK stack analytics service were integrated into the AOEDT system as HLA federates by adding them to the asset plan before re-deploying the updated AOEDT architecture. The analytics capability was used to assess and evaluate the DT AI flight dynamics performance, progressive AI model training improvements, perform comparative analysis of flight performance and adherence to flight plans as well as monitoring and evaluating modelled and real battery health and performance.

Consistent data modelling, interoperability and integration are critical to the effectiveness of coherent federated simulation systems, and it is essential that any candidate DT adopts the appropriate systems data framework. However, the integration of the UAS DT battery model highlighted the data interoperability and modelling discrepancies that can arise when integrating real and simulated systems. In this case, the real battery telemetry data was far richer than that supported by the RPR FOM, however, the HLA standard allows extension of the FOM and this feature was used to incorporate data attributes from the real UAS battery data system.

PoC Lessons learned – Key Findings

The PoC demonstrated that simulation systems based on standardized distributed simulation architectures can provide a structured ecosystem and framework to enable and facilitate DT integration. The HLA framework was chosen and implemented as a method of mandating component compliance to a distributed simulation standard. This imposed component encapsulation, interoperability, modularity and loose coupling on conventional simulation federates and importantly, on the DT, ensuring it was able to perform and interact as a compatible system federate through adoption of the HLA API and HLA RPR FOM. Importantly, HLA provided a system configuration "pattern" enabling interoperable components to be easily integrated and composed with an MSaaS approach. This was achieved through well-managed configuration, system adaptation, and architectural re-configuration, to enable addition and removal of simulation federates and the frictionless integration of the UAS DT.

EVOLUTION OF THE POC INTEGRATION ARCHITECTURE

The success of the PoC demonstrates the feasibility of this approach. It lays the groundwork for a more comprehensive architectural solution to DT integration with military ALCS, addressing key technical and operational challenges related to multi-resolution modelling, training and analysis needs, in combination with data aggregation, fidelity management, security, and interoperability features.

Multi-Resolution Modelling

The multi-resolution modelling needs of constructive simulation extend beyond entity DTs, like a UAS, to require the incorporation of abstract and aggregate fine-grained telemetry into operationally usable constructs. This naturally leads to concepts of Aggregate Digital Twins (ADTs) and Hierarchical Digital Twins (HDTs) as frameworks designed to capture systemic behavior at scale while preserving links to underlying platform and process models.

ADTs are composite models that combine the state of multiple systems, platforms, or subsystems into a singular virtual representation optimized for higher-level use cases (Grieves & Vickers, 2017). Unlike conventional DTs, which typically mirror individual asset status, ADTs are explicitly designed to support theatre or enterprise-level decision-making. They summarize the state of asset groups, all APCs in a company for instance, into metrics such as "readiness," "logistics availability," or "mission effectiveness." These aggregate variables form inputs to simulation engines or analytics models, streamlining computation while maintaining situational relevance (Kritzinger et al., 2018).

HDTs extend this paradigm by organizing ADTs into nested, multi-resolution structures that reflect operational command hierarchies or system-of-systems architectures. For instance, a platoon-level twin may feed into a company-level twin, which in turn informs a battalion or brigade-level model. Similar vertical aggregation in civilian infrastructure (Ruhe et al., 2023), applies a real-time HDT to power grids to balance equipment fidelity with grid-wide behavior. In an ALCS context, an HDT can enable multi-echelon analysis, allowing commanders to "zoom" from brigade to platoon level depending on scenario needs, without restarting or fragmenting the simulation.

