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Digital Twins for Marine Operations: **From Surface to Deep Water**

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FOREWORD

Welcome to the UK-RAS White paper Series on Robotics and Autonomous Systems (RAS). This is one of the core activities of UK-RAS Network, funded by the Engineering and Physical Sciences Research Council (EPSRC). By Bringing together academic centres of excellence, industry, government funded bodies and charities, the Network provides academic leadership and expands collaboration with industry while integrating and coordinating activities across the UK.

This white paper explores the applications and uses of digital twins for marine engineering. Whilst prevalent in the aerospace and automotive industry, digital twins in the marine sector are a new development, which promise many operational and efficiency benefits. Digital twins are a powerful tool for interacting with robots, which can be rendered vulnerable by the unpredictable undersea environments. However, in order to fully capitalise on this enabling technology, we need to understand the challenges and opportunities for performance improvements. I hope this excellent white paper will enable research and development to ensure the UK can benefit from the future development of digital twins and RAS within marine applications.

The UK-RAS white papers serve as a basis for discussing the future technological roadmaps, engaging the wider community and stakeholders, as well as policy makers in assessing the potential social, economic and ethical/legal impact of RAS. It is our plan to provide updates for these white papers so your feedback is essential - whether it be pointing out inadvertent omissions of specific areas of development that need to be covered, or major future trends that deserve further debate and in depth analysis.

Please direct all your feedback to:
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We look forward to hearing from you!

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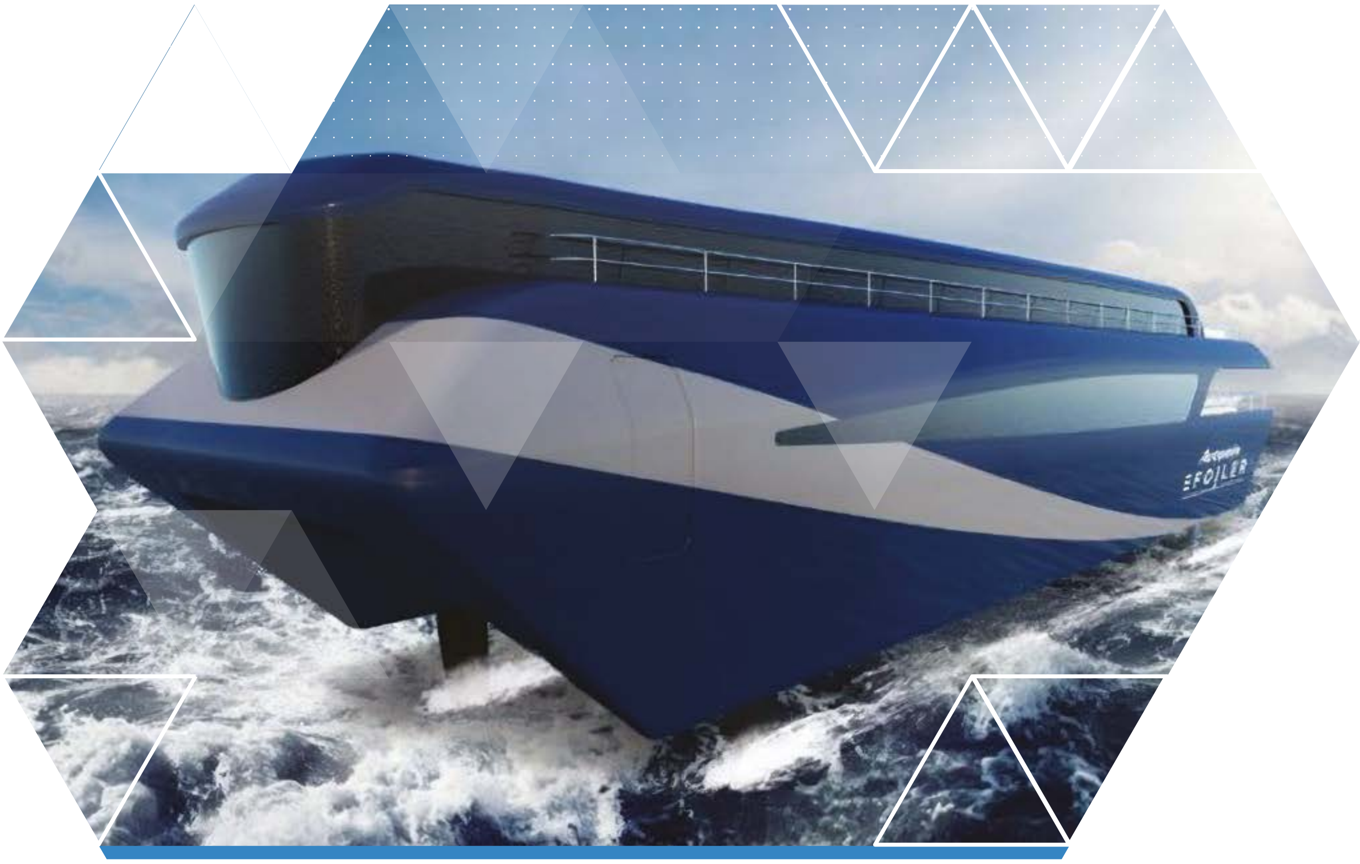
EXECUTIVE SUMMARY

