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Digital Human Twins and the Military Metaverse: Opportunities and Challenges

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Abstract

The military metaverse integrates immersive digital technologies, virtual worlds, artificial intelligence (AI), extended reality (XR), and digital twins to enhance capabilities across the defence enterprise. Within this framework, Digital Human Twins (DHTs) function as dynamic digital representations of military personnel and sometimes "things", supporting training, mission planning, operational decision-making, health monitoring, equipment design and acquisition and human-machine teaming. DHTs can be considered "actors" on a metaverse "stage". This paper explores the role of DHTs in defence, categorising them into real human-derived, artificial, hybrid, and anthropomorphic twins, each serving one or more military functions.

DHTs offer significant advantages in adaptive training, career development, operational effectiveness, and equipment optimisation, but also present challenges related to data security, AI reliability, ethical concerns, and trust in autonomous decision support systems. To address these complexities, we propose an extended version of the Digital Twin Capability Periodic Table (CPT), originally developed for engineering digital twins, by incorporating ethical considerations, psychological fidelity, social interaction, and autonomy levels. This structured framework can support the development and governance of DHTs across defence and other domains.

By adopting a comprehensive approach to DHT implementation, including interoperability, data governance, and ethical oversight, organisations can unify their human data and maximise operational benefits while mitigating risks. The paper concludes with strategic recommendations for implementation, emphasising research investment and trials, AI governance policies, exploiting the extended CPT, and cross-sector collaboration to refine and standardise DHT deployment.

1. Introduction and Context

1.1 The Military Metaverse: Definition and Significance

The military metaverse is an evolution in the application of immersive digital technologies to defence built on the convergence of technologies including digital twins, Artificial Intelligence (AI), virtual worlds, and eXtended Reality (XR). It is rooted in concepts popularised by science fiction, such as Neal Stephenson's 1992 novel *Snow Crash* (Stephenson, 1992), where the term "metaverse" was first coined, and this vision has grown from science fiction to practical, defence applications. Whilst there is no agreed definition for the Metaverse (Burden & Savin-Baden, 2024) for current purposes metaverse can be defined as "one or more interactive, interconnected, 3D digital spaces, existing in virtual and physical space, and populated by a large number of

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users, human and AI, who can interact for collaboration, work or play, have agency and which has persistence, and which may be accessed through a range of technologies including Virtual Reality (VR), Mixed Reality (MR) and possibly Augmented Reality (AR)" (Fawkes & Burden, 2025). At its core, the military metaverse is simply applying the metaverse concept to military endeavours, brings greater digital 3D immersive interaction into both the digital and physical domains.

1.2 The Past and Present: Foundations of the Military Metaverse

Military forces have long used simulation and virtual environments to enhance operational readiness. By the 1920s, electro-mechanical flight simulators like the Link Trainer emerged and with computer advancements, training devices evolved into interactive digital simulations. In the 1980s' the US SIMNET pioneered networked simulation and AI-driven semi-autonomous forces, leading to the 1990s' Close Combat Tactical Trainer, which connected hundreds of tank and vehicle simulators (Miller, 2015).

The military have also explored extended reality (XR) based applications in both training and operations. In the 1980s, the USAF Super Cockpit projected a 3D field of view to pilots, integrating eye, head, and hand tracking, AI, and 3D sound, though it never entered service (IEEE Pulse, 2019). Today, XR is widely used in military training and operations. Video games have also influenced military metaverse technologies, with the 1990s' Marine Doom training Marines and America's Army supporting recruitment and modern game engines like Unreal are now used in high-end flight simulators.

Today, metaverse technologies are gaining renewed relevance as the underlying technologies improve and have the potential to enhance many military activities such as equipment acquisition, training and operations. Further, as the nature of warfare evolves to encompass land, sea, air, space, and cyberspace domains this complexity necessitates training and planning environments capable of replicating multidomain operations (UK MoD, 2022). A military metaverse is potentially well placed to meet this need providing interactive 3D content across the enterprise within a unified digital framework.

Examples of such technology developments are cloud computing enabling virtual worlds accessible from anywhere, with AI and data analytics enhancing these environments with adaptive simulations and performance insights. Interoperability standards enhance connectivity and content sharing. Moreover, advancements in hardware such as XR headsets advance at pace. The war in Ukraine has introduced XR in various forms into the frontline such as the use of headsets for the control of first-person view (FPV) drones (Molina et al, 2024).

1.3 Towards a Military Metaverse

A metaverse is generally considered an umbrella term for the integration of technologies bringing together the physical and digital worlds (Nadella, 2021). A metaverse, particularly a "capital M" Metaverse, implies an all-encompassing 3D digital or digital-

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physical space. A multiverse is a metaverse that is comprised of separate, but highly integrated virtual worlds. The military metaverse, at its most basic, is simply the application of metaversal technologies for military means.

Bringing metaversal technologies together on a networked interoperable enterprise basis offers the prospect of a transformative potential for training, capability development, and international collaboration. The importance of the military metaverse stems from its potential to enhance military capabilities across the entire lifecycle, from capability acquisition and support through training, planning, and operations. It offers a way to integrate the physical and digital worlds through digital twins, and immersive technologies can enhance decision-making and collaboration across different domains (Fawkes & Cheshire, 2022).

A future military metaverse, as depicted in "Ender's Game" (Card, 1985), could merge training and real operations. Soldiers might transition seamlessly between virtual exercises and missions using the same technology. Virtual battlefield replicas could update in real time, creating a continuous cycle of planning, preparation, and execution. This integration would improve adaptability, decision-making, and mission success.

