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Challenges and Opportunities in Enhancing Department of Defense Ground Vehicle Capabilities Through Digital Transformation

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Abstract

This paper presents valuable insights from in-depth interviews with Department of Defense stakeholders and a rigorous examination of existing guidelines, standards, and pertinent literature. The paper focuses on critical aspects of digital modeling, data utilization, and data-driven decision-making, focusing mainly on the U.S. Army's ground vehicle applications addressing challenges and opportunities. Data-driven decision-making relies significantly on accurate digital twins, which are critical in preparing ground vehicles for their intended environments, especially in challenging environments like preparing vehicles for the Arctic. Thus, creating synergy between real-life applications and digital twins is crucial. However, the U.S. Army faces hurdles in obtaining comprehensive digital data from original equipment manufacturers, especially for older ground vehicle platforms, necessitating reverse engineering to address gaps. Challenges stem from the absence of standardized digital data practices, which triggers the need to establish a cohesive digital modeling framework. To this end, the paper proposes an Intelligent Front-End Framework. The proposed framework optimizes and integrates data management for defense applications and decision-making. To sum up, this paper emphasizes the significance of adopting digital technologies, optimizing and enabling data utilization, and addressing data challenges to enhance the operational readiness and effectiveness of the Department of Defense.

Introduction

The ongoing digital transformation within the Department of Defense (DoD) holds the potential to revolutionize various aspects of its operations, ranging from design and logistics to operations and sustainability. The integration of digital technologies promises substantial improvements in efficiency and effectiveness. Based on a series of interviews with DoD stakeholders, this research dives into the challenges and complexities of this digital transformative journey, mainly focusing on aggregating and incorporating digital models into broader system-level capabilities. While significant progress has occurred in digitization efforts, a critical need exists for a cohesive strategy to ensure that these digital models contribute effectively to mission analysis and optimization through digitalization (i.e., digital transformation).

Our research approach revolved around two core elements: (1) engaging in in-depth discussions with key stakeholders within the DoD and (2) conducting a rigorous examination of existing guidelines, standards, and pertinent literature. For (1), through stakeholder discussions, the authors tap into the wealth of knowledge and expertise possessed by DoD personnel actively involved in the subject matter. Their firsthand perspectives, experiences, and recommendations form a critical foundation for our research. For (2), our comprehensive review process delves into established best practices, industry standards, and the latest advancements in the field. This examination ensures that our research is firmly grounded and up-to-date, allowing us to benchmark our findings against existing frameworks. Combining insights from DoD stakeholders with a review of guidelines and standards, our research approach embodies a holistic, data-driven methodology designed to provide robust and actionable outcomes.

Background

The DoD is at the forefront of bold digital modeling initiatives, aiming to bolster its capabilities across diverse domains. These initiatives encompass a broad spectrum of activities, ranging from the digitization of components via scanning to the creation of intricate 3D models for various vehicle platforms, along with the development of sophisticated simulation models. These coordinated efforts highlight the increasing recognition of the potential benefits of digital technologies, including real-time analysis, predictive modeling, and overall improvements in operational efficiency. However, it is essential to understand that simply creating digital models, while a crucial step, does not guarantee their seamless fit and functionality within the larger framework of the DoD's operations. Despite the abundance of these digital models, significant challenges persist in ensuring their completeness, alignment with mission objectives, and compatibility across various datasets. These challenges are further compounded by the widespread nature of the digitalization process, involving numerous organizations from both the government and the private sector, often spanning international boundaries.

This paper highlights the potential risks to the accuracy of digital models. Unintentional changes, along with deliberate alterations by opposing forces (adversaries) via data hacking, present dangers that could undermine the accuracy and reliability of these models. As a result, creating a robust digital system requires a well-rounded approach. The DoD's digital transformation efforts must go well beyond just the skilled creation of digital data; they must also involve tackling the complex and detailed elements that impact the effective use of digital models across the broader operational setup of the DoD. With these insights in mind, the upcoming sections of this report dive into the specific factors crucial for developing a thorough and unified digitalization strategy.

The distinction between "digitization" and "digitalization" has emerged as a point of critical consideration. To this end, the essential message lies in maintaining data in a format that enables swift content analysis and ensures long-term accessibility through the application of Artificial Intelligence (AI) and Machine Learning (ML) techniques. In this context, "digitization" predominantly involves altering the form of information, while "digitalization" extends further by reshaping both the form and the processes for its creation and utilization. The terms "digitalization" and "digital transformation" share closely related definitions, signifying the profound impact of digital technologies on DoD operations.

Through conducting this research, spanning 2022 to 2023, discussions with DoD representatives have illuminated the changing landscape of the ongoing digital transformation within the DoD. These discussions brought together experts and stakeholders, thereby providing invaluable insights into the challenges deeply embedded in the DoD's digital implementation initiatives. Focused discussions explored digital modeling, data integration, and technological resilience, providing insights into the complex and detailed workings involved in making digital technologies more efficient and effective. The outcomes emphasized the DoD's dedication to fostering a robust digital ecosystem ready to amplify mission success, operational efficiency, and overall readiness in an increasingly complex digital domain.

Current Status of Digital Data and Modeling Infrastructure

Based on the conversation with U.S. Army personnel, the Army acknowledges the potential that digital modeling offers for advancing ground vehicle capabilities. However, this recognition comes with practical challenges that demand careful consideration, particularly in acquiring comprehensive digital data across various vehicle platforms. Within the ground vehicles used by the U.S. Army, the availability of digital data (e.g., geometry data, requirement data, performance data, and analysis data) varies significantly among different vehicle platforms. This variation becomes more apparent when examining vehicles in older platforms (e.g., High Mobility Multi-purpose Wheeled Vehicle [HMMWV], colloquially known as "Humvee"), which are in the process of being replaced by the newer Joint Light Tactical Vehicle (JLTV) Family of Vehicles (FoV; DOT&E, 2011). In the older platforms, the availability of up-to-date digital data is often limited. To address this information gap, the Army must consider reverse engineering. Reverse engineering involves scanning components, processing a point cloud, creating CAD models, and printing the components using a 3D printer via an additive manufacturing process. Therefore, this process involves systematically disassembling and meticulously analyzing physical vehicles to create accurate digital replicas that aim to capture their tangible counterparts' intricate features faithfully.

