DIGITAL TRANSFORMATION IN JOINT WAR FIGHTING – A 'DIGITAL TWIN' USE CASE

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Abstract

Integration and joint war fighting in today's landscape are aided by niche technology to maintain strategic edge and operational effectiveness. Digital Twin technology in recent times has emerged as a transformative paradigm in military applications. This paper comprehensively reviews the ongoing studies around the world in digital twin, presents various case studies and result of the studies. The paper touches upon definitions of digital twins, clears few myths surrounding the concept, presents strategic and tactical implications and also lists the challenges in adaptation of this technology in military application. The paper concludes by outlining future perspectives on the continued development and integration of digital twin technology in joint war fighting, emphasizing the need for adaptive strategies to harness its full potential while addressing associated challenges.

Introduction

We live in the 'digital age'. Defence technology is inherently complex. The 'digital age' is making things across the world, including defence technology, more challenging to deal with and cope with. The digital age means "the present time, in which many things are done by computer and large amounts of information are available because of computer technology".[1] While extended concepts like Industry 4.0, the Internet of Things, big data and Artificial Intelligence are already tilting the dynamics of most processes, the academic study surrounding the management, adaptation and regulation of these niche technologies are gaining prominence under the umbrella of Digital Transformation. The primary aim of digital transformation is to solve challenges thereby increase efficiency and effectiveness. Few works state that companies have to develop and implement digital transformation strategies else will have perish.[2] The improvements in computational power, better compiler languages and evolving underlining technology are significant attributes of this revolution. Adapting technology to better the efficacy of offensive and defensive warfighting needs to reap the benefits of this evolution. The 'digital twin' is one such use case for all-round capability enhancement.

Understanding Digital Twin (DT) is essential as it is not only emerging and evolving but is also surrounded by many myths. The origin of the Digital Twin is attributed to Michael Grieves and John Vickers of NASA; Grieves presented the concept in a lecture on product life-cycle management in 2003.[3] The National Aeronautical Space Administration (NASA) released a paper in 2012 titled "The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles'' setting a key milestone for defining Digital Twins.

Defining Digital Twin

As new the field of digital twins is, so is its definition. Various studies have suggested various definitions of digital twins. NASA stated in 2013 that ''A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin."[4] Also, Madani, in 2019, stated, "Digital Twin is a virtual instance of a physical system (twin) that is continually updated with the latter's performance, maintenance, and health status data throughout the physical system's life cycle". Though various definitions have evolved surrounding digital twin, a significant leap to fame in digital twin technology was by Gartner, one of the world's leading research organisations, published the 'Hype Cycle for Emerging Technology' studies and termed digital twin technology the 'innovation trigger technology' that triggers other technologies. Gartner also proposed that this technology would change other technology within 5-10 years, as shown in Fig. 1.