1.4 Digital Twins and Digital Human Twins

Digital twins are virtual replicas of physical entities or systems that support data collection and exploitation and can be used to help model, plan, manage, operate and maintain such physical elements, and can provide a single source of data and process models (World Economic Forum, 2024). In a military metaverse, digital twins serve the same role and should be accessible across the defence enterprise Whilst digital twins normally represent physical entities such as pumps and vehicles, digital human twins (DHTs) function as digital representations of real or virtual humans. Unlike avatars which are a purely visual (and possibly audio) representation of a person, and may be controlled by a human or computer/AI, the DHT is not only controlled by a computer/AI but also models significant elements of the physiological and psychological elements of a human (real or imagined) (Papachristou et al, 2024). They are also a dynamic, evolving model that integrates an array of real-time data from its physical counterpart (Lin et al., 2022).

2. Digital Human Twins in the Military Context

2.1 Types of Digital Human Twins

In the military context, Digital Human Twins (DHTs) can represent warfighters, staff, adversaries, civilians and other stakeholders, and are more than just avatars; they can be considered active agents within the metaverse environment, or in other words as actors on the military metaverse stage. DHTs can be derived from various sources and serve different purposes as follows (figure 1).

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1. Real Human Derived DHTs: These are digital representations of actual individuals, created using data from sensors, wearable technologies, and other data collection methods. The data can include physical, social, behavioural, physiological, psychological, cognitive, and biological aspects (Burden & Savin-Baden, 2019). Real-time data collection allows for dynamic updates of these twins, mirroring changes in the person, and as the data is retained and built upon, the DHT may evolve with the actual human, even having memories.
2. Artificial Human DHTs: These are digital entities not directly tied to any specific individual. They are designed based on data sets that may include an amalgamation of population data and psychological factors and knowledge, or they might be specifically designed for a given scenario (Burden, 2019). They can simulate various roles and behaviours to create dynamic and immersive training or analytical environments. They can include conversational AI-driven personas that function as interactive agents rather than just passive simulations.
3. Hybrid DHTs: These combine elements of real and artificial data. They might be based on a real person's data but augmented with artificial intelligence (AI) for enhanced performance or prediction. In the form of an AI-enhanced decision support persona a hybrid DHT could learn from multiple human inputs and continuously refines its advisory role in real-time. These can be used to explore "what if" scenarios, test different skill sets, or predict potential outcomes.
4. Anthropomorphic DHTs of “Things”: This category represents another interesting dimension of DHTs, where digital twins of equipment, platforms, projects and organisations are given human-like attributes. These "platform personas" can act as a repository for knowledge, experiences, and lessons learned. They can also interact with human personnel in a more intuitive way. For example, a "wise" ship with its own digital persona that can provide guidance and support such as depicted by the "Rommie" AI of the Andromeda science fiction TV series (Burden, 2025).

Table 1 highlights the data sources, advantages and challenges of each type of DHT.

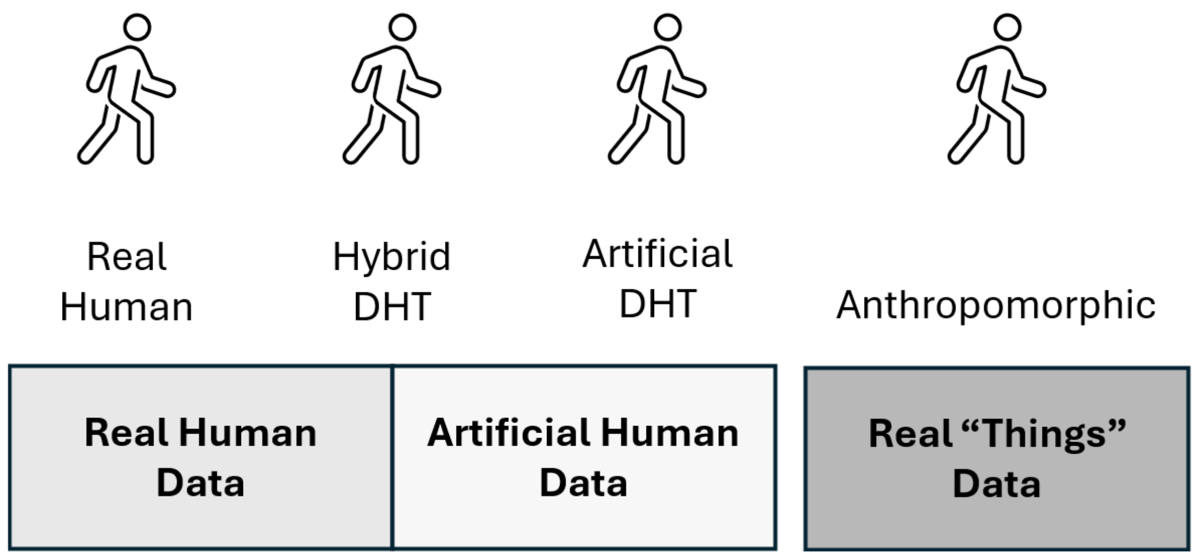

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Figure 1 – Types of Digital Human Twins

DHT Type	Data Source	Advantages	Challenges
Real Human-Derived DHT	Wearables, physiological monitoring	Realistic, high accuracy	Privacy concerns, Ethical concerns, Biases and Errors data security
Artificial Human DHT	AI-generated, simulation-based	Scalable, cost-effective	Less personal adaptability
Hybrid DHT	Mixed real & artificial data	Enhanced realism	Ethical concerns, Integration
Anthropomorphic DHT	Digital twin of a system (e.g., aircraft, ship)	Improves human-machine interaction	Complexity in system modelling

Table 1 – Data sources, advantages and challenges of each DHT

The idea of DHTs as actors on the military metaverse stage is further enhanced by the integration of AI. AI can help to create more timely, immersive, dynamic and intelligent simulations, generating non-player characters (NPCs) with more realistic behaviours for training. AI can also be used to deliver adaptive training or optimise infrastructure and the wider ecosystem.