However, the process of reverse engineering, though methodical, has challenges and potential limitations. Developing precise digital representations requires a deep knowledge of each vehicle's design and construction details. Despite these dedicated efforts, a drawback emerges: digital renditions may unintentionally overlook specific subtle characteristics and variations inherent to their tangible counterparts. Also, the utilized/original components for generating the digital representation may include notable manufacturing discrepancies (errors) and could fall outside acceptable tolerances. Consequently, the resulting digital models may not faithfully portray the initial design intent. Furthermore, reverse engineering typically captures shape without capturing behavioral, performance, or contextual parameters that interplay with the geometry. These parameters ensure that the digital models accurately simulate real-world conditions and behaviors.

Moreover, a critical consideration arises: Should we also capture the test/qualification processes that the engineering teams underwent to qualify these parts? This concern arises from the possibility that a 3D-printed version will not meet specifications or performance requirements. In order to address this concern, our research aims to determine what needs to be captured in this regard, recognizing that comprehensive data on the testing and qualification processes is crucial for validating the accuracy and functionality of the digital models and their real-world applications.

As a result of the complicated engineering tasks involving reverse engineering, a significant challenge arises: the lack of a streamlined digital data acquisition process and comprehensive data repositories. This absence introduces a range of complexities when constructing digital models for the diverse ranges of ground vehicles. The absence of standardized digital data further amplifies the challenges in establishing a cohesive digital modeling infrastructure (i.e., a well-organized and interconnected system for creating digital models), which is essential for fully leveraging the potential of digital modeling within the operational domain of the U.S. Army.

Figure 1 illustrates the development of a jet engine in a streamlined circular and iterative digitalization process. Although primarily associated with aircraft, it shares essential principles with ground vehicle development, including those designed and manufactured for the U.S. Army. While the specific applications differ, the fundamental approach to systems engineering, digitalization, and iterative processes remains similar. Both disciplines involve deconstructing complex systems into interconnected components, iterative design refinements, adaptation to evolving requirements, rigorous testing, risk mitigation, compliance with safety standards, and environmental considerations. These shared principles highlight the fundamental principles of systems engineering with a circular and iterative digitalization process, making it a valuable digitalization framework for innovation and efficiency across various engineering domains, including aerospace and ground vehicle development.

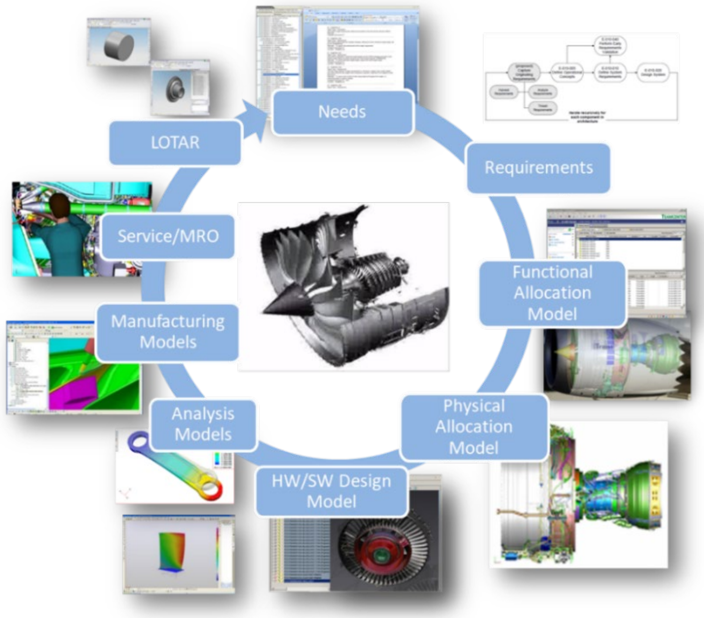

Figure 1. Iterative Circular Digitalization Process in Systems Engineering

Figure 2 examines the model-based digital product data (Hartman & Zahner, 2017) connecting the other information domains in an enterprise setting. The digital product data (Figure 2, lower bottom) is a critical bridge connecting multiple data domains within an organization, fostering streamlined operations and informed decision-making. It supports analytics and insights (Figure 2, top left) by providing the foundational data for uncovering patterns, anomalies, and actionable insights that inform product optimization and strategic decisions. Moreover, digital product data influences user interfaces and experiences, ensuring that interfaces are responsive and intuitive, enhancing overall user satisfaction. Data collection and integration (Figure 2, middle) act as a central repository, consolidating information from various product lifecycle stages and enabling seamless team collaboration.

Research shows that digitalization in the ground vehicle value chain offers rich research opportunities in all connected fields throughout the enterprise, including supply chain management, digital twins, virtual prototyping, and AI for optimization and predictive analytics (Panchal & Wang, 2023). Lastly, the digital product data extends its reach across the entire enterprise (Figure 2, right), enhancing organizational capability by ensuring all departments have access to the latest product information. This interconnectedness empowers organizations to operate efficiently, innovate effectively, and maintain competitiveness.