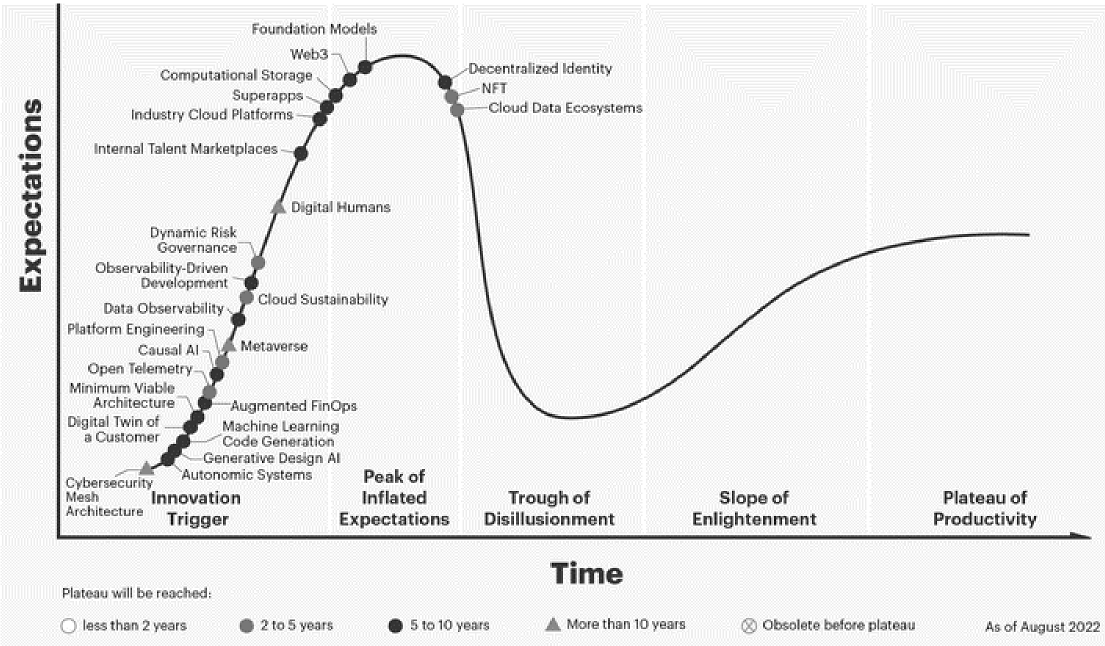

Figure 1: Garther Hype Cycle for Emerging Technology
(Source: www.gartner.com, 2022)

Digital twins bridge the gap between the physical and digital worlds by providing an interface that links past data and present processes. They also can make predictions for the future through the culmination of induced intelligence and actionable data. Twin is created by collecting live data from sensors embedded in physical systems. Specific test points whose output cannot be predicted on physical systems can be performed on digital twins repeatedly until satisfactory results are achieved. Based on these results, the behaviour of physical entities can be predicted without actually validating that on the physical systems. This approach enables costly, complex and challenging estimation of physical systems easy and foolproof. By making fine tweaks on the digital twins, the effect on the physical system can be analysed to test and run complex military scenarios, be it operations or maintenance domain. This also provides a validation mechanism for modifying, optimising, and implementing changes to existing systems.

With the increased complexity of technology, data-driven systems, better sensors, artificial intelligence and fast computing power, the 'digital twin' can prove to be a force multiplier for military warfighting ability. Its acceptance in services, development life cycle and field adaptation, is not farfetched but a reality. The digital twin creation process is reflected in Fig. 2.

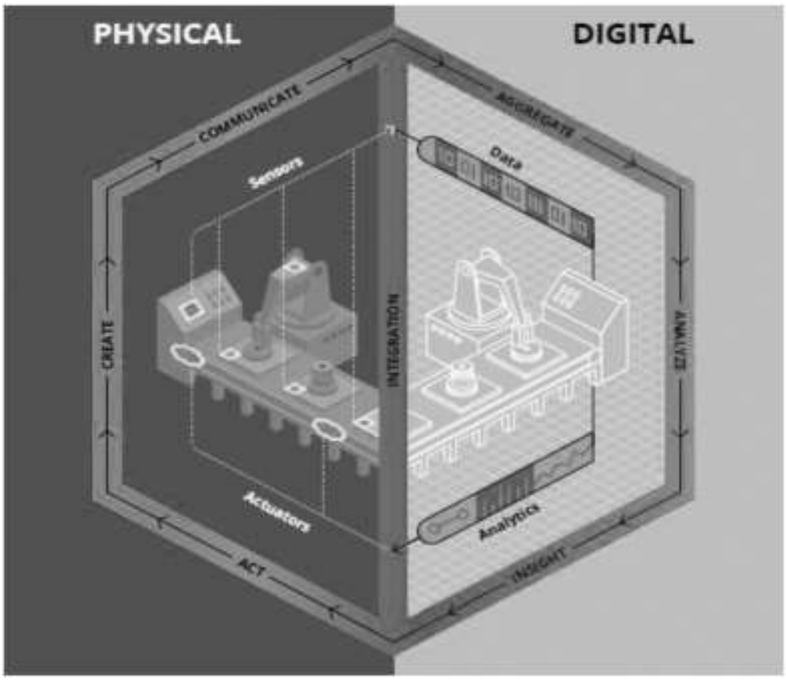

Figure 2: Digital Twin creation process[5]
(Source: Parrott, Aaron, and Lane Warshaw. 2017)