Despite being potentially beneficial for many marine applications, the deployment of robotics and autonomous systems (RAS) such as autonomous underwater vehicles (AUVs), ships, vessels, offshore assets in a marine environment poses many challenges from a safety and reliability standpoint. First, the environmental disturbances can degrade the performance of RAS. Second, RAS are vulnerable to cyber-attacks which can potentially lead to dangerous scenarios by affecting the information transmitted among connected vehicles/devices. In addition, the current state-of-the-art technology of RAS does not allow humans to have access to the real-time life cycle of RAS remotely.

Digital twins are a virtual and identical representation or model, with full characterisation, of a physical product or system. Digital twins are improving operations of many businesses. The worldwide market for digital twin platforms is forecast to reach $86 billion by 2028. Commercially, digital twins have been used in various applications, ranging from facility maintenance to engine modelling to assess system reliability and the response to certain events. Digital twins can also be used to better understand human behaviour in various contexts, such as the impact of high cognitive load, stress, and group dynamics on decision-making, and how individuals, crowds and populations respond to threats and crises. However, there is no formal and consistent definition of a digital twin for marine operations. This is because, when deployed in a marine environment, the existing digital twin models face many unique challenges caused by limited communication bandwidth in an underwater environment, cybersecurity, data quality and trust, model uncertainty and environmental disturbances.

In this white paper, we will explore the challenges and opportunities of digital twins for marine operations and the key enabling technologies (KETs) required to resolve the issues of implementation with digital twins. A brief overview of digital twin research across the UK and use cases of digital twins for marine operations will be highlighted along with key enabling technologies and recommendations for the future development of digital twins for marine operations.



"By combining the virtual and physical worlds in simulations, data can be analysed, and systems may be monitored to prevent unnecessary outcomes, reduce downtime, discover new opportunities, and even prepare for the future [1]."