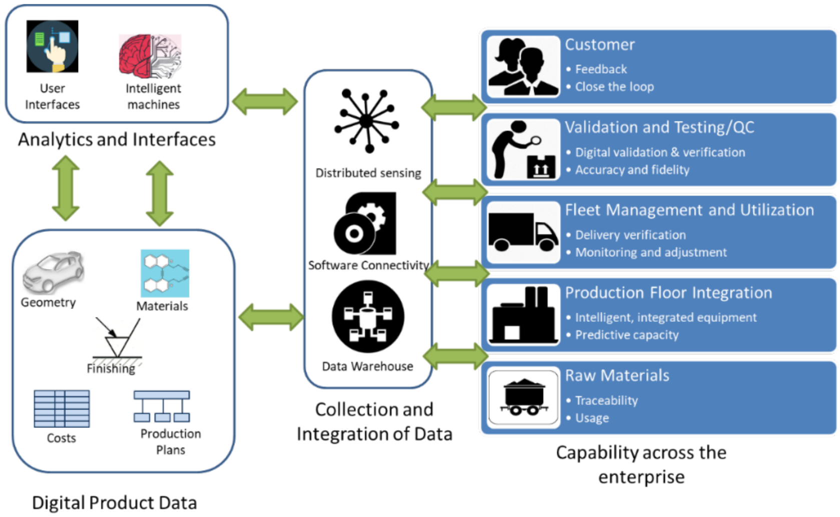

Figure 2. Digital Product Data Integration and Enterprise Connectivity Adapted from Kinnet (2015)

Figure 3 examines the data exchange between physical and virtual vehicle models, a critical element of digitalization in product design and development. This data exchange streamlines communication and synchronization between the physical prototype (Figure 3, left) and its digital counterpart (Figure 3, right). It increases accuracy through precise measurements, iterative refinements, and comprehensive simulations, fostering early issue detection and cost savings. This data exchange significantly shapes decision-making throughout the design and development process, providing real-time feedback, facilitating iterative refinements, and enabling comprehensive evaluation of design alternatives. Consequently, decision-makers benefit from a wealth of insights, leading to more informed and cost-effective choices in the quest for optimal vehicle design and development.

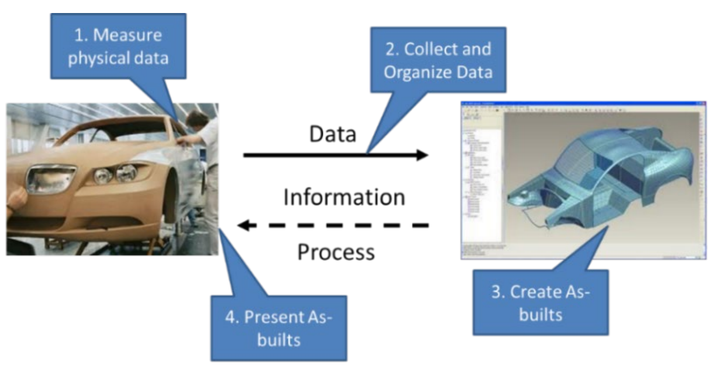

Figure 3. Data Exchange Between Physical Model and Virtual Model

Figure 4 demonstrates the versatile application of digital models across a product's lifecycle, spanning from the "As Designed" to "As Manufactured" and "As Used" stages. This concept parallels their role in bridging the gap between these states, exemplified by jet engine blades (similar to the aircraft component example in Figure 1) and maintaining a consistent engineering philosophy with ground vehicles utilized by the U.S. Army. A comprehensive digital representation initially captures the blade's intended design, serving as the foundation for anticipated performance with minimal variability. During manufacturing, rigorous inspections ensure precise conformance with design specifications, fostering robust quality control.

However, inherent manufacturing variability introduces distinctions between "As Designed" and "As Manufactured." Over the product's operational life, real-world usage data seamlessly integrates with the digital model, empowering engineers to monitor performance, promptly identify deviations, and enable predictive maintenance vigilantly. This variability assumes particular significance under "As Used" conditions, where mechanical and thermal stresses subject the product to rigorous trials. These advanced digital models are indispensable tools, elevating product performance and efficiency, fortifying reliability, and upholding stringent safety standards through meticulous data-driven optimization practices.

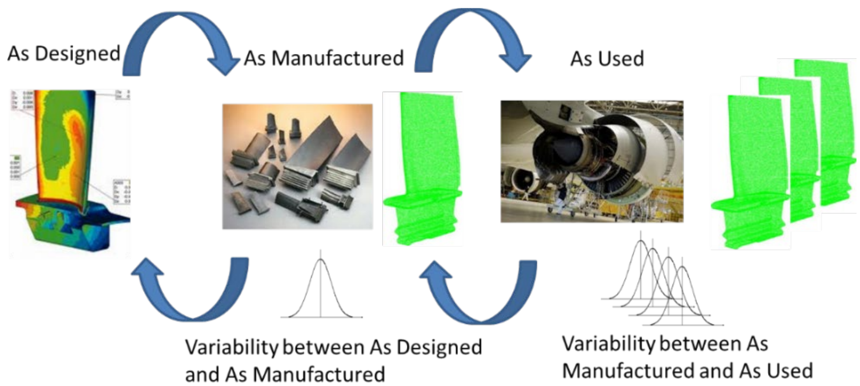

Figure 4. Comparison of Product: As Designed vs. As Manufactured vs. As Used

The U.S. Army's recognition of the promise offered by digital modeling in the context of ground vehicles contrasts with the practical realities stemming from varying degrees of digital data availability, complexities of reverse engineering, and the lack of standardized data repositories. While capturing the digital representation of legacy weapons platforms will involve much manual work and effort, it is not without benefits. It will simply be a choice the Army will need to make in light of concerns around intellectual property (IP), budget, and readiness. Speaking of IP, contracts with Original Equipment Manufacturers (OEMs) should include some level of access to digital products and process data to support sustainment over the lifecycle. In the ongoing balance between goals and limitations, the U.S. Army is grappling with various difficulties while striving to build a robust digital modeling infrastructure. However, as the U.S. Army implements robust infrastructure for digital modeling, it will markedly elevate its operational capabilities and broaden its scope of accomplishments.

Digital Modeling for Ground Vehicles

Within the evolving landscape of ground vehicle capabilities, a central focus emerges on the transformative potential of digital modeling. This discussion notably underscores the crucial role that digital modeling plays in understanding the complex nature of ground vehicle performance, especially in demanding environmental conditions. Furthermore, the synergy between non-destructive testing (NDT) and digital modeling is essential. NDT, through its non-invasive data acquisition, complements digital modeling capabilities. While NDT provides real-world insights, digital modeling excels in analyzing, simulating, and predicting performance under diverse conditions. This harmonious collaboration empowers engineers and decision-makers to make well-informed choices in design, maintenance, and optimization, thereby enhancing the reliability and safety of ground vehicles across a spectrum of operational scenarios.