Breaking Myths of Digital Twins

Before dwelling on the applications of digital twins in joint warfighting and their adaptation into service, it is appropriate to break some myths surrounding digital twins and draw fine differentiations between a few already existing terminologies. Most readers by now could have dwelled into the questions as to how 'digital twin' is different from 'simulators' or 'emulators'. These systems already exist in military applications, especially in the training domain. Refer to the Table 1, below that summarises the key difference between them. Apart from DT being real-time, the critical differentiator is speed, use, and ability to integrate sensors/ IoT devices and big data. Also, researchers argue that DT is more suitable for operational training than others as it can provide a vast gambit of possibilities that can otherwise not be tested or seen on physical systems.

Parameter	Digital Twin	Simulator	Emulator
Definition	Digital replica of a physical entity, reflecting real-time data	System that mimics the behavior of a system in a controlled environment	System that replicates another computer system's hardware and software environment
Purpose	Monitoring, analysis, and optimization of physical entities	Training, testing, and research	Running applications on different hardware or maintaining legacy systems
Real-Time Data Integration	Yes	No	No
Lifecycle Management	Yes, covers entire lifecycle	No	No
Behavioral Mimicry	Yes, real-time and predictive behavior	Yes, mimics behavior under various scenarios	No, focuses on replicating environment rather than behavior
Example Use Cases	Predictive maintenance in manufacturing, smart cities	Flight simulators, medical training simulators	Video game emulators, software testing for different OS
Hardware Replication	No	No	Yes
Software Replication	Partial, usually involves specific applications	No	Yes

Table 1 Comparison between DT, Simulator and Emulator ***(Authors Compilation)***

A few terms exist Within the digital domain, such as digital shadow and digital model. The critical difference between them is the ability to interact with physical and digital objects and their modus-operandi. It is important to note that any change in the physical entity must be incorporated into a digital object. However, in terms of digital twins, this happens in an automated and real-time manner. These systems are represented in Fig. 3[6]

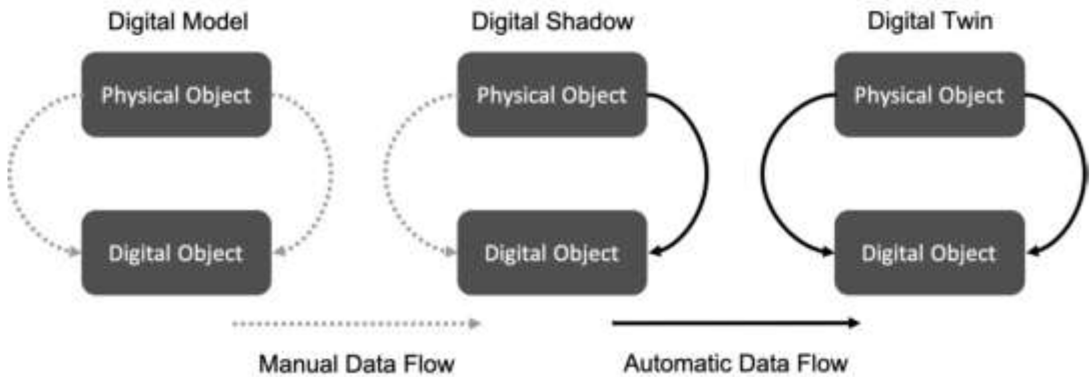

Figure 3: Fuller Model of DT

(Source: Fuller, Aidan, Zhong Fan, Charles Day, and Chris Barlow. 2020)

Further, Grieves, in 2017, proposed a few more concepts in the context of the digital twin's product life cycle, which are listed in **Table 2**[7]

Concept	Description
Digital Twin	A complete virtual description of a physical product that is accurate to both micro and macro level.
Digital Twin Prototype	The virtual description of a prototype product, containing all the information required to create the physical twin.
Digital Twin Instance	A specific instance of a physical product that remains linked to an individual product throughout that products life.
Digital Twin Aggregate	The combination of all the Digital Twin Instance.
Digital Twin Environment	A multiple domain physics application space for operating on Digital twins. These operations include performance prediction, and information interrogation.