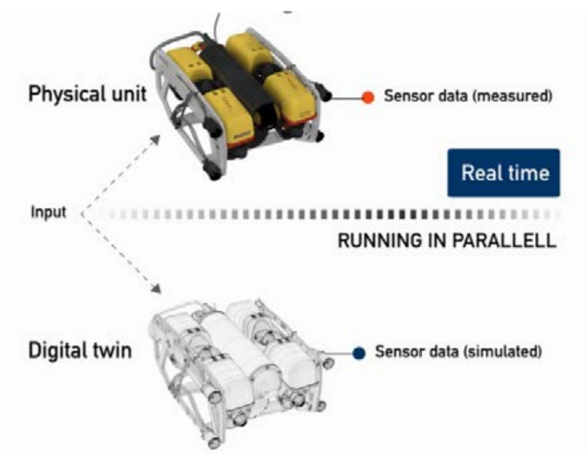
CONTENTS

1. DIGITAL TWINS

System modelling is an approach used in engineering to evaluate the behaviour of a system for different working conditions. Without models, it would be necessary to create the working conditions on the real system, which is usually economically and time intensive. In addition, a model can also be used to design feedback controllers that guarantee certain requirements such as safety, stability, and optimality, which would be prohibitive to do directly on the real system. Clearly, this is possible only if the model provides an accurate approximation of the relationship between the physical variables of interest, otherwise any insights provided by the model are of little relevance for the real system operation. Ideally, the model should be a twin of the real system, so that any change and analysis of the real system can be performed on the digital copy within a short time and with minimal economic costs.

Digital twins (DTs) are known as a key enabling technology (KET) to enable the performance of the digitalisation. The original concept of a DT was proposed by Michael Grives from the University of Michigan in 2003 [2]. The DT was then publicly promoted by the National Aeronautics and Space Administration (NASA) and applied to space exploration in 2012. Nowadays, the DT concept is key to unlocking the potential of digital transformations for many industries, ranging from manufacturing, aerospace, agriculture, healthcare and marine, etc [3].

The digital twin concept is varied by users and use cases. The most common definition of a DT can be understood as: “a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning, and reasoning to help decision-making” [4]. A DT originally comprises three components: the digital (virtual part), the real physical product, and the connection between the digital and physical parts [2]. As illustrated in Figure 1.1, this DT model is made up of three main components: (1) a model (virtual twin), i.e., Component 1; (2) a bi-directional flow of data between the physical system and the model, i.e., Component 2; and (3) a model update so that the model changes over time according to the physical system, i.e., Component 3. Lately, a DT has been extended to five components to include data and service as a part of a DT [5].



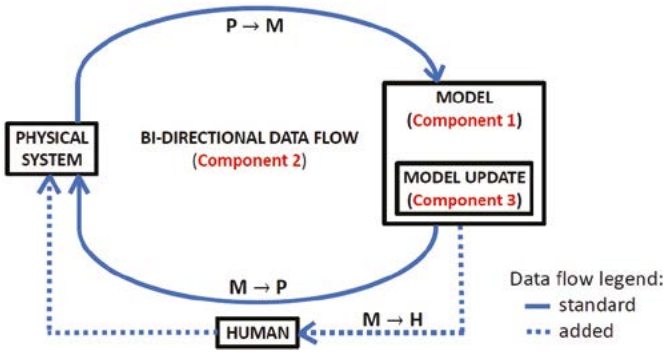


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FIGURE 1.1:
Diagram of the main components and the data flows of a digital twin.

2. CAPABILITY LEVEL

The capability of a digital twin (DT) is determined based on what features are and are not embedded in a DT model. Typically, the capability level of a DT can be ranked on a scale from 0 to 5, where: 0-standalone, 1-descriptive, 2-diagnostic, 3-predictive, 4-prescriptive, and 5-autonomous [6].