Central to this discussion is the strategic goal of utilizing digital models for simulations that forecast outcomes like those seen in previous research, where researchers assessed model-based, decision-support frameworks (Malak et al., 2009; Tsutsui, Guariniello, et al., 2023; Tsutsui, Shi, et al., 2023). The overarching goal is to equip decision-makers with a proactive understanding of ground vehicle behavior under various environmental conditions, enabling them to anticipate and strategize for diverse vehicle use conditions. This forward-looking approach empowers the U.S. Army to make well-informed decisions that optimize ground vehicle configurations and operational strategies, thereby enhancing their efficiency and effectiveness in traversing the demanding terrains in harsh environments.

Venturing beyond traditional boundaries, this research discussion introduced thought-provoking inquiries into the untapped potential of digital models. Exploring scenarios that go beyond the norm opens pathways to adaptability and customization. By capitalizing on the flexibility offered by digital modeling, decision-makers unlock opportunities to tailor ground vehicles to meet the specific operational demands of challenging environments. This adaptable methodology ensures that ground vehicles remain finely tuned to navigate the distinct challenges presented by these harsh landscapes.

This ongoing conversation underscores the profound significance of digital modeling in unveiling ground vehicle capabilities. Through the strategic deployment of digital models for predictive insights and the exploration of innovative scenarios, the U.S. Army effectively positions itself at the forefront of harnessing technological advancements to address the complexities of operating vehicles in the most challenging environments, like those in the Arctic and beyond.

Ground Vehicle Requirements for the Arctic Environment

In May 2022, the Army announced its plan to establish a new Alaska-based division, the 11th Airborne Division (Congressional Research Service, 2023). This initiative involves activating new units and reconfiguring two existing Alaskan Infantry Brigade Combat Teams (IBCTs). As this new division takes shape and additional forces take their positions in Alaska, the dynamics of ground vehicle requirements, specifically concerning the JLTVs, could potentially undergo significant changes.

Engaging in conversations with Army personnel highlights a significant focus on the crucial task of adapting ground vehicles to excel in the challenging conditions of Arctic environments, where the vehicle operating temperature can plummet as low as -50 degrees Fahrenheit (Eversden, 2022; Zielinski & Maguire, 2022), while another source (Rozell, 2011) even suggests that temperature may drop to as low as -80 degrees Fahrenheit. Characterized by their extremely cold temperatures, these landscapes demand vehicles that meet functional requirements and demonstrate resilience in harsh climatic conditions. Therefore, examining ground vehicle requirements for the Arctic becomes a vital consideration, emphasizing the essential role of digital modeling in guiding design and decision-making processes.

At the core of these discussions lies Army Regulation (AR 70-38, 2020), as shown in Figure 5, Army Techniques Publication (ATP 3-90.97, 2016), DoD Comprehensive Selected Acquisition Report (SAR) on JLTV (DAMIR, 2019), and Special Report (Walsh et al., 1989). The reference to the AR document (AR 70-38, 2020) emphasizes the establishment of operational benchmarks based on diverse climate classifications. At the same time, the detailed conversations further emphasized the significant role of temperature-related considerations in guiding the formulation of design attributes and performance benchmarks for ground vehicles well-suited for Arctic terrains.

High Temperature

- Differential expansion of dissimilar materials
- Increased rate of chemical reactions
- Lower lubricant viscosity
- Electronic circuit instability
- Outgassing

Rain

- Moisture in parts
- Corrosion
- Attenuation of electromagnetic radiation
- Reduced off-road mobility

Icing and Snow

- Reduced visibility
- Attenuates electromagnetic signals

High Humidity

- Triggers Condensation
- Initiates fogging
- Oxidation/corrosion
- Increased chemical reaction
- Changes in material properties
- Degrades optical and infrared properties
- Modifies lubricants' behavior
- Changes elasticity/plasticity

Low Temperature

- Changes physical properties of materials
- Hardness and brittleness
- Differential contraction
- Increased viscosity
- Stiffening of shock mounts
- Condensation and freezing of water

High Elevation (low pressure)

- Liquids leak
- Lubrication capacity decreases
- Electrical breakdown
- Heat transfer is less efficient
- Liquids vaporize
- Less efficient combustion

Salt/Saltfog

- Acceleration of metallic corrosion
- Loss of mechanical and structural strength
- Surface deterioration
- Alteration of electric properties

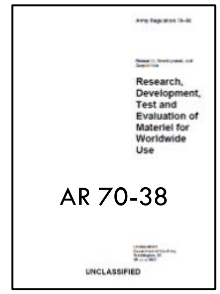

Figure 5. Effects of Different Environmental Conditions (AR 70-38, 2020)

These comprehensive guides establish essential criteria for effective ground vehicle operations and equipment affected by the distinctive challenges posed by the Arctic's harsh environments (Table 1). These documents' guidelines lay the foundation for formulating design principles and operational strategies, ensuring ground vehicles' adaptability and robustness to perform effectively in the harshest cold conditions.

Furthermore, the discussions with U.S. Army personnel revealed a key emphasis on the complex relationship between temperature, vehicle performance, materials, and components. This complex mix of factors shapes the detailed considerations behind crafting ground vehicles suited for Arctic missions. The significant impact of temperature (i.e., thermal loading) on various vehicle aspects underscores its importance as a critical factor influencing the fundamental characteristics of vehicles designed for Arctic use. This understanding calls for a comprehensive design approach that covers vehicle dynamics and thoughtfully incorporates the Arctic environment's distinct thermal dynamics.