Table 2 DT Concept and its definition ***(Source: Grieves, M., Vickers, J., 2017)***

DT in Military Applications

The applications of digital twins are not limited to product life cycle in general or R&D in particular. In defence application parallels, its applications are not limited to maintenance or sustenance only. Characteristics like adaptability, implementation efficiency, interoperability, fidelity and accuracy of results make this technology niche and most suitable for joint warfighting mechanisms, which are plural and complex. The individuality of each service equipment, training, and bias can be overcome using a robust digital twin. The subsequent paragraphs highlight the known and established applications of DT in the context of military applications.

Operations and Mission Planning

One of the significant fields in which DT is contributing immensely is aviation. Aviation, by nature, is expensive and multi-dimensional. Further, aircraft training, testing and maintenance are very costly and dynamic. Air operations are limited by safety, weather and enemy tactics, adapted through training. The OEM manuals and procedures usually guide the aspects like limitations of operations and maintenance. Thus, the variables can be many, but academic or design constraints loosely bind them. The resources available to stretch and test these operational parameters are limited or cannot be simulated. In these scenarios, DT comes in handy. DT, aided by sensors onboard, provides real-time dynamic solutions to pilots on aspects like fuel consumption, route predictions, airframe stress, and profile or missile launch validations. Further, based on historical data, future actions can be predicted by aircraft behaviour in battle or routine flight. Aspects like probable component failure, fatigue, and an alerting system can add value and increase situational awareness within the aircraft.

Adaptive Vehicle Manufacturing (AVM) is a US Defense Advanced Research Project Agency (DARPA) that started in 2010 and aims to shorten the R&D cycle and cost of weapon systems. DT is expected to aid these systems in all warfighting domains, including cyberspace, simulation, experiment, processing, testing and production.[8] The announcement of the US F-35 fighter jet clone to predict component failure, future performance, life expectancy and failure rates. US Army is conceptualizing the use of DT in collaboration with Wichita State

University to increase efficiency and training on the Black Hawk helicopter fleet. General Electric has started a Technology Acceleration Centre to bring operators, engineers, and manufacturers together to step up the adaptation of DT. With the ability to monitor data from sensors onboard and validate the parameters on its digital twin, it can define how complex wars are fought. In a model-based system engineering study, DT was used on a UAV to validate the route selection process through mission objective achievement. The results of the study were auspicious and path-breaking. In the Fig. 4 (a and b), the UAV is on a last-mile delivery mission to supply a friendly target, as indicated in blue. Based on its history, the system has acquired knowledge of adversary presence through its onboard sensors (EW data, Geo-location data, range of adversary weapon system, etc.). These data are now tried on the digital twin of the UAV. Based upon mission objectives of time on target, payload, speed, range and endurance, route optimization is to be undertaken by the digital twin well within time. The DT in this study suggested three routes, A, B and C and suggested taking Route B to keep UAVs safe from adversaries. As per the simulation setting and risk assessment, this is the least vulnerable route[9].