Using ADTs and HDTs in ALCS offers significant benefits, including modular architectures, analytical traceability and realistic simulation without heavy computational demands. They also enhance integration of live readiness data with synthetic environments, boosting training fidelity and decision support. Nevertheless, challenges remain. Systems must carefully manage aggregation to ensure causal fidelity, maintain semantic alignment between DT data structures to prevent runtime incompatibilities (Grieves & Vickers, 2017), as well as handle data-sharing restrictions that may limit lower-level data transparency. Comprehensive, layered verification and validation (V&V) is essential to enable accreditation and preserve confidence when DTs, ADTs and HDTs are injected into ALCS, and must continue for a DT's whole life cycle. Initial model-in-the-loop tests (U.S. DoD, 2012), verify DTs physics and timing, however, one connected to live telemetry, DT operating envelopes evolve, requiring periodic, rolling re-checks that compare recent predictions with real performance. In a hierarchical federation, ownership transfer and timing between models must be managed, while errors are continuously monitored as part of a background quality assurance service that ensures data dependability. Despite these challenges, ADTs and HDTs provide a robust conceptual and technical bridge between detailed operational data and abstracted simulation environments. When combined with HLA and domain-specific data models, they offer a path to building adaptive, modular, and secure ACLS that reflect multi-domain operations.

Training and Analysis

Any broader architectural solution must consider the distinct purposes of training and analysis, as these differences shape the design of integrated DT architectures. Training-oriented simulations, such as CAX, are designed to support the development of decision-making skills, process familiarization, and joint coordination across echelons. They are usually real-time, involve human-in-the-loop interactions, and end with structured after-action reviews (AARs). Such simulations must offer high availability, responsiveness, and control interfaces for instructors. For example, exercises using Joint Theatre Level Simulation (JTLS) or NATO's Joint Conflict and Tactical Simulation (JCATS) involve orchestrated events in which trainees react to evolving conditions based on injects and predefined scenarios.

By contrast, analysis-focused simulations evaluate systems, strategies, or doctrinal options through data-driven analysis, campaign modelling, and statistical replication. They typically run faster than real-time, often in batch mode, and are focused on outcome metrics, not participant behavior, prioritizing fidelity and traceability over interactivity, frequently integrating with optimization tools or machine learning algorithms.

An Extended ALCS Integration Architecture

These multi-resolution concepts are brought together with training and analysis considerations into an extended integration architecture that builds on a distributed simulation HLA framework, incorporating ALCS, DTs, and other HLA federate components, RTI time management, data distribution, ownership transfer, and standard FOMs.

The proposed architecture centers on a tiered digital twin model (Figure 5) that enables scalable simulation fidelity through aggregation and disaggregation mechanisms. At the foundational level, entity-level DT federates represent individual platforms and systems, such as UASs, vehicles, or weapon systems, providing real-time telemetry, health status, and behavioral modelling (Desai et al., 2023). These are encapsulated by aggregate digital twins that represent tactical units such as platoons or companies, aggregating entity-level data into operational indicators like readiness, morale, and combat effectiveness (Zheng & Tian, 2022). At the top of the hierarchy, higher-echelon twins model force elements such as battalions or brigades, providing a strategic overview of the simulation state (Lee et al., 2020).

This multi-resolution approach supports dynamic shifts in model fidelity governed by rule-based triggers, operator inputs, or intelligent control via a cognitive digital twin, providing a DT management service (Figure 6). A cognitive twin component operates as a semantic and operational filter, monitoring simulation context, determining when to increase or reduce resolution, and enabling efficient resource usage while preserving operational realism. This is essential in scenarios requiring real-time response to evolving battlefield conditions, such as adversarial interference, or decision-support requests (Zeng et al., 2022).