2.2 Avatars and DHTs

Avatars, customizable digital representations in virtual environments, and DHTs both represent individuals in the metaverse, allowing interaction and identity expression. However, avatars focus on visual representation and interaction, while DHTs simulate physical, cognitive, and emotional traits using data from various sources. DHTs support applications like personalized healthcare and training, whereas avatars are used for social interaction and self-expression. Despite differences, avatars and DHTs could merge, with advancing avatar technology integrating real-time data to create more sophisticated virtual representations for broader military metaverse applications.

3. Military Use Cases for Digital Human Twins

3.1 Military Personnel Context

Recruiting, training and retaining warfighters is vital for military effectiveness, given the need to fill a vast array of roles, often on a large scale. The military workforce is typically young and serves in short, 2-3 year roles. Rapid global changes demand agility and adaptability in military operations, with an increasing need for digital proficiency in areas like cyber and space. The 2023 UK military's statistics illustrate the scale of this challenge: 142,500 regulars and 34,000 reserves, with substantial yearly turnover. The 2023 UK Defence Command Paper (Ministry of Defence, 2023) (DCP) emphasised the importance of adapting to a fast-changing world by prioritising personnel, aligning career structures with modern aspirations. This includes promoting flexible 'zig-zag' careers, adaptable to the digital era's working styles. Personalised, data-driven learning is also a focus, enabling tailored skill development and effective readiness assessment. Accordingly, the DCP stated that "as a top priority, we will look to digitalise and simplify our whole force people system".

Current UK military digital systems are fragmented, hindering data access and technology integration. The Haythornthwaite Review (Ministry of Defence, 2023a) noted that for MoD digital people systems "data is hard to access, technology is ageing, and .... a fractured ecosystem has created the need for manual workarounds ... there is no single view of data across the Armed Forces". Like many sectors, defence relies on outdated personnel systems that poorly support data use at the scale and complexity of military operations. A transition from this fragmented state is needed, with DHTs offering a way to unify warfighter data and enable new methods of exploitation.

The proposed DHT or digital warfighter twin would exist right from a recruit's initial interest in the military. This digital counterpart would be a constant through their career, facilitating seamless transitions between recruitment, training, and active service. It would support the warfighter in adapting to various roles, minimizing skill decay, and navigating through 'zig-zag' career paths. These twins could be exploited by the military in a variety of ways, with applications ranging from training and mission planning to medical support and enhancing soldier performance. Here are some key areas, some aspirational, some already a reality.

3.2 Education and Training

Digital Human Twins (DHTs) in military education and training could function as AI-driven virtual instructors, adaptive training partners, and real-time performance evaluators (Pickle et al, 2024). Integrated with conversational AI, DHTs could act as intelligent Non-Player Characters (NPCs) in training environments, simulating complex scenarios and responding dynamically to trainee interactions. DHTs could enable warfighters to train with virtual representations of colleagues - even when they are unavailable. They could also support After Action Reviews (AARs) by autonomously analysing training outcomes, identifying skill gaps, and providing personalized feedback to enhance learning retention. Conversational AI-powered DHTs could be used as virtual instructors, assessors, and adaptive training agents, improving warfighter engagement and knowledge retention.

3.3 Career Planning

Digital Human Twins (DHTs) could support military career planning by acting as personalised digital mentors that evolve alongside an individual's career. By integrating real-time performance data, training history, and operational experience, DHTs could provide tailored personalised recommendations for skill development, role transitions, and leadership preparation. Conversational AI-driven DHTs could assist personnel in navigating career paths, ensuring seamless transitions between roles while minimising skill decay (Fawkes, 2024). Additionally, they could serve as institutional memory

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repositories, preserving insights from past personnel and facilitating knowledge transfer to new generations of warfighters and their supporting personnel.

3.4 Health Monitoring

DHTs could be used to monitor the health and well-being of warfighters in real-time. By collecting data from wearable sensors and other sources, DHTs could provide personalised health insights, predict potential health risks, and facilitate early interventions (Paul et al, 2024). DHTs could automate aspects of health monitoring, providing predictive diagnostics, injury risk assessment, and proactive intervention to improve warfighter resilience. Moreover, DHT breaks the one-size-fits-all model in medicine and allows for individualised approaches, leading to more personalised and effective healthcare solutions. Furthermore, by identifying risk factors and quantifying the sources of injuries, DHTs can help develop preventative strategies and minimise the negative impacts of physiological and biomechanical issues on warfighter readiness (Cheng et al., 2022; Lloyd et al., 2023).