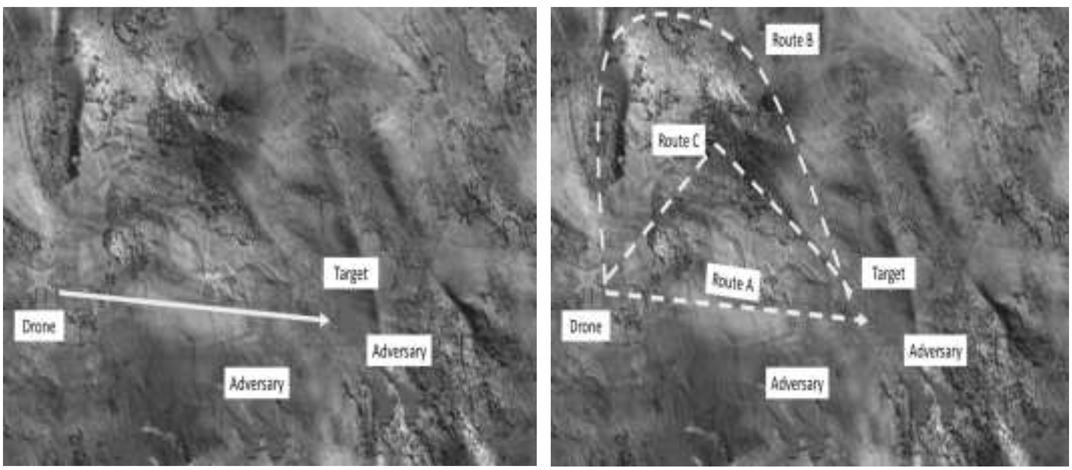

Figure 4 (a) Mission Plan[10] (b) System suggested route[11]
(Source: Lee, Eugene Boon Kien, Douglas L. Van Bossuyt, and Jason F. Bickford, 2021)

Joint warfighting is not just about terminal weapons. Command and control centre plays a critical role in field commanders' decision-making. DT has also paved the way in this complex

C4ISR domain to run and validate complex decision-making matrix and provide better and more robust strike solutions. In the 1991 Golf War, the US Army provided a battlefield environment simulation system[12] for its M1A1 tanks, catering to terrain, roads, buildings, rivers and vegetation to carry out effective strike planning. Simulating the same using DT for accurate battle simulation or training has created a scientific, high-precision and credible environment. Massive data must be captured in real-time scenarios to make such complex systems work. One suggested and workable solution is using data-acquiring sensors and IoT devices during routine training and actual scenarios. Based on the data gathered, DT can simulate a mature decision-making environment. A representation is indicated in Fig. 5.[13] This calls for greater joint training for data generation and integration of systems and logistics to improve accuracy and timelines. At strategic level, the DT can significantly enhance command and control capability through better situational awareness, strategic planning, fusion of various data source like satellites', ground assets and drones. In USA it is reported that a joint all domain command and control (JADC2) is aimed at being constituted for joint planning cross domains of land, sea, air, space and cyber.

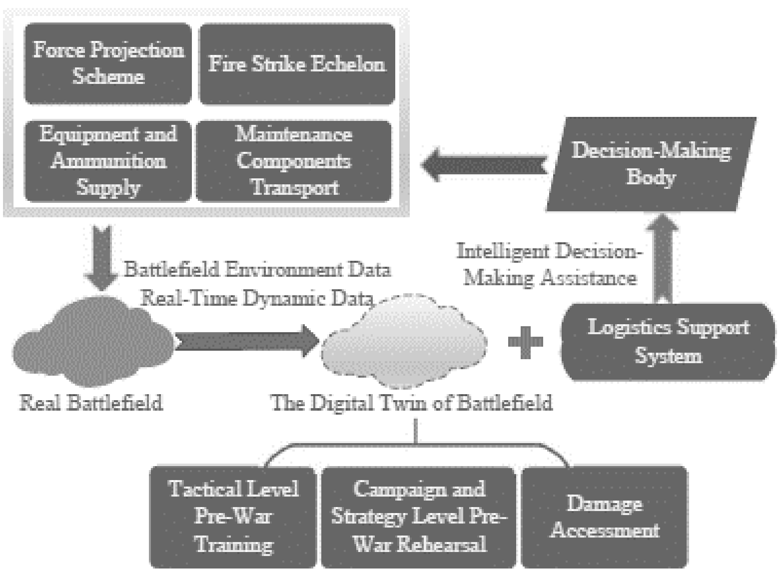

Figure 5: DT representation of battle Mission System[13]

(Source: Li, Suliang, Qiliang Yang, Jianchun Xing, and Shenggui Yuan, 2020)

Military Engineering and Equipment

USAF and NASA have proposed the Airframe Digital Twin (ADT) framework, which aims to replace traditional deterministic individual aircraft tracking systems with more sound, probabilistic, risk-based and accurate systems. This system has also been validated by the National Research Council of Canada (NRC). NRC defines ADT as "a digital representation of as-built/as-maintained airframe system, i.e. an integrated multiphysics, multiscale, probabilistic simulation of an as-built airframe system that uses the best available models, sensor information, and input data, to mirror and predict activities/performance over the life of the corresponding individual airframe system." The NRC's vision of ADT is represented in Fig. 6.[14] It consists of five building blocks. They are represented by numbers 1 to 5, where 1 is the Common fleet database, 2 is individual digital twin, 3 is quantitative risk assessment, 4 is individual physical aircraft, and fifth is Bayesian Inference[14].