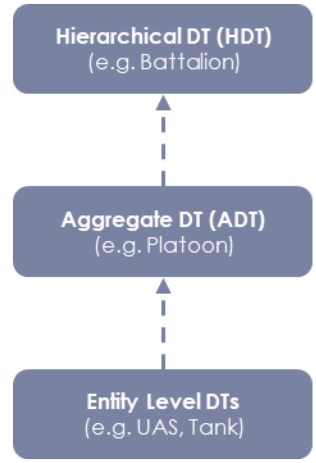

Figure 5 Tiered DT Approach

Defined aggregation and disaggregation functions handle data movement across these resolution layers. Aggregation consolidates telemetry and behavioral data from multiple entity-level twins into composite metrics used by aggregate twins. Disaggregation allows the simulation to instantiate higher-resolution models in response to operational cues, for example, activating UAS and infantry twins when a contact report occurs near a logistics node. This approach reflects the operational need to maintain broad situational awareness while adapting and selectively applying detail where mission relevance or uncertainty requires deeper analysis (Kott et al., 2017). Entity-level DTs publish data using the RPR-FOM, while ADTs and HDTs use NATO Education and Training Network (NETN)-FOM modules to enable multi-resolution, scalable simulation data exchange (Lee et al., 2020). HLA gateways manage data transformation between layers and ensure semantic coherence between federates operating at different resolutions.

A DT broker component bridges between assets and the simulation, coordinating data exchange across entity, aggregate and hierarchical twins. The broker handles schema validation, time synchronization and message routing, ensuring each simulation component and consumer receives correctly formatted data, at the appropriate cadence, with the necessary level of detail (Lee et al., 2020), and enforces authentication, role-based filtering and authorization with a zero trust approach. User-facing components include a role-based C2 dashboard connected to the DT broker, enabling analysis of cognitive-twin what-ifs, aggregate metrics and shared situational awareness (Lee et al., 2020).

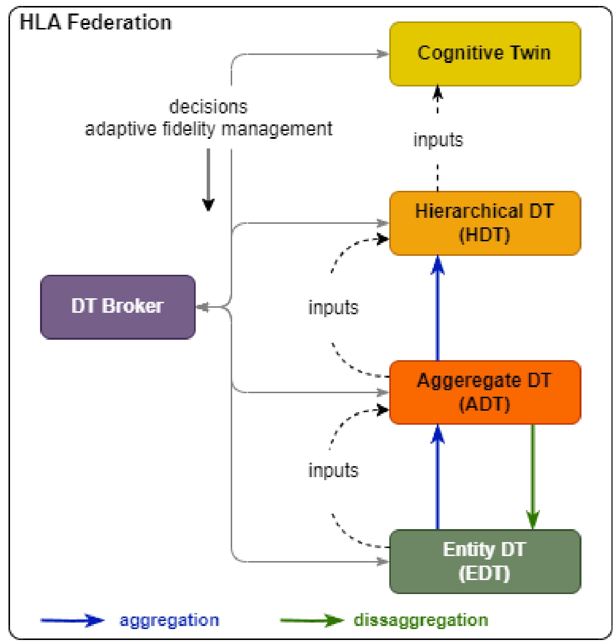

Figure 6 Extended High-Level Architecture

The architecture is deployable as a hybrid edge-and-cloud platform, where latency-sensitive entity twins and HLA federates execute on edge servers while aggregate twins, analytics, and the broker scale elastically in the cloud, all containerized under Kubernetes (Burns & Beda, 2019). This arrangement ensures timely decision-support while maintaining the compute depth needed for multi-resolution modelling (Lee et al., 2020).

Extended ALCS Integration Architecture Use Cases

The following hypothetical use cases illustrate the methods and benefits of applying the proposed architecture to address training and analysis aspects of constructive simulation.

Battalion-level urban training scenario

In the first representative use case, a mechanized battalion rehearses an urban break-in over a three-hour live-virtual-constructive exercise. Only two rifle platoons and their vehicles are present on an instrumented range, while the remainder of the battalion, air support, and adversary forces are simulated. During the run, instructors must track ammunition, casualty estimates, sensor coverage, and morale in real-time and inject unexpected events, such as an insurgent-flown UAS or an improvised explosive device (IED), and issue immediate route or fire adjustments. The learning focus is on platoon coordination and rapid refuelling under threat while maintaining a reliable, common operational picture (Lee at al., 2020).