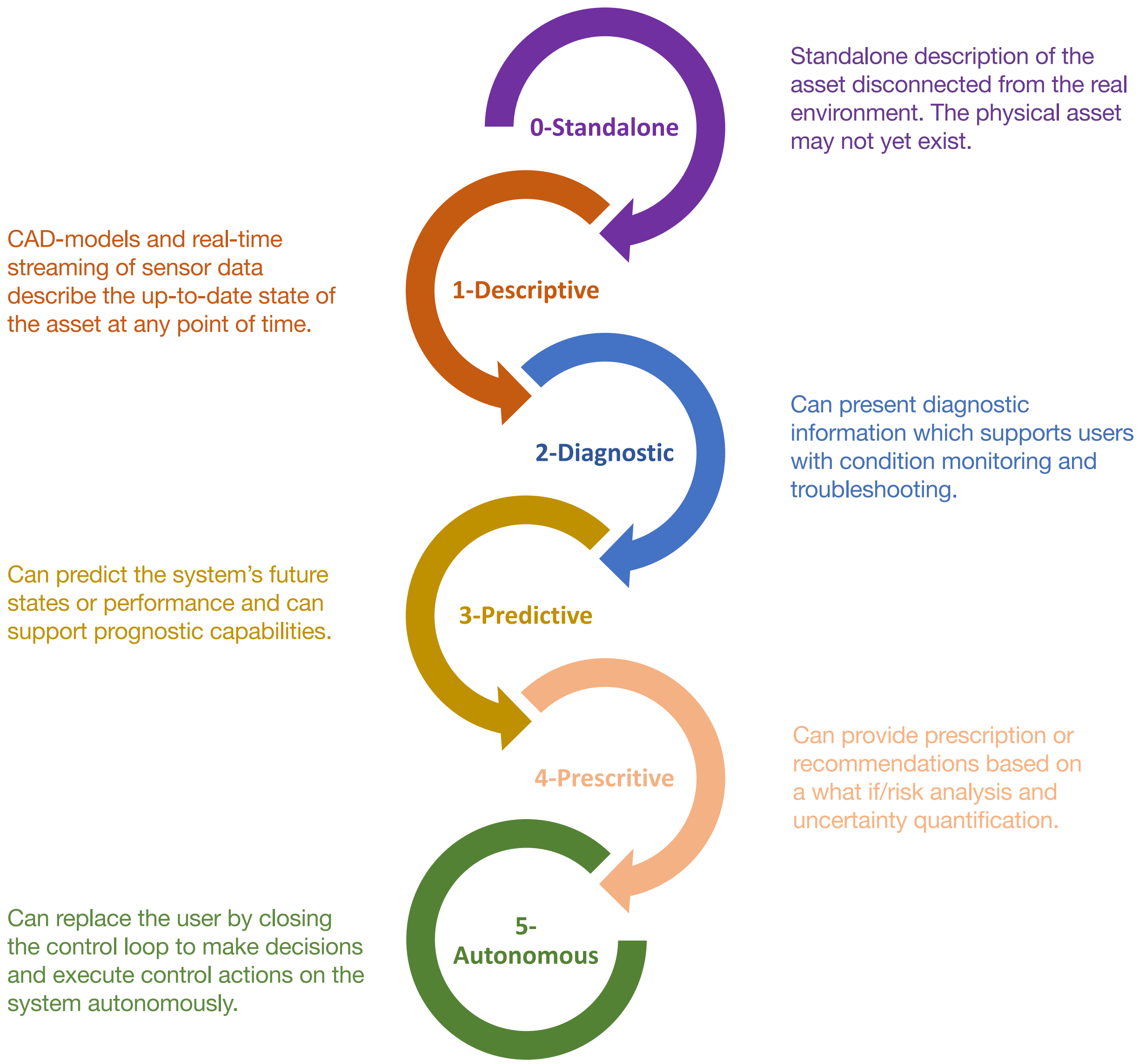


FIGURE 2.1:
Capability level of digital twin

3. APPLICATIONS OF DIGITAL TWINS

Digital twins can be used for system prediction, system simulation, asset interoperability, maintenance, system visualisation, and production simulation [7]:

3.1 SYSTEM PREDICTION:

Using both historic and real-time data, these digital twins can predict the behaviour and future state of a physical system. Predictive digital twins can be used to estimate life cycles of the physical assets.