3.5 Human Factors Studies and Equipment Acquisition

DHTs offer support to military equipment development and deployment. They could support the testing and refinement of military equipment and systems under various scenarios identifying potential equipment malfunctions or inefficiencies before actual deployment. Additionally, they could facilitate the analysis of how different equipment affects warfighter performance and endurance. By enabling virtual trials, DHTs could contribute to more informed decisions in equipment design, leading to improved functionality and compatibility with warfighter's needs. DHTs could also enable the analysis of physiological, psychological, and environmental factors, allowing for the development of strategies to improve performance. This includes monitoring physical load and supporting evidence-based decisions for military equipment and configurations.

3.6 Warfighter Monitoring and Operational Planning

DHTs could be integrated into decision support systems to provide commanders with comprehensive dashboards and real-time insights into the physical and cognitive state of warfighters. These tools could offer insights into the readiness of personnel for specific roles, the impact of their training, and overall unit preparedness. They could be integrated into mission planning and rehearsal tools, allowing commanders to simulate and analyse different scenarios before deployment. This could help identify potential risks and optimise strategies for various contingencies. The European Defence Agency (EDA) is conducting a study on the use of digital twins for military purposes, including mission planning and execution (FlySight, 2024).

3.7 Operating Autonomous Systems

DHTs could be linked to Soldier Robotic Twins (SRT), which are mechanical versions of soldiers, or Augmented Soldier Robotic Twins (ASRT), which can perform complex tasks, including remote control of robots, and can act as an 'Alter Ego' of the human

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soldier (Saggio, 2024). This could involve the use of immersive and telepresence technologies to replicate the warfighter's physiological, psychological, and cognitive attributes in the digital world at distance.

3.8 Human Machine Teaming

Anthropomorphic Digital Human Twins (DHTs) of equipment and platforms could be used to continuously monitor a situation in real time, employing computer vision and AI-driven techniques to analyse sensor data and platform status. Alongside this, the DHT could monitor the cognitive state of the human team, assessing workload and stress levels. This information could be leveraged to deliver context-aware insights, optimise situational awareness, and enhance decision-making by presenting information at the right time and in the most effective format. Additionally, these AI-enhanced DHTs could facilitate complex actions through simple instructions and, when necessary, act autonomously to support mission objectives. By integrating conversational AI, anthropomorphic DHTs could actively assist human warfighters in combat scenarios, providing real-time intelligence, workload monitoring, and tactical recommendations (Strong et al, 2018).

Beyond individual anthropomorphic DHTs, "Platform Personas" could function as persistent, intelligent entities representing entire military platforms (Burden, 2025). These personas would integrate historical knowledge, operational experiences, and real-time system data to enhance platform performance and decision support (Strong & Maltby, 2018). For example, an AI-driven "wise" aircraft persona could continuously learn from past missions, optimise maintenance schedules, and dynamically adjust performance parameters based on environmental and tactical conditions. In a combat aviation setting, an "e-Pilot" system[1], similar to R2D2 in *Star Wars*, could monitor both the human pilot and aircraft performance during critical phases of flight, providing assistance, risk alerts, and enhanced aircraft control to improve safety and mission effectiveness.

By leveraging AI-driven platform personas, military forces could benefit from greater continuity of operational knowledge, improved system autonomy, and more effective human-machine collaboration. However, the deployment of AI-driven DHTs in combat scenarios introduces challenges of accountability. If a DHT makes autonomous tactical recommendations, should responsibility lie with the human operator, the AI system, the defence contractor or military leadership? Ensuring transparency in AI-driven decision support is necessary for maintaining trust in human-machine collaboration.

3.9 Virtual Staffs and Advisors

In many military organisations, certain skills and expertise are always in short supply, and the communications and career challenges in the military can exacerbate this issue. Real Human-Derived DHTs and Artificial Human DHTs could capture wisdom and expertise either by individuals or by topic, ensuring 24/7 availability at the point of need.

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[1] http://www.cranfield.ac.uk/research-projects/epilots

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These DHTs could support a wide range of roles, from technical specialists, medics, and mechanics to staff officers, LEGADs (Legal Advisors), CIVADs (Civilian Affairs Advisors), and POLADs (Political Advisors). By integrating Conversational AI, DHTs could function as Virtual Expert Advisors, providing real-time operational support in decision-making, training, and mission planning. Similar to HQ Persona, Virtual Liaison Officers (VLOs), and Virtual Combat Assistants (VCAs), these AI-enhanced DHTs could process large volumes of data, generate actionable insights, and assist commanders in evaluating tactical scenarios. Their ability to deliver situational awareness, predictive analysis, and cognitive augmentation would enhance military effectiveness while also addressing the challenge of keeping field headquarters small and concealable. Through dynamic interaction with human personnel, these intelligent DHTs could bridge the gap between raw data and strategic action, improving efficiency and responsiveness in complex operations (Burden, 2025).

In summary, DHTs offer a range of potential military applications, from enhancing training and mission planning to improving medical care and soldier performance. They could provide realistic simulations for training, support mission rehearsals, and enable personalised healthcare by monitoring real-time physiological data. DHTs also could contribute to injury prevention, optimise warfighter performance, and enhance decision-making by offering cognitive and operational insights. Additionally, they have applications in robotic systems, remote medical support, and digital engineering, improving military equipment design. As research and technology advances, DHTs could play an increasingly integrated role in the military metaverse and military activities.

3.10 Linking DHT Types and Roles

Whilst generally all of the different DHT types described earlier can be used in any of the above roles, the following should be noted:

- The Anthropomorphic DHT makes no sense in Education & Training, Career Planning and (human) health monitoring as it is representing a system not a person;
- In roles such as career planning and health monitoring artificial human and hybrid DHTs are taking the role of mentor/monitor, no the role of the subject;

Human Machine Teaming is relevant whatever type of DHT is being considered, as in all cases the humans are interacting with a “machine”.