Theatre-wide logistics analysis scenario

The second use case supports a month-long analytical study of two corps moving along four main supply routes in a contested theatre. Planners run hundreds of Monte Carlo iterations overnight to gauge depot throughput, convoy vulnerability and phased force-deployment schedules under combinations of cyber, kinetic, and weather disruptions. Outputs populate a cost-loss trade-off matrix that feeds routing, stock-pre-positioning, and budgetary decisions for the next fiscal cycle (Zheng & Tian, 2022).

Execution in the training scenario

At start-up, an ADT represents each platoon and publishes 30-second updates of morale, mobility, and consumption to a brigade-level HDT. When the cognitive twin detects an unscheduled UAS track above the logistics hub, it raises a rule-based trigger that instructs the DT broker to disaggregate the affected platoon ADT into multiple entity-level twins (Desai et al., 2023). These entity twins stream 1 Hz telemetry, such as vehicle positions, sensor detections, and fuel state, upward through the broker, which validates schemas, tags provenance, and rolls the data back into the parent ADT and HDT. Downward messages follow the same path in reverse. With the cognitive twin formulating a jammer-on command and a reroute waypoint set, the broker attaches short-lived tokens, encryption and authentication, and the orders arrive simultaneously in the live vehicle radios and the virtual UAS model. This bidirectional loop keeps instructors informed at platoon fidelity while avoiding the cost of permanently running high-resolution simulations (Rose et al., 2020).

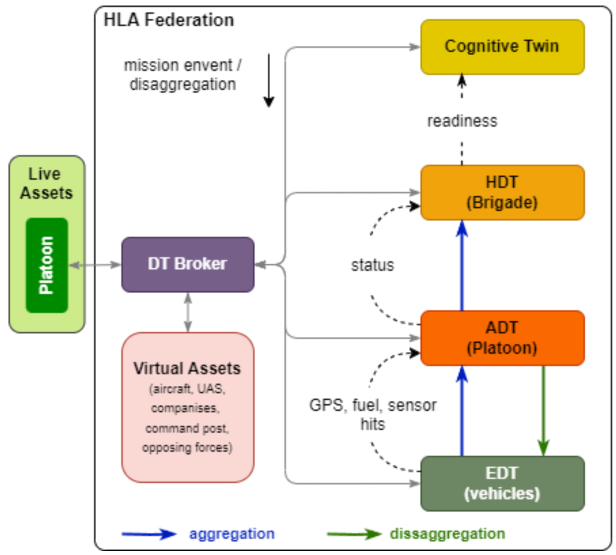

Figure 7 Training Use Case Execution

Execution in the logistics-analysis scenario

For theatre analysis, only HDTs, composed of corps and depots, and ADTs, composed of convoys and supply nodes, remain active, updating hourly. The entity twins remain dormant to conserve cloud resources. Each convoy ADT aggregates average speed, fuel burn, and cyber-latency reports, captured whenever entity twins were active in earlier iterations, and forwards these metrics upward to the corps-level HDT, which recalculates predicted stock-out dates. If an IED or cyber breach scenario exceeds a risk threshold, the cognitive twin spawns a fine-grained entity twin for the convoy segment, collects five-minute telemetry on damage and delay, and rolls the results into updated route-delay factors before the next analytic batch. Downward traffic in this use case carries analyst-driven policy injections, such as new escort ratios, alternate ports of entry, or priority cargo lists, rather than real-time commands. The broker signs and disseminates packets to the relevant ADTs for the next simulation cycle. Because the run is offline, no message targets live assets, yet zero-trust controls still preserve provenance and coalition data separation (Farooq & Zhu, 2017).