3.2 SYSTEM SIMULATION:

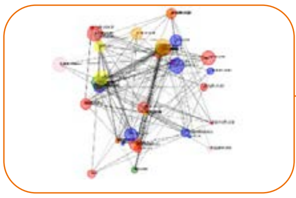
Building upon the mathematical formulations, physics property of the physical assets and engineers' experiences, these digital twins can simulate the interactions between interdependent and interlinked variables of complex systems. These allow engineers to test "what-if" scenarios in a large-scale setting.

3.3 ASSET INTEROPERABILITY:

Asset interoperability twins can extract multiple data from assets along various dimensions, including asset features, characteristics, properties, statuses, parameters, measurement data, and capabilities.

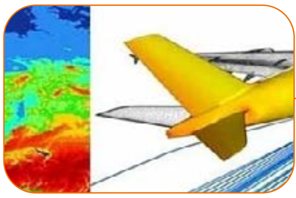
3.4 MAINTENANCE:

These digital twins can predict the life cycle and estimate the remaining useful life (RUL) of the assets. These information can assist maintenance personel to plan ahead any maintenance or repair tasks by providing them with in-depth information about the physical asset or system.



3.5 SYSTEM VISUALISATION:

These digital twins are used to visualize a system during its "operating" life cycle phase. These digital twins can also act as virtual sensors to measure and display the variables or key performances, which could not be measured by physical sensors directly.



3.6 PRODUCT SIMULATION:

Digital twins can generate different design models of a potential future product to examine the feasibility of the design models. This will help to eliminate the need to build costly prototypes and allow for quick testing of thousands (in some cases millions) of product variances.

4. DIGITAL TWINS FOR UNDERSEA OPERATION

For undersea operations, a DT can be deployed for four main applications:

Simulation and Design: Digital twins can be used to simulate the physical assets working under different harsh conditions [8]. They can be utilised to optimise the design parameters of the physical system. They can also be utilised to train individuals using 'what if' scenarios. For example, for offshore floating wind turbine, simulating workload and the effects of turbulent flows can help to select the optimal parameters for mooring systems.

Condition monitoring: Digital twins can be used in real time (or near real-time) to monitor and predict internal changes, or damage under the effects of environmental disturbances [9]. They can be applied for predicting the remaining useful life (RUL) of a physical asset. For example, a digital twin of a mooring line for an offshore floating wind turbine can be used to predict excessive tension when more severe environmental conditions like storms and/or hurricanes occur.

Adaptive control: Real time adaptive control based on the feedback of a digital twin has rarely been deployed, but obviously it is a prominent advantage of digital twins for marine vehicles such as Remote Operating Vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs) [10]. For example, AUVs and ROVs inspecting an offshore floating wind turbine can be severely affected by environmental disturbances such as turbulent flows that make the control of AUVs and ROVs challenging. By using a digital twin to predict the effects of turbulent flows in real-time, it is possible to design learning techniques and robust controllers for the vehicles to reduce the effects of environmental disturbances.

Verification and Validation: Digital twins can be applied for verification and validation. There are three main approaches that use DTs for verification and validation (V&V): exploratory investigation, testing and formal proving [11].

Credit: Babcock International

5. CHALLENGES

Digital twins technology has many advantages as discussed in the previous sections. However, the technology currently faces many challenges in model selection, communication, computing, sensors, plus the dynamic and unstructured undersea environment. These challenges have been discussed during the ‘The First Robotics and Digital Twins workshop’ held in May 2023 at the Queen’s University Belfast and are as follows:

- **Model Selections:** DTs are virtual representations of a system within an ecosystem. It is used to model and predict a system’s performance and degradation through its life cycle. One of the challenges for DTs is to select adequate models of the twin that accurately predict the performance of the physical system under the effects of internal changes and external disturbances, while satisfying the system physical constraints such as computing capacity and communication limits [12].
- **Communications:** The traditional industry application of digital twins relies on robust and continuous communications with the deployed system. In marine environments, the communication signals will be affected by external disturbances like currents, aquatic life, waves and winds, which affect the communication signals. In addition, underwater wireless communication is limited in both bandwidth and coverage, which impose greater challenges for undersea applications such as AUVs and cabling/mooring systems. Presently, data rates for the acoustic uplinks from commercially available modems are limited to <<40kbps over an 8 kHz bandwidth and carrier frequencies below 20 kHz and ranges up to 3 km. Alternatively, for shorter range (<<300 m) and frequencies between (120-180 kHz), data rates up to 62.5 kbps are available; however, relaying is required to achieve larger coverage [13], [14]. While these bandwidths might be good enough for navigation and control of underwater

vehicles, higher communication bandwidth is necessary to enable the applications of digital twins for undersea environments due to the requirements of condition sensors and extra information requirements to provide additional information used in decision making.

- **Computing:** The utilisation of the DT requires a parallel utilisation of models and sensor readings in real-time or near real-time. The virtual part is usually built based on a high-fidelity simulation model, for example based on finite element methods for mooring system, CAD models for ship/vessel design, etc, which are usually very time consuming [15]. For an application such as real-time life cycle modelling and adaptive control, real time computation for the simulation model is necessary leading to the incorporation of machine learning, reduced order modelling, high performance computing and artificial intelligence to provide an accurate model that is able to simulate in near real-time.
- **Sensors:** Ideally, DTs can capture every aspect of what is happening within the physical asset of its surrounding environments. Therefore, to capture changes in the physical asset to update the models within the DT, a network of sensors needs to be in place [16]. How to select the sensors and their locations to measure the responses of physical assets is a challenging issue, highly dependent on the required information and system specific issues. Additionally, managing the deployment and maintenance of so many sensors is complex and time consuming.