4. Challenges in Implementing Digital Human Twins

Digital Human Twins (DHTs) present numerous opportunities for military applications but also come with significant challenges across multiple domains, including data management and security, technological limitations, ethical considerations, practical implementation, cognitive modelling, and verification and validation. The challenges are also multidisciplinary in nature with multiple use cases, stakeholders, vendors and data standards with a backdrop of ever advancing technologies.

4.1 Data Challenges

One of the primary concerns with DHTs is the reliability and accuracy of the data used to create and update them together with the data ownership and user consent. The effectiveness of simulations and decision-making depends on high-quality data, and errors in data collection or processing can lead to flawed conclusions. Additionally, historical data availability is often limited, making it difficult to verify the accuracy of predictive models. Ensuring data quality involves addressing issues such as signal-to-noise ratio, interoperability between systems, and handling missing data effectively. Machine learning models used in DHTs require vast amounts of data for training, which may be difficult to acquire, especially in military environments where data sensitivity and security concerns limit accessibility. Other approaches such as knowledge graphs may require less data and less processing power, and be more explainable, but the methodologies and tools to build and use them at scale are only just emerging (Hogan et al, 2022). Bias in AI-driven DHTs poses risks for personnel management, medical assessments, and mission-critical decision support. Transparent explainability mechanisms and human oversight are necessary to mitigate algorithmic bias in military applications.

4.2 Technological Challenges

The current state of sensor technology poses a significant barrier to the effective implementation of physiological DHTs. Motion capture systems and physiological monitoring devices may not yet be advanced enough to function reliably in harsh military conditions. Additionally, running high-fidelity biomechanical and physiological models requires significant computational power, which can be difficult to achieve in field conditions where mobile or edge computing resources are limited. Real-time processing remains a major hurdle, as complex simulations must be computationally efficient while using limited sensor data. Another significant issue is model validation - ensuring that digital representations accurately reflect real-world human physiology and behaviour is difficult, particularly because many models rely on data from cadavers or population studies (Pickle et al, 2024). Furthermore, integrating multiple models - such as biomechanical, physiological, and cognitive models - into a single cohesive system remains an ongoing challenge. The complexity of representing human factors, including emotional and psychological states, adds further difficulty to developing accurate and functional DHTs.

4.3 Practical Implementation Challenges

Deploying DHTs in military environments involves several practical challenges, including sensory mismatches caused by immature technologies that create discrepancies between digital and physical representations. DHT models must account for individual variability in body shapes, sizes, and physiological responses, but many rely on population averages or cadaver-based data, limiting individual applicability and requiring personalised adjustments. Real-time data gaps in high-stress or combat scenarios pose further difficulties, while a lack of standardisation across sectors complicates integration into existing military frameworks (Grant et al., 2024). Scalability is also a concern, as models must function across diverse scenarios and personnel, demanding adaptable and cost-effective solutions. High costs related to data generation, model training, and system maintenance can be prohibitive at scale, and interoperability between different digital twin models and military systems must be addressed to ensure seamless platform integration.

4.4 Cognitive and Behavioural Modelling Challenges

Human behaviour is inherently complex, and capturing its full range in DHTs is a considerable challenge. Military personnel operate in highly dynamic and unpredictable environments, making it difficult to develop models that accurately reflect real-world decision-making and emotional responses. The integration of the Theory of Mind (ToM) - which enables AI to predict and understand human behaviour - is another significant hurdle (Cuzzolin et al, 2020). Effective ToM implementation requires extensive real-time behavioural data collection and adaptation of computational models to accommodate diverse human responses. Moreover, ensuring that these models can scale to handle complex, high-stakes military scenarios remains an ongoing challenge.

4.5 Verification, Validation, and Uncertainty Quantification (VVUQ)

Ensuring the accuracy and reliability of DHTs is a continuous process that requires ongoing verification, validation, and uncertainty quantification. As digital twins evolve, their models must be regularly updated to reflect changes in the physical counterpart, data inputs, and operational requirements. Extrapolation remains a major concern, as many models are untested in extreme or unforeseen conditions. Establishing standardised methods for VVUQ is essential to maintaining confidence in DHT-generated insights. Scalable algorithms are necessary to handle complex, multiscale, multiphysics, and multi-code digital twin systems. Additionally, developing online VVUQ approaches will be critical for enabling real-time verification and validation in automated digital twin operations (Grant et al, 2024).

4.6 Security and Ethical Considerations

The use of DHTs in military contexts raises ethical concerns, particularly around privacy, data security, and the extensive use of biometric, behavioural, and cognitive data, which may be misused if not properly protected (Saggio, 2024). Informed consent is complex in environments where participation may not be fully voluntary such as the military, and transparency is essential, as flawed or biased models could lead to poor strategic decisions. Additional concerns include the influence of AI on human autonomy (Sbailò, 2024), risks of profile-based discrimination, and challenges in governing digital twins after the individual is inactive or deceased. Legal and ethical issues also arise from unclear data ownership and competing stakeholder interests in DHT-generated information. Deepfake vulnerabilities further increase risks by enabling fabricated intelligence, impersonation, or manipulation of mission-critical data, making strong authentication, secure AI models, and adversarial detection essential for military cyber defence.

Overall, while DHTs offer significant potential for improving military training, mission planning, medical support, and decision-making, their successful implementation requires overcoming multiple challenges.