Table 1. Equipment Affected by Arctic Environment (Walsh et al., 1989)

Assembly	Mechanical	Electrical	Fluid	Structural
Power source	-	Battery, cables, Fuse, Connector	Acid	Mount
Starter system	Switch, belt, bearings	Glow plugs, cables, fuses, relays, alternator	Lubricants	Mount
Fuel system	O-rings, filter, seals, fuel lines, bearings, valves	Fuel pressure sensor, solenoid valves, motor	Fuel	Fuel tank
Engine	Rings, bearings, gaskets, O-rings, springs, chain drive, seals, valve guides	Glow plugs	Sealants	Engine mounts
Lubrication system	Seals, o-rings, bearings, piping, filters, connectors	Pressure sensors, level sensors, temperature sensors	Lubricants	-
Exhaust	Fasteners	Exhaust gas pressure sensor	-	-
Controls	Switches, governor	Switches, meters, connectors, voltage regulator	-	-
Gearbox/clutch	Bearings, seals, spring, gasket, coupling	-	-	-
Generator	Bearings, seals, brushes, springs, coupling	Wiring, coil, stator, connectors, field detector	-	Mounts
Frame mount	Fasteners, bushings	Grounding strap	-	Frame anchors, mounts
Cooling system	Seals, bearings, hoses, fan, radiator	Wiring, temperature sensors, liquid level sensors	Coolant	Mounts

Given these recent developments, the Army's establishment of the 11th Airborne Division in Alaska will most likely introduce an additional aspect to the domain of ground vehicle requirements. With new division units, reconfigured IBCTs, and increased forces in the Arctic region, the evolving demands for JLTVs may experience significant adjustments. As the Army's strategic posture adapts to this changing context, integrating ground vehicle requirements with the evolving divisional structure remains critical, shaping the path toward optimized operational effectiveness and strategic agility.

Data-Driven Decision-Making for Ground Vehicle Selection and Preparation

The pursuit of data-driven decision-making takes center stage when selecting and readying ground vehicles, especially in unique environments like the Arctic. The objective is to leverage the insights from extensive data to inform and guide the streamlined process of choosing and preparing vehicles that meet operational requirements and exhibit resilience in extreme conditions.

A comprehensive array of data attributes facilitates informed decisions for U.S. Army personnel. Considerations span a broad spectrum, encompassing critical factors such as mobility, tire selection, powertrain specifications, oil/fuel selection, structural attributes, shock absorption capabilities, reliability metrics, gradeability performance, and other relevant attributes (AR 70-38, 2020). This diverse range of data collectively serves as the bedrock upon which experts meticulously craft robust and informed decisions, ensuring that the selected ground vehicles are fit for purpose and optimized for the specific challenges of Arctic environments.

A critical focus that emerged from the discussions with the U.S. Army personnel was the detailed understanding that different vehicle types and platforms require varying levels of data detail. Recognizing this diversity underscores the significance of tailoring data acquisition efforts to the specific requirements and complexities of each distinct vehicle type and platform. Furthermore, the spotlight turns to the essential role of accessing OEM data, an indispensable resource that serves as a cornerstone for effective decision-making. Accessing OEM data becomes a valuable asset, offering a reliable and authoritative foundation for data-driven choices.

Introducing a potential disruption, the change of the supplier for JLTVs from Oshkosh to AM General (Tadjdeh, 2022; Tricomo, 2023) raises concerns regarding access to OEM data. This shift could impact the availability of crucial data required for data-driven decision-making in ground vehicle selection and preparation. The transition between suppliers may introduce complexities in obtaining OEM data, potentially hindering the seamless and informed decision-making process that relies on comprehensive and accurate OEM data. Since the JLTV supplier is changing from Oshkosh to AM General (Magnuson, 2023), addressing the potential implications on data access and ownership becomes essential in maintaining the decision-making framework's robustness.

Exploring data ownership and access further, the conversation with the U.S. Army personnel unveiled a detailed examination of contrasting approaches: owning data versus accessing data. The discussion dived into the complexities of data rights, ownership, and their implications for informed decision-making. Challenges often stem from the complexities of data access and ownership agreements. The dialogue emphasizes the importance of balancing owning and accessing data, recognizing the vital roles in cultivating a comprehensive and knowledgeable approach to selecting and preparing ground vehicles.

In short, the discussion about requirement-driven decision-making for ground vehicle selection and preparation reflected a solid commitment to using the requirements specified in the reference document (AR 70-38, 2020) as a guide. These discussions encompassed a wide range of aspects, carefully chosen to ensure optimal performance and adaptability of ground vehicles in the challenging Arctic environment. The discussion also emphasized the importance of accessing OEM data while addressing data ownership and access challenges, resulting in a comprehensive framework that empowers decision-makers to confidently tackle the challenges of vehicle selection and preparation with precision.

Analyzing the Potential of Integrated Digital Transformation

Conversations with U.S. Army personnel offered valuable insights into ground vehicle modeling and preparation within the DoD scope. These discussions, centered on the challenges and possibilities associated with ground vehicles in extreme environments, unveil compelling opportunities for leveraging mission-aware integrated digital transformation to maximize the operational advantage of the DoD.

Central to these conversations is the significant role of digital modeling, which emerges as a powerful tool for enhancing the decision-making process. By creating accurate digital replicas (i.e., digital twins) of ground vehicles, the DoD gains the capacity to simulate and evaluate vehicle performance under various conditions. In scenarios like the Arctic, known for its extreme cold, this simulation-driven approach proves invaluable for well-informed decision-making about vehicle selection, operation, and strategic adaptations.

Moreover, it is worth noting that these digital twins' accuracy hinges on maintaining a comprehensive per-vehicle part number database throughout the sustainment process. Within this context, the comprehensive per-vehicle part number database should include information about the specific software versions used in each vehicle. In the context of digital twins and ground vehicles, software versions can be critical because they may impact how the vehicle operates, its capabilities, and its compatibility with other systems. Including information about the software versions in the database ensures that the digital twin accurately represents the vehicle's configuration and capabilities, which is essential for effective simulation and decision-making. Maintaining a real-time data stream of the vehicle's operating environment is crucial. While much of the discussion centers around comprehending the thermal environment, the scope extends beyond that. Marine/saltwater exposure and humidity can also accelerate material degradation. Therefore, the effectiveness of the per-vehicle twin relies on its ability to comprehensively understand the actual operating environment, ensuring a more accurate basis for decision-making.

