Changing Definitions of Digital Twins In Ship Design

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Synopsis

The 'digital twin' is now a recognised core component of the Industry 4.0 journey, helping organisations understand their complex processes, resources and data to provide insight into their business and help optimise their operations. However, there is still some confusion over the title, with the term 'digital twins' sometimes meaning different things to different people. This often leads to a mysticism and uncertainty around the technology and can mean that organisations are divided by a common language.

This paper explores the different roles, definitions and purposes of a digital twin in an attempt to demystify the technology. By exploring different case studies and applications can we once and for all define a digital twin?

Keywords: Digital Twins; Warship; Technology; Maritime

1. Introduction

‘Digital Twins’ have become a common buzzword in engineering (Gautier, 2020), used to describe everything from Computer Aided Design (CAD) models to predictive maintenance techniques. This can sometimes mean the phrase is over-used and used to support over promised product solutions. However, with the global sector expected to be worth $86 billion by 2028 (Grand View Research, 2022), there is no denying that there is value within the hype. The excitement surrounding digital twins is due to their ability to provide valuable insights and improve products and processes, making them a valuable tool for industries involved with large-scale products or projects such as engineering, automobile manufacturing, aircraft production, railcar design, building construction, manufacturing and power utilities. With such potential for success, it’s no wonder that digital twins have become such a buzzword in engineering and beyond.

Despite the hype surrounding digital twins, it is widely perceived that they have yet to fully live up to their potential. One reason for this is that many people are still confused about what digital twins actually are and how they can be used (Zhabitskii et al, 2021). The term has been used to describe everything from CAD models to predictive maintenance techniques, leading to confusion and misunderstandings about the true capabilities of digital twins. Another reason why digital twins have yet to live up to the hype is that their implementation can be complex and challenging (Zhabitskii et al, 2021). Creating a digital twin requires a significant investment in technology, data collection, and analysis. It also requires a deep understanding of the physical object or system being modelled, as well as the ability to integrate data from multiple sources and use advanced analytics to generate insights.

While digital twins have the potential to revolutionize many industries, there is still much work to be done in order to fully realize their potential. In order to move forward with this work and create a pathway to full implementation we need to understand the different definitions of digital twins and what they mean.

Author’s Biography

Jake Rigby is the Global Head of Innovation and Research at BMT, responsible for the portfolio management of internal research projects. He is a chartered engineer and Member of the Royal Institute of Naval Architects originally training as a Naval Architect specialising in ship signatures before his current role in Research and Development. Jake is also responsible for Academic Engagement at BMT. In recognition of his work to progress Academic Engagement in the maritime sector he was recently awarded the title of Honorary Associate Professor at the University of Exeter.

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2. Definitions

In its original conception (Grieves 2014) a digital twin is a digital model of a manufactured, physical system. It has evolved to cover not just manufactured, physical systems, but also natural physical systems, processes and any other type of complex system. While computer-aided design (CAD), from which digital twins emerged, is sparse and static, a full digital twin is rich in detail and can be incorporated into a simulation where forces (or inputs in the case of non-physical systems) are applied to it over time and their effects actioned by the model.

To fully understand and appreciate the potential of digital twins, it is necessary to recognize and accept the four broad categories and definitions that exist, each with their own definitions and challenges. They each provide a relative step up in complexity and capability summarised in Figure 1 below and described below.

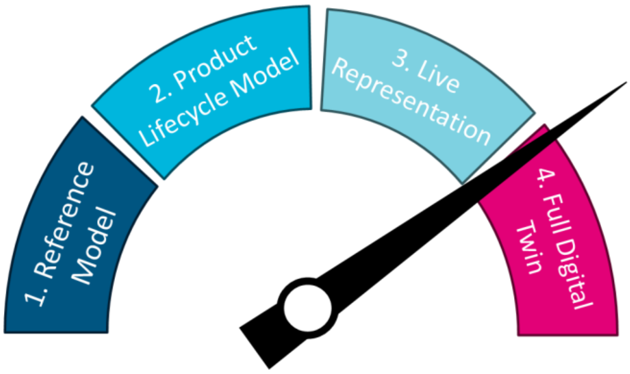

Figure 1 – Spectrum of Digital Twin Categories

1. Reference Model: This category comprises 3D models that serve as a reference for assessing the impact of operational and design decisions. These models can be checked against the physical system to ensure accuracy and consistency.

2. Product Lifecycle Model: This category contains rich data on the asset, including information on its design, manufacture, operation, maintenance, and disposal. This data can be used to provide through-life support and manage obsolescence.

3. Live Representation: This category takes digital twins a step further by providing a real-time feed of live data from the physical system. This enables real-time monitoring and analysis of the system's performance.