4.7 Unique to the Military?

The challenges associated with DHTs are not exclusive to the military. Many other sectors face similar technical, ethical, and operational issues, particularly in areas concerning data privacy, fidelity, trust, and autonomy. While the military applications of DHTs are often tied to defence operations, training, and mission planning, comparable concerns can exist in the following domains.

- **Health:** Digital human twins could be used for personalised medicine, surgical planning, and patient monitoring, allowing healthcare professionals to simulate and predict patient responses before treatment. However, these applications raise concerns regarding data privacy, informed consent, and security, similar to those in military DHTs where personal data is used for performance assessment and decision support.
- **Engineering and Manufacturing:** In aerospace, automotive, and industrial production, digital twins replicate physical products and processes for optimisation, predictive maintenance, and efficiency improvements. Ensuring fidelity between digital models and real-world counterparts is necessary, just as in military DHTs, where accuracy in representing personnel or systems directly impacts decision-making and operational effectiveness.
- **Transport:** Digital twins can play a key role in autonomous vehicle systems, smart city infrastructure, and traffic management. Just as military DHTs must ensure secure, real-time data processing to support operations, transport systems require robust cybersecurity measures to protect against hacking, data manipulation, and privacy breaches that could disrupt public safety.
- **Arts and Entertainment:** The use of digital avatars, AI-generated virtual characters, and deepfake technologies in media, gaming, and film raises concerns about realism, authenticity, and ethical implications. Like military DHTs, there are questions regarding the control, modification, and ownership of digital representations, particularly in cases where AI-generated personas might be used posthumously or without consent.

While the military metaverse presents distinct operational challenges, the broader implications of DHTs highlight a shared need for ethical governance, interoperability, and trust in AI-driven digital representations across multiple industries.

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5. Applying the Digital Twins Periodic Table to DHTs

5.1 The Digital Twin Capability Periodic Table

Many of the challenges of DHTs are associated with the lack of a standard approach to their development and maintenance. Digital twins used in engineering have a longer heritage and may provide inspiration for the development of DHTs. The authors have looked to the Digital Twin Consortium (DTC) (Digital Twin Consortium, n.d.) which is a non-profit organisation established in 2020, focused on driving the development and adoption of digital twin technology across various industries by collaborating with academia, government, and industry partners. The DTC Mission is to "accelerate the adoption of digital twin technology by promoting awareness, interoperability, and best practices" with focus areas including defining digital twin standards, developing capability frameworks, identifying use cases, and facilitating collaboration between members. A key DTC output has been the "Digital Twin Capability Periodic Table" (CPT)first published in March 2022, with version 1.1 released in April 2024 (Digital Twin Consortium, 2024).

The CPT is a framework that helps organisations understand and assess their digital twin capabilities and can be used to identify gaps in an organisation's digital twin capabilities and to prioritise investments in new technologies and resources (*Capability Matrix*, n.d.). It can also be used to compare digital twin capabilities across different organisations. Although it is early days for the CPT, some use cases are evolving. NTT Data uses the CPT to identify and select capabilities (e.g., real-time data streaming, AI insights) which are then combined, making their composable Digital Twin-Enabled Microfactory adaptable for various smart manufacturing scenarios (Digital Twin Consortium, 2025). While specific standards bodies (like ISO) and industry-focused associations offer alternative digital twin frameworks, the DTC's CPT provides an architecture and technology-agnostic common language for defining capabilities across diverse industries. This approach potentially allows for more flexible, composable digital twin solutions compared to vendor-specific alternatives.

The CPT consists of categories based on the digital and physical aspects of a digital twin. The six main categories in the CPT are listed and described in Table 2.

Category Name	Category Description
Data Services	Enables data access, ingestion and data management across the platform from the edge to the cloud. It establishes the physical to virtual connection and receives data directly from equipment sensors or control systems, performs localised processing and distributes to other tiers.
Integration	Enables data access to existing internal and external enterprise systems and applications. Enables communication across different digital twins.
Intelligence	Provides an environment for the development and deployment of industrial digital twin solutions. It provides the services for data

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	integration, basic and advanced analytics, AI, orchestration and other digital twin process capabilities.
User Experience	Provides the user with the ability to interact with digital twins and visualise its data.
Management	System and ecosystem management capabilities.
Trustworthiness	Security, privacy, safety, reliability and resilience capabilities.

Table 2 - Digital twins CPT category descriptions.

We propose what we believe is a novel approach by exploiting the Digital Twin Capability Periodic Table (CPT) to address the management of DHTs to provide a more unified and comprehensive approach. Table 3 takes each capability category and applies it to the military DHT.

Capability Category Name	Warfighter DHT Capability
Data Services	DHTs use data services to manage information from edge to cloud, linking the warfighter to their digital replica through sensor data. Basic processing at the edge reduces latency and bandwidth demands. Processed data is shared across the platform for further analysis and modelling.
Integration	DHTs must integrate with internal and external enterprise systems to provide a complete view. This allows access to data from sources such as health records, training databases, and personnel systems. DHTs should also share data with other digital human twins to support modelling of team dynamics and collective behaviours.
Intelligence	The intelligence capability supports DHT development through data integration, analytics, AI, and orchestration. It combines various data sources to model the warfighter. Analytics predict performance and risks, while AI aids behaviour modelling and decision-making. Orchestration coordinates components to improve efficiency.
User Experience	A user experience capability supports interaction with DHTs and data visualisation. Clear visualisations convey the warfighter's status, predict performance, and highlight issues. Interactive tools like chat and 3D avatars enable scenario simulation and intervention planning. Natural language processing allows conversational, human-like interaction with DHTs.
Management	Management ensures DHT scalability, reliability, and maintainability. System monitoring tracks performance and addresses issues early. Ecosystem management coordinates models, data, and applications for smooth integration and operation.
Trustworthiness	Trust is critical for DHTs due to sensitive data. Security and privacy safeguard access and confidentiality. Accurate predictions support safe decisions, while testing and redundancy ensure

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	reliability and resilience. AI explainability reduces risks of opaque decision-making.