Further emphasizing this potential is the ongoing discussion surrounding ground vehicle requirements in extreme settings. Here, the necessity of operational adaptability comes to the forefront. The digital twins equip the DoD to analyze and tailor vehicles for non-standard conditions rapidly. By simulating the effects of extreme temperatures on vehicle components and materials, the DoD can proactively address potential performance constraints and seamlessly optimize vehicle designs to align with the unique demands of specific environments. However, the path to realizing these benefits is not without its challenges. The dialogue highlights complexities related to data accessibility and ownership, particularly concerning acquiring digital data from OEMs. In order to navigate this terrain, mission-aware digital integration emerges as a strategic avenue for establishing collaborative partnerships and securing timely access to crucial data. The DoD can construct a comprehensive overview of ground vehicle capabilities and limitations by gathering data from various sources.

Beyond its role in decision-making, integrating digital models and data across varied ground vehicle platforms holds promise for streamlining logistics and maintenance processes. Leveraging these digital models allows the DoD to anticipate maintenance needs, optimize supply chains, and devise strategies for vehicle repairs or component replacements. This proactive approach minimizes operational downtime while maximizing operational readiness, regardless of the vehicles' operation locations. Furthermore, the discussion highlights how digital models can undergo customization for different mission profiles and scenarios. With the ongoing discussion of mission-aware integrated digital transformation, the DoD can create specific simulations that accurately mirror various operational scenarios' unique challenges and specific needs. This tailored simulation capability enhances the accuracy and relevance of decision-making processes.

Collecting these insights points to the digital implementation effort to boost the DoD's operational advantage. By utilizing digital modeling, simulations, and data-driven decision-making, the DoD can skillfully adapt ground vehicles for various environments, improve mission readiness, and maximize resources. Tackling data access and ownership complexities is crucial, as it holds the key to unlocking the full range of possibilities in integrated digital transformation. As the DoD tackles these challenges, the benefits become apparent through enhanced operational excellence.

Test, Evaluation, and Data Throughout the Acquisition Process

The DoD employs a structured five-step process for Testing and Evaluation (T&E), as depicted in Figure 6 (Johnson et al., 2005). In Step 1, stakeholders identify T&E information, focusing on their needs and evaluating systems across various stages, from concepts to production systems. In Step 2, stakeholders scrutinize evaluation objectives during the pre-test analysis phase, determine data types, and design test scenarios using validated models and simulations. In Step 3, tests are planned and executed during test activity and data management, focusing on gathering accurate and complete data while assessing historical data availability. In Step 4, post-test synthesis and evaluation involve comparing measured outcomes with expected ones, identifying deviations, and utilizing Modeling and Simulation (M&S) techniques to analyze data meaningfully. Finally, in Step 5, decision-makers use the synthesized T&E information and other factors to determine the course of action, potentially leading to further iterations of the DoD T&E process to refine system capabilities.

It is worth noting that the structured T&E process outlined by the DoD (Johnson et al., 2005) will need to continually transform itself for better verification and validation practices when considering the fact that we move toward a more agile acquisition process (DeLaurentis et al., 2022). In order to deliver products and capabilities faster to meet rapidly evolving defense needs through a more agile acquisition process, we will need to integrate digital twins and move the five steps faster and more efficiently.

Regarding testing and evaluation standards for military equipment's environmental resilience, NATO AECTP 300 (2006), *Climatic Environmental Tests*, establish a comprehensive frameworkClick or tap here to enter text.. These standards, devised by NATO, aim to assess the endurance of military gear and equipment across a spectrum of weather conditions. The evaluations ensure the equipment can withstand environmental stresses throughout its operational life. The NATO testing regimen encompasses various specific tests, as shown in Table 2.

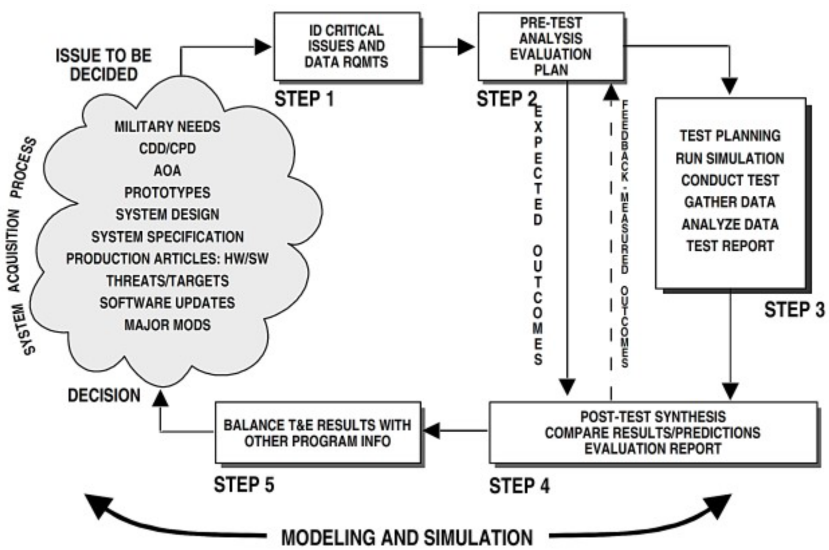

Figure 6. Testing and Evaluation Process
(Johnson et al., 2005)

Table 2. Climate Environmental Tests (NATO AECTP 300, 2006)

Method	Title
301	General Requirements
302	High Temperature
303	Low Temperature
304	Thermal Shock
305	Solar Radiation
306	Humid Heat
307	Immersion
308	Mould Growth
309	Salt Fog
310	Rain and Water Tightness

Method	Title
311	Icing
312	Low Pressure
313	Sand and Dust
314	Contamination by Fluids
315	Freeze and Thaw
316	Explosive Atmosphere
317	Temperature, Humidity and Altitude
318	Vibration, Temperature, Humidity, and Altitude
319	Acidic Atmosphere lifespan

Exploring further into the discussion with the U.S. Army personnel revealed a practical approach to utilizing specific documents in the informed decision-making process. The authors learned that the following key steps are crucial guides in this process: the Initial Capability Document (ICD), Capability Design Document (CDD), and Capability Production Document (CPD). Figure 7 depicts the steps involving the ICD, CDD, and CPD. The ICD serves to identify essential mission capabilities, assess gaps and their priorities, recognize operational risks, and highlight the imperative to address these gaps. Meanwhile, the CDD plays a vital role in confirming Key Performance Parameters (KPP); describing their thresholds and goals; evaluating costs, schedule, and technology risks; and assessing system affordability vis-à-vis the delivered operational capability. KPP types for JLTV include mobility, transportability, survival, payload, sustainment, net-ready, and system training (DAMIR, 2019). Lastly, the CPD ensures that the delivered system aligns with the initially defined needs outlined in the ICD. This comprehensive approach underscores the importance of meticulous planning and assessment in military operations.