4. Full Digital Twin: The ultimate goal of digital twin technology is to achieve a closed-loop cycle between the live asset, modelling sensors, and operational decision-making (see Figure 2). This category represents the pinnacle of digital twin technology, driving performance and enabling real-time optimization. A full digital twin can have the definition as follows "A virtual representation of physical assets, processes / people / places / systems / devices that can be used to support decision making when fed or provided with real-world data. Note: Key point is the link to real-world data and active decision support" (Mansfield and Rigby, 2020)

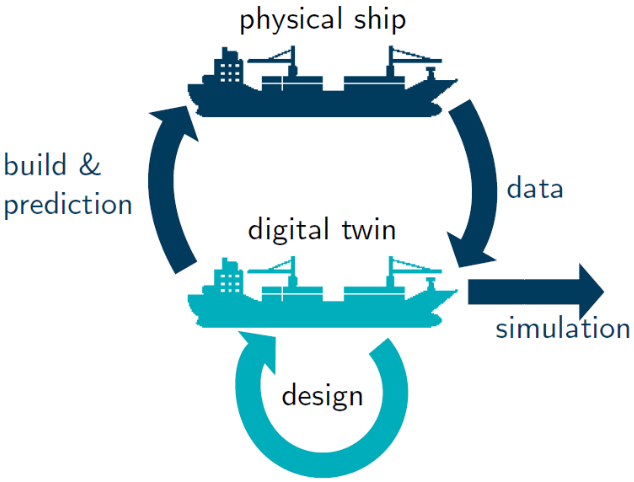

Figure 2 - Description of a Full Digital Twin with a Closed Prediction Loop

Throughout their development and media coverage the real focus on Digital Twins has been on the later "Full Digital Twin" examples, but they can be extremely difficult and costly to build in practice, as the twin needs to be designed as part of the system, from the very start. By understanding all four categories and their respective benefits and challenges, we can demystify the concept of digital twins and unlock their full potential no matter what stage of development you are at.

The following section outlines some additional terms and buzzwords that are used in relation to digital twins that you may come across. Definitions are provided in this paper for information but they are only for reference and will not be discussed further:

Digital Shadow:. We define a digital shadow as a digital twin that is being continuously updated, in real time, with data from the physical system. There seems to be some disagreement between sources about this definition (e.g. Bergs et al (2020) and, Sepasgozar(2021)), but in general the distinction lies in the direction(s) of the data flows between the physical and digital systems.

Digital Twin Ecosystem: In order to extract the full benefit from digital twins the wider ecosystem and connected systems need to work together. The Digital Twin Ecosystem can therefore be defined as multiple connecting twins interacting together to provide fleet wide benefits and insights. This will require adaptability and scalability in the twin structure.

Digital Thread: A framework that connects data flows and produces a holistic view of an asset's data across its lifecycle from requirements, concept, design, engineering, manufacture, operation/in-service and disposal. A Digital Thread represents the 'single data source of truth' weaving through the entirety of the asset lifecycle. For example, the Mean Time Between Failure (MTBF) of a pump will initially be a value derived during design. This value will then be updated during the in-service based on analysis of data input from the physical asset. The term **Digital Tapestry** is often also used to signify the complexity of the problem and how digital twins may require many interlinking digital threads from different organisations (i.e. many threads = Digital Tapestry). The US Department of Defence (2018) also has the following to add around the application of Digital Threads, "It serves as the central reference point for models and data across the lifecycle. The authoritative source of truth will provide traceability as the system of interest evolves, capturing historical knowledge, and connecting authoritative versions of the models and data.".

Lean Digital Twin: A Lean Digital Twin is a Twin created through the principles of benefit and requirements management to enable maximum benefit at minimal costs. Lean Digital Twins often utilise existing infrastructure and software systems, for example on a ship they could use the Integrated Platform Management System (IPMS) as the core twin architecture.

3. Digital Twin Examples

To build on the previous sections high level definitions of the different categories of Digital Twins, this section provides greater detail and examples for each.

3.1 Reference Models

Starting off with category 1 and the simplest of the Digital Twin forms, the reference model. This could take the form of something as simple as a 3D CAD model used to refer back for greater information or for training. An example of this is the BMT virtual walkthrough / design reference models used for training and familiarisation of crew before boarding a large vessel. Rather than trying to learn from 2D maps and or trial and error on the job, a 3D reference model not only provides a convenient way for new crew members to walk around the ship unaided, but it also cost effectively allows for wider training scenarios to be carried out. Although limited to capture changes only when externally initiated, this reference model has a wide range of uses to support the design process and provide significant value to the operators. An image showing an example of a virtual walkthrough is presented in Figure 3.