Table 3 – Military DHT Capabilities

Applying the CPT to DHTs in the military metaverse can help identify the specific capabilities required for different use cases. For example, a DHT used for training and simulation might require advanced visualisation and interaction capabilities, while a DHT used for personalised healthcare might require robust data acquisition and analysis capabilities. Table 4 below lists some of the potential benefits and challenges of taking a CPT approach to warfighter DHTs and also some of the limitations.

Potential Benefits	
Structured Approach	The CPT provides a structured and systematic approach to identify the key capabilities required for DHTs in different military applications.
Enhanced Collaboration	The CPT can facilitate collaboration among stakeholders, including developers, end-users, and technology providers, by providing a common framework for understanding and defining DHT capabilities.
Improved Interoperability	The CPT can promote interoperability by ensuring that DHTs are developed with standardised capabilities and interfaces.
Accelerated Development	The CPT can accelerate the development and deployment of DHTs by providing a clear roadmap for capability requirements and technology selection.
Potential Challenges	
Complexity	The CPT can be complex to implement, especially for organisations new to digital twin technology.
Evolving Technology	The CPT needs to be regularly updated to keep pace with the rapidly evolving digital twin technology landscape.
Human Factors	The CPT primarily focuses on technical capabilities and may not adequately address the human factors and ethical considerations associated with DHTs.

Table 4 – Benefits and challenges of applying the CPT approach to military DHTs

5.2 Extending the CPT for DHTs

While the Digital Twin Capability Periodic Table (CPT) provides a structured framework for managing digital twin capabilities, Digital Human Twins (DHTs) introduce unique challenges, particularly in their psychological aspects, that require additional considerations. To better align the CPT with the complexities of human representation in military applications, we propose four key extensions that address ethical, psychological, social, and autonomy-related factors. These extensions can help ensure

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that DHTs are not only technically robust but also ethically sound, psychologically accurate, socially competent, and appropriately autonomous.

5.2.1 Ethical Considerations

A new Ethical Considerations category should be incorporated into the CPT to address bias, privacy, consent, and data ownership associated with DHTs. Unlike traditional digital twins, which primarily replicate physical systems, DHTs involve sensitive human data, raising concerns about who owns and controls the twin, how data is collected, and whether individuals consent to its use. Ethical risks also extend to AI bias in decision-making, where flawed or skewed training data could result in misrepresentation, stereotyping, or discriminatory behaviours in military simulations and decision-support systems. Additionally, long-term data retention policies should be defined to establish when and how DHTs should be decommissioned, particularly when the warfighter leaves service or if they outlive the physical individual they represent.

5.2.2 Psychological Fidelity

The Psychological Fidelity category should be added to assess how well a DHT captures and replicates psychological and behavioural characteristics of an individual or an archetypal persona. This extension ensures that DHTs do not merely mimic physical attributes but also reflect realistic cognitive, emotional, and stress-response behaviours. Military applications often require simulations of decision-making under pressure, cognitive load, emotional resilience, and mental fatigue, all of which impact training effectiveness and operational readiness. High psychological fidelity is essential for AI-driven DHTs used in combat training, leadership development, and crisis response simulations, ensuring that trainees engage with realistic human-like agents that enhance their situational awareness and psychological preparedness.

5.2.3 Social Interaction

A dedicated Social Interaction category should be introduced to evaluate how effectively DHTs simulate social behaviours such as teamwork, leadership, and group dynamics. Unlike engineering-based digital twins, military DHTs must interact in collaborative and adversarial settings, requiring complex social modelling. This includes the ability to understand and respond to hierarchy, demonstrate leadership behaviours, engage in negotiations, and simulate real-world interpersonal challenges such as conflict resolution. For instance, in simulation-based training, conversational AI-powered DHTs can act as adaptive teammates or adversaries, dynamically adjusting their social interactions based on human input and mission objectives. By refining social modelling and interaction fidelity, military organisations can enhance realism in training scenarios and improve the effectiveness of mission rehearsals, war gaming, and joint operations planning.

5.2.4 Agency and Autonomy

The Agency and Autonomy category should assess whether a DHT functions as a passive digital replica, an interactive virtual assistant, or an independent AI-driven agent

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with self-determined behaviours. This distinction is vital for military applications where some DHTs must operate strictly as mirrors of human counterparts, while others may require decision-making capabilities in mission simulations, operational planning, and human-machine teaming. For example, a Virtual Combat Assistant (VCA) could autonomously provide tactical recommendations, cognitive load balancing, and adaptive intelligence support to soldiers in combat. Conversely, a real human-derived DHT may need to be constrained to ensure fidelity to the original person it represents. By defining levels of autonomy, this category ensures that DHTs align with military requirements for human-AI collaboration, mission-specific adaptability, and ethical oversight.