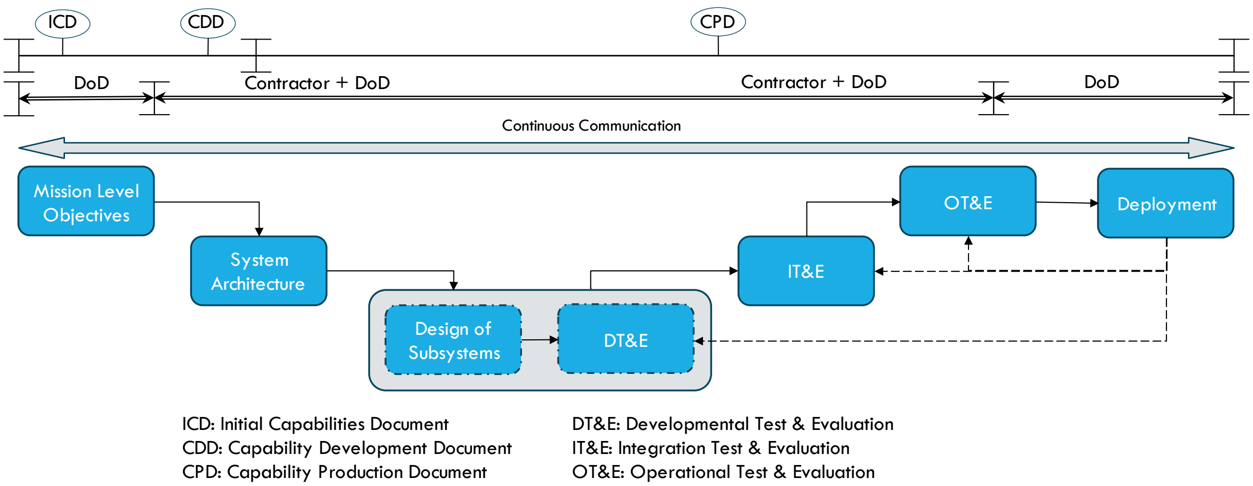

Figure 7. Data Generated Throughout the Acquisition Process

Enhancing Data Utilization and Institutional Memory With an Intelligent Front-End (IFE)

Building upon insights gained from conversations with DoD stakeholders and emphasizing the crucial role of efficient data utilization, the authors aim to transition the conversation from simply understanding the current landscape to presenting a comprehensive framework that elevates both data utilization and institutional retention. Introducing the Intelligent Front-End (IFE) framework, this section dives into optimizing data management, integration, and utilization. By developing a workforce for the digital enterprise (Hartman et al., 2019), empowering decision-makers, and reinforcing the DoD's institutional memory, the IFE framework aligns seamlessly with our ongoing mission of achieving effective digital transformation.

Efficient use of data cannot be just "nice to have" in domains like military operations, equipment maintenance, and decision-making. It is a must. When people interact with data, they unintentionally send signals about what matters. However, making the most of these signals requires an innovative approach to turn them into concrete improvements. This is where the IFE comes into play. As a bridge between existing systems and modern data needs, the IFE decodes these signals and transforms them into practical enhancements, blending human insights with technological advancements.

The innovative approach behind the IFE dives into the domain of user signals. IFE elevates data delivery, making it precise and exceptionally user-friendly. Thus, users can use this system as a reliable data partner, thereby helping users meet the demand for accurate, adaptable, and user-centric data utilization. With the IFE constantly learning, improving, and fine-tuning responses, it is like having a knowledgeable data ally. This carries significant implications in various contexts, from informed decision-making to streamlined operations. All these pieces come together, and the IFE becomes a transformative force across the spectrum. In the following section, the description will dive into the interactions among users, the existing/legacy systems, and the IFE within the context of three distinct phases (Phases 1–3).

In Phase 1 (Figure 8), "Learning," the IFE operates discreetly in the background as an intermediary between users and the currently used/legacy systems. The system transmits user queries (Q) to the currently used systems and promptly relays the resulting responses (R) back to the users. During this phase, the IFE takes on the role of an attentive observer, closely studying the interactions between users and the currently used/legacy systems. This process of observation and learning helps the IFE gain insights into user preferences, patterns, and the effectiveness of responses. Additionally, users have the option to provide quick feedback (i.e., User rating of R) by giving a simple one-click rating to indicate how useful they found the provided response.

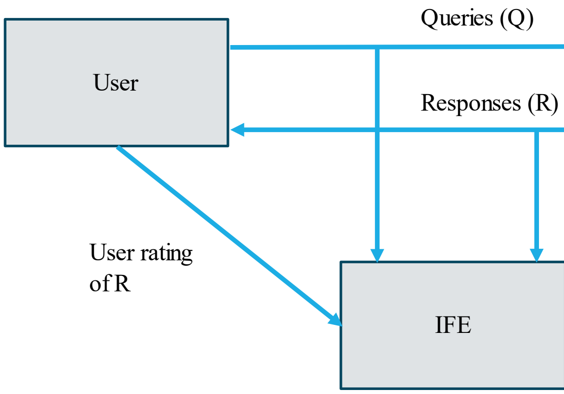

Figure 8. Phase 1: Learning (IFE is Passive)

In Phase 2 (Figure 9), "Dual Deployment," users are given a dual-choice option. They can either directly engage with the familiar legacy systems as they have done in the past (Figure 8), or they can opt for an alternative route by using the IFE. This is similar to taking the traditional road or exploring a new, more optimized path. During this phase, the IFE becomes more actively involved. The IFE steps in to optimize the communication process by adjusting both the user queries (Q') and the responses received (R'). This proactive approach ensures that the delivered information is finely tuned to meet the specific needs and expectations of the users. This dual deployment lasts until the new IFE improves over the old IFE (i.e., User rates R vs. R").