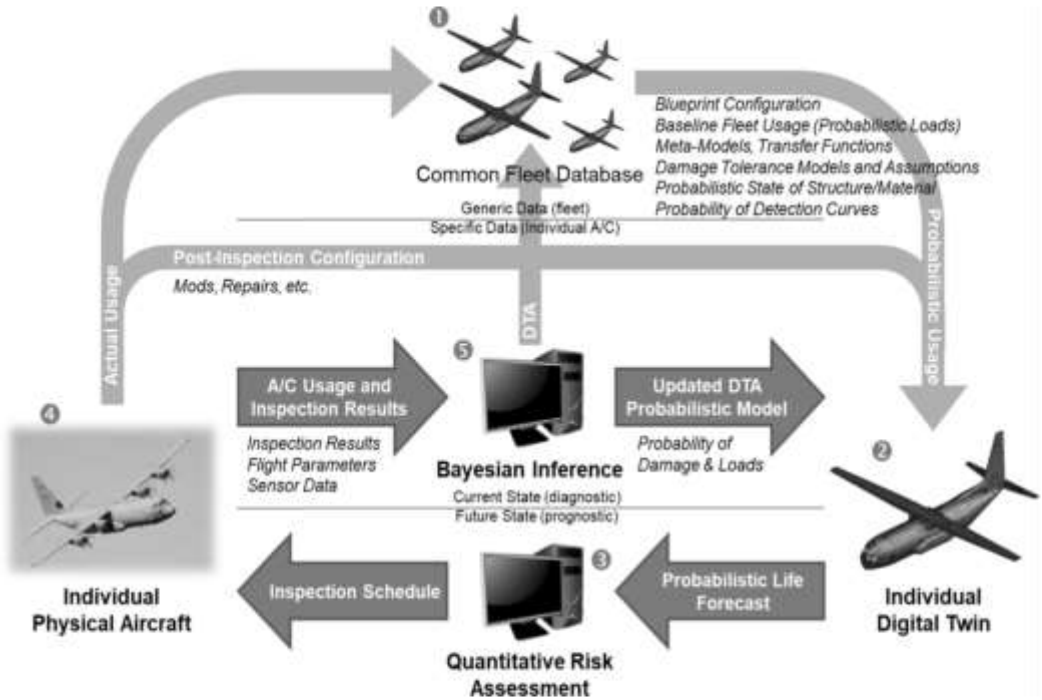

Figure 6: NRC vision of ADT

(Source: Liao, Min, Guillaume Renaud, and Yan Bombardier, 2020)

The study by NRC concluded that the Royal Canadian Air Force (RCAF) could adopt the ADT framework for better component life monitoring, extension, durability/ damage, and risk assessment management programs. The study also suggests utilizing high-fidelity DT for the life cycle management of individual and common fleets.

Four significant aspects of military equipment, are design, test, production and maintenance, as indicated in Fig. 7.[15] These four aspects contribute towards the total life cycle of the equipment.