By extending the Digital Twin Capability Periodic Table (CPT) with these four categories, Digital Human Twins can be better structured to meet the demands of military applications. These extensions provide a tailored framework that moves beyond traditional digital twin principles, ensuring that DHTs are ethically responsible, psychologically realistic, socially competent, and appropriately autonomous. As military forces increasingly integrate AI-driven digital twins into training, operations, and human-machine teaming, a more comprehensive CPT will support the responsible development, deployment, and governance of these advanced technologies. Table 5 lists the CPT category descriptions plus the 4 extensions proposed to accommodate DHTs.

Category Name	Category Description
Data Services	Manages data access, ingestion, processing, and distribution across platforms.
Integration	Facilitates data access and communication between enterprise systems and twins.
Intelligence	Supports digital twin development, deployment, data integration, analytics, and AI.
User Experience	Provides the user with the ability to interact with digital twins and visualise its data.
Management	System and ecosystem management capabilities.
Trustworthiness	Security, privacy, safety, reliability and resilience capabilities.
Ethical Considerations	Addresses bias, privacy, consent, and data ownership issues.
Psychological Fidelity	*Ensures realistic cognitive, emotional, and behavioural representation.*
Social Interaction	*Simulates teamwork, leadership, and interpersonal military dynamics.*
Agency and Autonomy	*Defines DHT independence, decision-making, and adaptability levels.*

Table 5 – Proposed digital human twin CPT categories

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6. Discussion and High-Level Strategy

The implementation of DHTs in the military metaverse and beyond presents a significant opportunity to enhance defence capability acquisition and support, training, and operational effectiveness. It is envisaged as a template or checklist for planning and implementing DHTs in the military and other sectors in a structured and repeatable manner. They can provide a common language for defining DHTs across diverse use cases helping to accelerate DHT exploitation and avoid vendor-specific alternatives. This transformation is not solely about technological advancement but also about integrating the human element into digital defence ecosystems. DHTs offer a shift from traditional 2D representations to immersive 3D environments, enhancing situational awareness and decision-making. Furthermore, the evolution from objective data analysis to subjective experiences allows for a more comprehensive understanding of human performance, well-being, and adaptability in complex scenarios.

Realising the potential of DHTs requires moving beyond siloed technology deployment toward integrated systems that interact with AI simulations, predictive analytics, and real-time battlefield data. This shift depends on collaboration among military branches, technology providers, and policymakers to build a cohesive digital ecosystem. A structured implementation strategy will be required and the CPT provides a clear framework for this. A key element of this strategy is investment in research and development (R&D) to advance core technologies such as AI, XR, sensors, and data analytics. Further, developing open standards and ensuring interoperability across platforms is essential for seamless DHT integration into defence systems.

Additionally, establishing ethical guidelines is critical to address concerns around data collection, storage, privacy, and responsible AI use. Stakeholders from defence, government, and technology sectors should be actively involved in defining protocols that promote transparency and accountability in DHT deployment. Alongside ethical considerations, developing a skilled workforce is necessary to support the design, deployment, and maintenance of DHT systems. Investment in education and training programs will be essential to ensure personnel can effectively utilise and manage these technologies.

To drive innovation, cross-disciplinary collaboration should enable data and model sharing while addressing privacy, security, and AI ethics in digital twin technology. A phased approach could begin with use cases like training, then expand to real-time monitoring and decision support. Public virtual worlds might also serve as testing grounds for refining DHT capabilities.

Security must be a top priority throughout all stages of DHT development and deployment. Robust cybersecurity frameworks and safeguards should be implemented to protect sensitive data, ensure system resilience, and prevent potential adversarial manipulation. Given the complexity of military DHT adoption, a clear roadmap with short-, medium-, and long-term goals is necessary to guide progress and engage multiple stakeholders.

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7. Conclusion and Recommendations

In conclusion, Digital Human Twins have the potential to revolutionise the military metaverse and wider defence across a wide range of use cases. However, this potential can only be realised through careful planning, robust investment, and an ethical-based approach. The challenges are significant but not insurmountable, and by drawing on and building on existing frameworks like the Digital Twin Capability Periodic Table, the path to effective implementation can be navigated. Furthermore, these issues are not unique to the military, and there are lessons to be learned from the deployment of DHT technologies across many other sectors. Based on the analysis, the following recommendations are proposed:

7.1 Prioritise Data Security and Privacy

Prioritise data security and privacy by implementing robust protections, conducting risk assessments, and establishing ethical guidelines aligned with legal and human rights standards.

7.2 Invest in Research and Development

Continue investing in research and development to enhance DHT fidelity, focusing on realistic human behaviour simulation, military user trials, and addressing current technological limitations.

7.3 Foster Collaboration and Interoperability

Encourage collaboration among all stakeholders to ensure interoperability, standardisation, and inclusive participation in DHT platforms across the supply chain.

7.4 Develop a Comprehensive Implementation Strategy

Develop a comprehensive implementation strategy and roadmap that addresses technical, ethical, and organisational challenges, including closing knowledge gaps and building relevant skills for DHT adoption.

7.5 Promote Policy Development

Policymakers need to develop a baseline understanding of the technologies and concepts associated with the military metaverse to ensure responsible and ethical technology adoption.

7.6 Leverage the Digital Twin Periodic Table

Utilise the extended Digital Twin Periodic Table as a framework for defining and categorising DHT capabilities, facilitating collaboration, and accelerating development.

By addressing these recommendations, the military and beyond can effectively leverage the potential of digital human twins, unifying its people data, and enhancing readiness and operational effectiveness.

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