Figure 3 – Screenshots from BMT’s Aircraft carrier virtual walkthrough

3.2 Product Lifecycle Models

The next category up is a Product Lifecycle Model – similar in a way to the previous reference model but with more rich data included, and critically this toolset is updated through life as changes are made and the system improves.

An existing example is the multiple vessel specific component databases, used to track certification and maintenance on board a vessel, especially popular amongst combat and mission systems. These databases could be expanded to include a much broader range of information. Ideally this information collection and updating would be automated as well to facilitate wider timely information updates.

3.3 Live Representation

The next step up in the category list includes a live feed of sensor data to ensure a continued and trusted input source of information.

An example of the live representation in action is the “research and development of digital twin for ship structure (Phase 1)" project conducted by Japan Ship Technology Research Association (JSTRA) (2023). JSTRA is conducting feasibility studies for the development of basic technologies towards the realization of the “digital twin” models for ship hull structures. Using highly accurate simulation methods, these models reproduce the structural behaviour of actual ships throughout their lifecycle at various stages from design to construction and operation in a computer-driven virtual environment.

However the maritime world is far behind that of what is available for the aeronautical sector, for example, Rolls-Royce has been at the forefront of creating digital twins of their gas turbine engines. By measuring the engine’s condition and ambient environment around it, Rolls-Royce’s digital twin enables engineers at the company’s operational headquarters in Derby to monitor the condition of an engine in flight, for example between London and Jakarta, with the data relayed back by satellite link. This allows them to observe any fluctuations in engine performance that might indicate a component in need of repair or replacement (Rolls Royce, 2023).

3.4 Full Digital Twin

Although real examples of “full” closed loop Digital Twins in the maritime sector are rare, there are a surprising number in the wider world, in applications you wouldn’t normally consider as a Digital Twin. For example, Transport for London (TfL) and Siemens Mobility Limited have recently implemented a new traffic light system in southwest London, which utilizes cutting-edge technology to optimize traffic flow (Intelligent Transport, 2020). The Real Time Optimiser (RTO) system, takes into account a wide variety of data sources to make intelligent, data-driven decisions about traffic signal timings. This system is an example of a "Full Digital Twin," providing a closed loop between live data and operational decision making. In this case, the digital twin is the traffic light system in London, which collects data from all road users and uses it to make intelligent decisions about how to optimize traffic flow. Real term benefits already seen by the system include improving local air quality, reducing congestion, and enabling more people to get around on foot and by bike.

The use of a Digital Twin in London's traffic light system is an exciting development that has the potential to revolutionize how we manage urban transportation. By using real-time data and intelligent algorithms, we can make our cities safer, more sustainable, and more efficient. This technology represents a significant step forward in the field of urban transportation management and has the potential to serve as a model for other cities around the world.

4. The Lifecycle of a Digital Twin

These different definitions of a digital twin are not mutually exclusive, and it is common to see an evolution and transition between the different model types as part of a lifecycle; the following section takes the example of a ship and describes how the twin could evolve over its lifecycle. In the earliest life of the digital twin, it represents something yet to be physically realised. It is, in essence, a very detailed CAD. This design evolves over a number of iterations, where the digital twin forms the basis for deciding and planning changes to the arrangement. Eventually it becomes the blueprint from which the ship is manufactured or a reference model. Now, as a representation of a real system, it becomes a repository for the state of the system, in some circumstances in real time, which enables condition monitoring, decision support, and operational management and observation.

All of these developments are supported by simulations of different types. Early in the design phase, simulation might concentrate on gross issues such as the ship’s seakeeping qualities. Later, virtual walkthroughs might be used to assess and improve human interaction aspects, potentially through the immersive experience provided by virtual reality (VR); see figure 3. Throughout the ship’s life, the simulation is used to predict the ship’s operational characteristics; sea trials provide only a very small window onto the full range of possible environmental conditions. Once the ship is built, virtual walkthroughs provide an obvious first phase of crew training, for example learning standard operating procedures and practising emergency escape routes. Once commissioned, the simulator supports decision-making, by enabling operators to explore the effects of different decisions in a safe environment and over a wide variety of environmental conditions.

Maintaining the digital twin during the operational life of the ship requires data to be fed back from the physical system to the digital. This feedback can be offline, for example condition data uploaded during routine maintenance, or online. With the explosion of Internet of Things (IoT) sensors, condition data can be uploaded in real time, enabling predictive maintenance.

Finally, a simulation can become a full digital twin working as a real-time shadow of the ship. Consider a complicated, expensive maritime operation that is to be undertaken for the first time and in challenging environmental conditions. In the decision support phase, the simulator is used to try out a variety of different approaches. This is followed by a training phase, where the ship’s crew practises the selected approach in the safe and relatively cheap simulator, across a variety of conditions. Then, when the real operation takes place, data is transferred from the ship (or, indeed, multiple ships and other assets) back to the simulator to allow the management team to observe and supervise the operation in real time.