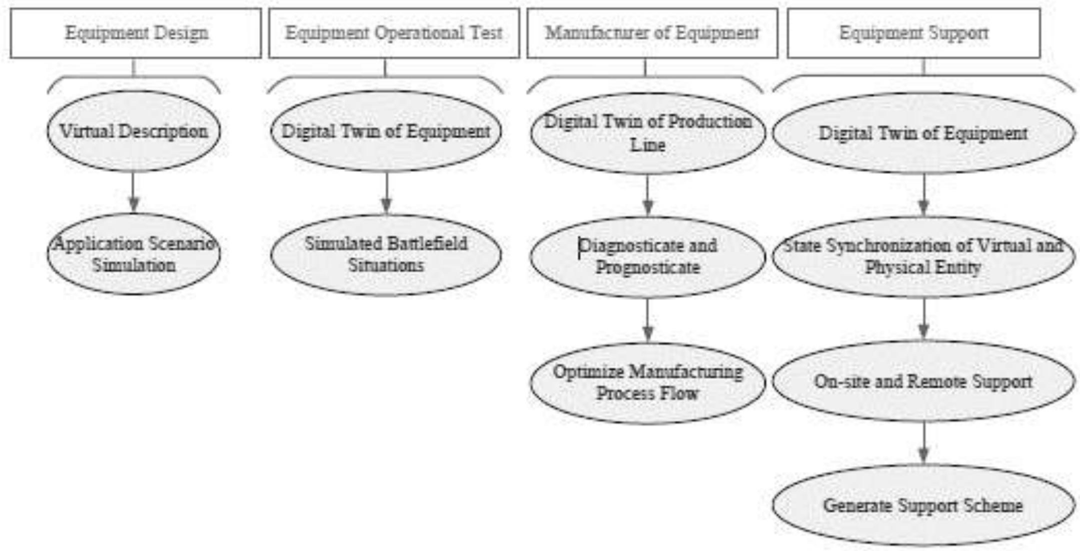

Figure 7: DT in four significant aspects of military equipment

(Source: Liao, Min, Guillaume Renaud, and Yan Bombardier. 2020)

Maintenance costs are attributed to about 30-40% of the profits incurred by the companies. During the said period of rectification or MRO, the operations are affected. DT poses a unique opportunity to use its clone with a large amount of sensor data for easy repair assessment, reducing downtime significantly. The data and DT validation outcome can bring aspects and clauses that can form part of service-level agreements and contracts. This will lead to data-driven maintenance planning.

DT in Space Operations

Space and satellite-based warfare is professed and is a time-tested operational philosophy. The application of DT in space, especially in satellite management, anti-satellite attacks, EW mapping and GPS positioning. Any downtime or mismanagement of satellites can lead to prolonged unavailability of vital data. A DT-based fault diagnostics and health monitoring (FD-HM) has dramatically increased interoperability and expressiveness[16]. Data-driven algorithms are employed to implement fault prediction, diagnostics and maintenance. This will ensure constant cover of satellites over battle areas and provide safety to satellites.

DT Applications in the EW Environment

The electromagnetic clout and density have increased with the increase in digital footprint in war zones. With modern concepts of active decoys, low probability of intercept and better material engineering, all three organs of the EW tree face challenges. With the application of DT in this domain, the ever-challenging aspects of threat determination, library updating, offensive action, and evasive solutions can be tactically validated. Most EW systems used in military applications have large amounts of data. These data can be effectively used to digitally recreate the electromagnetic scenario of the natural world. Further, the ranges of adversary emitters can be parametrically tweaked and probabilistically located. With onboard sensors and ground-based clones, the EW cycle can further be tightened and provide immense training value to operators. In a joint warfare scenario, the determination of friend and foe becomes more complex. DT can discern and provide actionable solutions with robust algorithms and computational power.

Other Applications

Military operations are complex and include a wide range of assets, from offensive to defensive to support services. Technology can be a strong catalyst for onboarding individual systems in a joint warfare scenario. Various publications and scholarly works are carried out in various fields, which can play a critical role in joint military applications. Some of the applications are listed in Table 3 :-

Domain	Application	Description	Reference
Manufacturing	Predictive Maintenance	Monitor, predict and schedule maintenance based upon health of system	Tao, F., et al. (2019). "Digital Twin in Industry: State-of-the-Art." *IEEE Transactions on Industrial Informatics*, 15(4), 2405-2415
Healthcare	Digital Solider Clone	Monitor soilder vitals and health when in battle field through sensors	Lloyd et al. 2023. "Maintaining Soldier Musculoskeletal Health Using Personalised Digital Humans, Wearables And/or Computer Vision." *Journal of Science and Medicine in Sport* 26 (June): S30–39.
Battle Area Vehicle/ tank movement optimization	Vehicle performance and route optimization	Simulates and analyzes vehicle performance parameters and path	Boschert, S., & Rosen, R. (2016). "Digital Twin—The Simulation Aspect." *Mechatronic Futures*.
Logistics Management	Supply chain optimization	Monitor stock, network and demand scenarios and cater to needs dynamically	Barricelli, B. R., et al. (2019). "Human Digital Twin for Fitness Management." *IEEE Access*, 7, 134374-134388
Communication	Network and optical communicatio n management	Simulate and monitor latency, network and performance for better communication	Macchi, M., et al. (2020). "A Digital Twin Framework for Telecommunications Network Management." *Procedia CIRP*, 93, 1072-1077