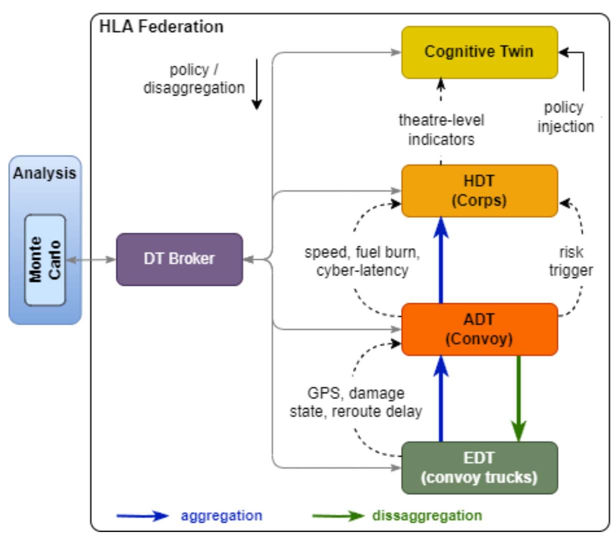

Figure 8 Analysis Use Case Execution

Comparative view of bidirectional exchanges

The training vignette demands second-to-minute telemetry from entity twins, aggregated into platoon readiness for real-time display, enabling instructors to orchestrate live manoeuvres. Therefore, high-rate upward telemetry and downward time-critical control messages are essential. Conversely, the analytic study tolerates minute-to-hour horizons. It focuses on aggregated trends, requiring coarser upward traffic, while downward traffic consists of campaign-level policy changes that affect only future iterations and remain inside the simulation. By adjusting cadence, provenance rules, and access policies, the same brokered architecture, anchored on ADTs for unit-level realism and HDTs for campaign coherence, meets both high-tempo instructional needs and longer time analytic exploration (Lee et al., 2020).

CONCLUSION

Integrating DTs into ALCS for training and analysis offers significant enhancements to the fidelity and resolution of models incorporated into M&S systems through the unique, bi-directional digital to physical data links that enable dynamic synchronization of models and real, physical assets. However, for M&S systems to leverage these capabilities, DT definitions, clearly bounded twin instantiations, bidirectional interoperability, layered reference architectures, and shared standards must be addressed as foundational principles of an integrated DT and M&S solution. The PoC demonstrates that a standards based, federated, interoperable architecture enforces compliance on the DT, facilitates data integration between M&S and DT components, and forms the basis for addressing fundamental integration requirements.

Extending the PoC architecture provides a structured and scalable approach to a DT solution that can address key ALCS requirements to meet both training and analysis requirements. It leverages NATO and industry best practices, from HLA and MSaaS, to multi-resolution aggregation and disaggregation methods, data modelling, and advanced aggregate and hierarchical DT concepts proven in other industries. By addressing the challenges of multi-resolution consistency, fidelity management, security, and bi-directional data flow, the architecture provides a unifying framework where live, virtual, and constructive elements can coexist.

Critically, the architecture differentiates between training and analysis requirements by allowing configuration of resolution and timing. In training mode, it enhances realism and interactivity through high-fidelity injects and live data integration, emphasizing the real-time performance, synchronization, and scenario control, required for human-in-the-loop exercises. Analytical simulations gain depth and accuracy through detailed, high-fidelity outputs, while retaining the breadth and speed needed for robust analysis across many scenarios. Adherence to interoperability standards enables the flexibility to incorporate use case-specific DTs and facilitate system integration with NATO activities, such as simulation federations in CWIX exercises or the NextGen M&S capability development program.

Going forward, the PoC architecture offers a potential pathway to integrate a new, DT-enabled dynamic dimension into traditional M&S systems, providing capabilities that can enhance operational effectiveness. However, it is important to acknowledge that DTs at every tier, from EDT, to ADT and HDT remain immature for constructive applications. Future work must develop and validate multi-resolution approaches incorporating hierarchical and aggregate DT concepts, their fidelity management, and effective integration, synchronisation and exploitation of live, bi-directional data - all within a secure ecosystem that can provide a practical enhancement to ACLS, for both the NATO training enterprise and analytical capability for evidence-based planning.

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