Thus the combination of digital twin and simulation supports the full lifecycle of the ship, through design, build, training, condition monitoring, preventative maintenance, decision support, operational planning and monitoring.

5. Timeline to Digital Twin Implementation

A possible timeline for the development of digital twins in the maritime sector and specifically in defence could involve several stages. The first stage would involve research and development into the key fundamentals of digital twinning and how it may improve decision-making. This stage would also involve developing standards to support the integration of supply chain operations and the development of digital twins for operational enhancement and strategic planning.

The second stage would involve building digital twins at the equipment level and through standards and architectures that allow digital twins to be aggregated. Technology is readily available from industry to enable the adoption of digital twins, but access to data requires planned management and investment (De Gruyter, 2021).

The third stage would involve implementing digital twins in various use cases such as logistics, asset management, and support. This would require a multi-year investment program and an active Defence Community-of-Interest (COI) to support their wide adoption and the creation of an effective Development Framework.

Throughout these stages we will see more and more twins moving up the value chain to the more complex Digital Twin Categories. For example they could move up the chain from Reference Models to Product Lifecycle Models. As you move up the chain the examples are currently increasingly rare but will grow over time.

- Reference Models – Currently predicted millions of examples
- Product Lifecycle Models – Currently predicted thousands of examples

- Live Representation – Currently predicted hundreds of examples
- Full Digital Twin – Realistically only tens of examples

We also however need to be realistic as to which categories of Digital Twin are achievable in the defence sector due to connectivity and security concerns. It may be that a "Live Representation" provides all the core benefits required or that data is stored on a local hard drive for and use by the ships crew or for download whilst alongside. Without the initial development and requirements management it is hard to say.

A common question is "to what level of resolution and fidelity should the digital twin be constructed?" At the very highest level, every single nut, bolt and weld would be captured, leading to a very complex model. The somewhat unsatisfactory answer is "high enough". In other words, they must be high enough to support all current and future uses of the digital twin and simulations based on it.

Overall, the development of digital twins in the maritime sector and specifically in defence has the potential to greatly improve decision-making, reduce business friction, optimize delivery of support, enable decisions to be made more effectively, and speed up investment decision making (De Gruyter, 2021). It will be exciting to see how this technology continues to evolve and shape these industries in the coming years.

6. Ships as Cyber-Physical Systems

Of course, a modern ship is no longer just a physical asset, but a cyber-physical system; it is a complex and fully integrated and connected combination of physical, computational, communicative and control elements (Gill, 2006). In this context, the digital twin no longer represents just the physical structure of the ship, but must also somehow incorporate its software systems, and a simulator that interacts with this digital twin must also interact with its software, blurring the line between digital twin and simulator.

Now the cyber-physical digital twin provides both a new facility and a new challenge. It can be used to test, in simulation, new software updates for the ship's systems, but it can also provide a new route for malign interference in that software, particularly if there is the ability to update the real systems remotely from the digital twin.

Increasingly, "software" includes artificial intelligence (AI) systems, many of which are trained using large sets of data. The initial training data can be generated by the digital twin placed in a suitable simulation, assuming that the resolution and fidelity of these are sufficiently high, and this process will need to be repeated as the physical system changes over time. During the life of the ship, the training datasets may need to evolve as new conditions are encountered, possibly updated with data recorded by the ships' sensors. Now the software updates happen in both directions: new training data sent from the ship to the digital twin, and updated AI models sent from the digital twin back to the ship.

7. Conclusions

In conclusion, it doesn't really matter what you call Digital Twins, as long as it is adding value to your operations or design process. The four categories outlined in this paper can help to pinpoint the complexity and benefits provided by each type and separates lower complexity systems from a "full" digital twin.

It is important to understand that Digital Twins are not just for the future, they are a reality now. The examples presented in this paper show how real Digital Twins are being utilised already. The key to future success is to ensure that the Twin is set out as part of a system, implemented from the start and processes incorporated to keep it alive. A Digital Twin can be built from the concept design starting as a reference model and supporting database but evolving into a category 2 life cycle model as it incorporates updated information from through life support. Additionally the Digital Twin of a ship should aim to be one combined model, rather than having multiple twins for every auxiliary and sub system. This combined methodology allows the full benefits to be obtained but is held back by multiple commercial and IP restrictions.

This paper presents a snapshot in development and in definitions, as time continues as our understanding of these systems grows so too will our definitions. However by outlining and explaining some of these multiple definitions we can hopefully work to demystify the buzzwords for everyone to understand.

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