Table 3: Indication of military application of DT *(Authors Compilation)*

Tactical and Strategic Advantages

Few case studies already emerging in military applications suggest that DT is here to stay and may have profound implications on joint warfare operations. The future scope can be tactical, capability building and strategic. As twins can validate data and situations that humanly cannot be possible, this will prove to be a significant testing, tactics development and 'proof of concept' validation platform. This overarching ability will help us continually adapt and innovate tactics against adversaries. The ability to accurately replicate physical entities will fundamentally change our capability. Tactical aspects of routine operations, mission planning and maintenance-logistic optimization will significantly enhance controlled parameters under field commanders.

With the evolution of computational power, better and stronger algorithms, speed, and capabilities requiring high precision and accuracy can be achieved in real-time. Certain aspects, like training on more realistic data acquired by onboard sensors, immersive training, and the ability to stretch beyond limits within a controlled environment, can be among the most prominent capabilities that DT can provide.

Strategically, most of the systems in service used for war fighting today are digital. The extensive data available to us about our systems can further be used to enhance strategic interests. Many applications developed in civilian parallels can also aid military applications. Fields like terrain mapping, communications, 3D modelling, city planning, vehicle mobility, and pharmacy have already been rolled out and are in use. Once the model matures, there will be a meteoritic rise in DT adaptation in complex battle planning, tactics and joint war fighting domains.

Challenges of DT Adaptation

The significant challenges surrounding the adaptation of digital twins in joint military operations are more infrastructural. To begin, the success of DT depends on the availability of a large dataset for scenario creation. If the system intended for DT is not digital or has provision to capture data through the installation of sensors, then implementation of DT becomes more complex. Thus, the availability of compatible and sustainable sensors is a big challenge for an extensive military application. Further, to make the system real-time and fast, the need for a reliable, secure and fast network is a challenge. The data flow is duplex. Ensuring fast throughputs remains a grey and independent area for deliberation. While the communication medium ensures speed, providing data safety is another challenge. The army-navy-air force-space force will require larger synergy and more comprehensive cover in a joint warfighting effort. Thus, ensuring security through encryption or other techniques remains a grey area. Highly computational machines and robust algorithms usually undertake processing within DT. Hence, developing robust algorithms becomes a key focus area to ensure the desired replication of physical system performance.

Further, though a steadfast approach is adopted in the conceptual and framework development of DT, it remains expensive as a concept for large-scale implementation. Finally, the ecosystem required for building a complex and overarching technology requires expertise and skill. Military application development is challenging as it requires high standards and accuracy. Currently, dedicated R&D institutions mostly owned by Governments and large corporate bodies are working on this technology. For large-scale adaptation and sustainability, larger ecosystems are to be built. Lastly, the ethical considerations on using digital twins for offensive military applications need more extensive debate and framework. In addition, the data privacy of physical entities must be protected.

Conclusion

Integrating digital twin technology into joint war fighting can revolutionize military operations at all levels—strategic, operational, and tactical. It has enormous applications in operations, maintenance and administration. Digital twins enhance situational awareness, optimize resource allocation, improve coordination, and augment human capabilities. However, adopting digital twins in military contexts also presents significant challenges, including data integration and standardization, cybersecurity, and ethical and legal considerations.

The continued development and integration of digital twin technology will shape the future of joint war fighting. As digital twins become increasingly advanced, they will drive the evolution of warfare tactics, the development of new capabilities, and the attainment of strategic advantages. Military forces must adapt and innovate to leverage the full potential of digital twin technology while addressing the associated challenges to ensure the ethical and secure use of these transformative technologies.

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NOTES

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