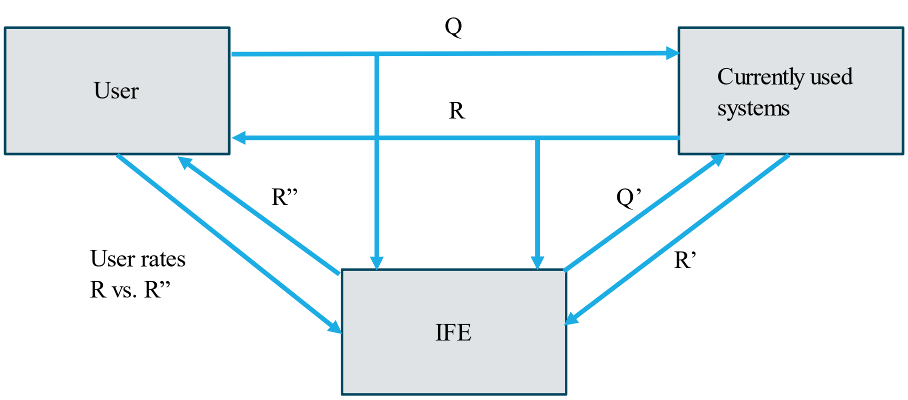

Figure 9. Phase 2: Dual Deployment (IFE is Active, but It Is Not Fully in Charge)

In Phase 3 (Figure 10), "Fully Deployed IFE," the IFE takes a central position, directly aligning itself between the user and the currently used/legacy system, thereby eliminating the need for dual deployment. All information and interactions flow exclusively through the new IFE, which serves as the primary conduit for user queries, responses, and data communication. This streamlined configuration ensures a unified and optimized user experience, where the IFE seamlessly facilitates data exchange while intelligently enhancing the interaction process.

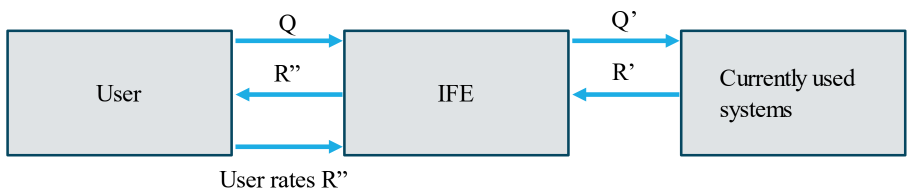

Figure 10. Fully Deployed IFE

Integrating the innovative approach using the IFE enhances data utilization and contributes to establishing and preserving institutional memory through digital technology. The IFE's perceptive understanding of data utilization patterns and user interactions plays a central role in accumulating valuable organizational insights. As users engage with data, the IFE captures these interactions, gradually constructing a digital repository of institutional knowledge. This synergistic relationship between refined data utilization and institutional memory enhances decision-making processes and facilitates the seamless transfer of organizational knowledge and expertise. This proposed approach ensures operational continuity and adaptive responses to dynamic challenges. Embracing the innovative approach of using the IFE highlights the potential to elevate data utilization, improve operational efficiency, and strengthen institutional memory's core basis/foundation, collectively shaping a transformative landscape for data-driven activities.

Conclusions

The conversations with DoD stakeholders have highlighted critical aspects of digital modeling, ground vehicle preparation, and data-driven decision-making within the U.S. Army. These discussions have revealed the potential benefits and challenges associated with leveraging digital technology to enhance the DoD's operational advantage. One key takeaway is recognizing the transformative potential of digital modeling in understanding and optimizing ground vehicle performance, particularly in extreme environments like the Arctic. The creation of accurate digital twins provides a powerful tool for simulating and evaluating vehicle behavior under diverse conditions, facilitating well-informed decision-making in vehicle selection, operation, and adaptation.

However, realizing these benefits entails navigating complexities. We must address challenges related to data accessibility, ownership, and the transition between vehicle suppliers. In order to navigate these challenges, a mission-aware integrated digital transformation approach is crucial. This approach involves collaborative partnerships, data integration, and tailored simulations to enhance decision-making accuracy and operational readiness. Furthermore, the discussions have highlighted the importance of maintaining comprehensive per-vehicle part number databases and real-time data streams to ensure the accuracy of digital twins. In order to support effective decision-making, these digital representations must encompass the vehicle's physical attributes, software versions, and the actual operating environment.

In addition to decision-making, integrating digital models and data holds promise for streamlining logistics, maintenance processes, and supply chain optimization. This proactive approach minimizes operational downtime and maximizes readiness. The DoD's journey toward digital transformation presents a wealth of opportunities to enhance operational excellence. By embracing digital modeling, simulations, and data-driven decision-making, the DoD can adapt ground vehicles for diverse environments, improve readiness, and maximize resources.

In our future plan, we aim to create a versatile decision/reasoning tool framework tailored to various cases, providing high-level guidance to sponsors based on crucial decision-making factors. This framework will allow us to prioritize modeling efforts to address specific decision needs. Additionally, when collaborating with a DoD unit, we intend to move toward obtaining clearance-required information and gaining insights into their decision-making processes. To this end, the research team would like to investigate the possibility of formalizing a DD 254 to specify the classification requirements for contracts with relevant entities to ensure access to essential files (e.g., ICD, CDD, and CPD) for future research. Finally, through these future initiatives, our goals are to refine our approach continuously, leveraging digital modeling and data-driven decision-making to meet evolving sponsor requirements, thereby assisting the DoD in enhancing its operational advantage.

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