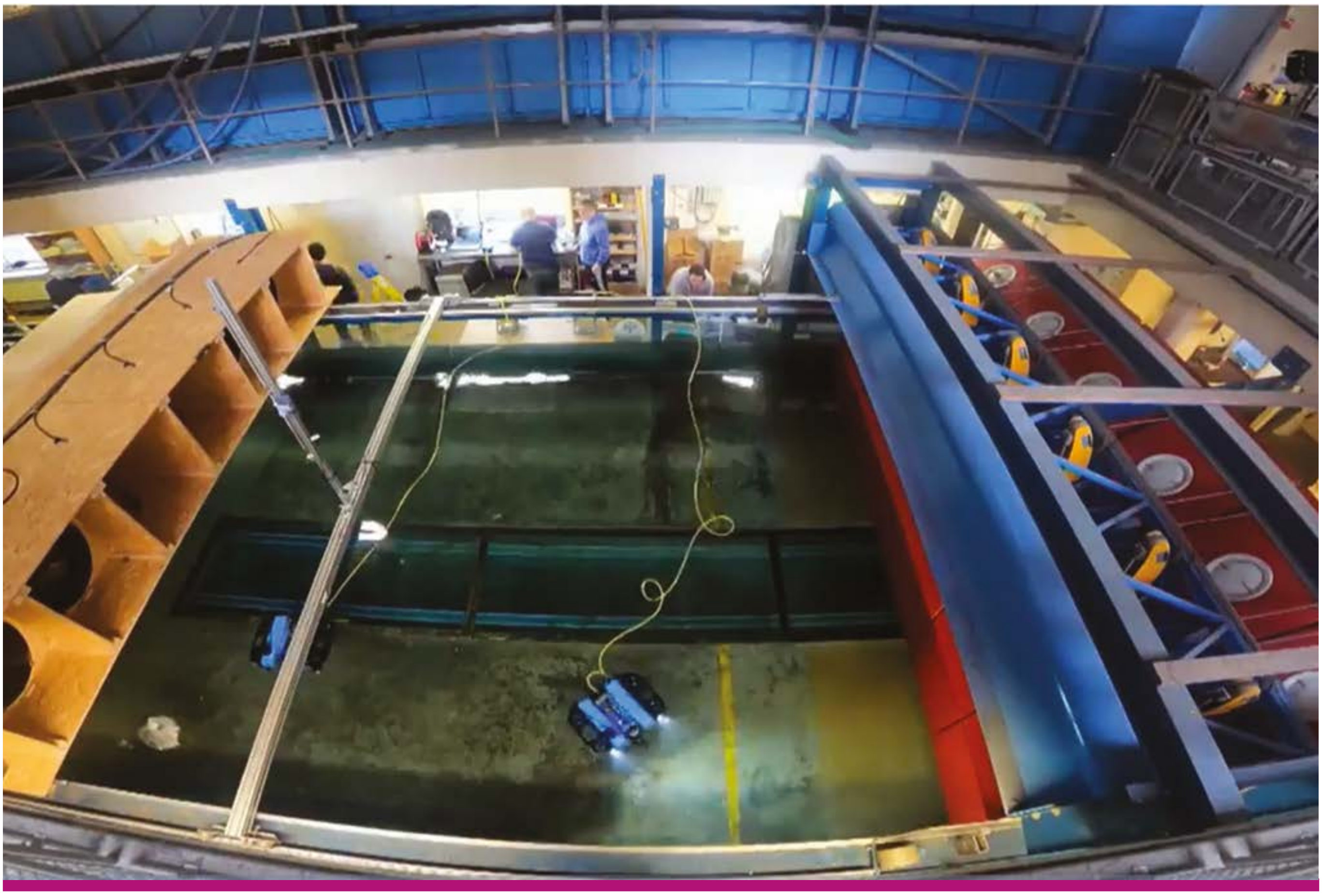


FIGURE 5:
Testing multiple collaborative autonomous vehicles at Queen's Marine Laboratory

- **Dynamic and Unstructured Undersea Environment:** The underwater environment is highly nonlinear and unstructured. The effects of wind, waves and currents are interdependent and are difficult to measure, model and predict [17]. Therefore, it is difficult to model a marine environment and its effects on the physical twin. Available information and maps of the undersea environment and sea floors is scare; until now, only 10-15% of sea floors have been mapped. Therefore, building a digital twin model for undersea inspection is challenging.
- **Verification and Validation:** Verification and validation (V&V) are two complementary techniques that help to ensure that digital twin models are correct and credible. Verification is the process of checking whether digital twin models are built according to the specifications and requirements that have been defined prior or not [18]. Validation is the process of checking that digital twin models are consistent with the reality that they represent. However, it is difficult to quantify the uncertainty of undersea environment due to the limits of sensing, quality data and information.
- **Trust:** DTs have both technical and non-technical challenges. The main non-technical challenge is the construct of trust for both the components and the whole of a DT. Components can quantify the quality, and thus trust, using uncertainty quantification via a multitude of various techniques [19]. A smaller uncertainty suggests that the component/data/simulation is trustworthy. However, the trust of DTs is complicated for analysis due to the multiple sources of uncertainties [20]. For the DT, there are digital factors such as cybersecurity and data ownership, while the physical factors include the incorporation of Human-in-the-Loop operations and other various safety factors. As DTs expand from laboratory demonstrations into industrial applications, this concept of trust becomes a large concern for system owners. A trust-aware DT can be created by the inclusion of simple and clear documentation, user-based design (especially for the user-interface) and the expert generation of specific models.

> “Instead of interacting with physical assets in hazardous environments such as an underwater/seabed environment, the human can now interact with the physical assets via digital twins.”

6. KEY ENABLING TECHNOLOGIES

To construct a DT, a variety of enabling technologies should be implemented. At 'The First Robotics and Digital Twins workshop', participants discussed the main key enabling technologies for digital twins that include high performance computing (i.e., reduced-order models), internet of things (IoTs), cloud computing, machine learning and artificial intelligence, sensors, and automation and autonomy.

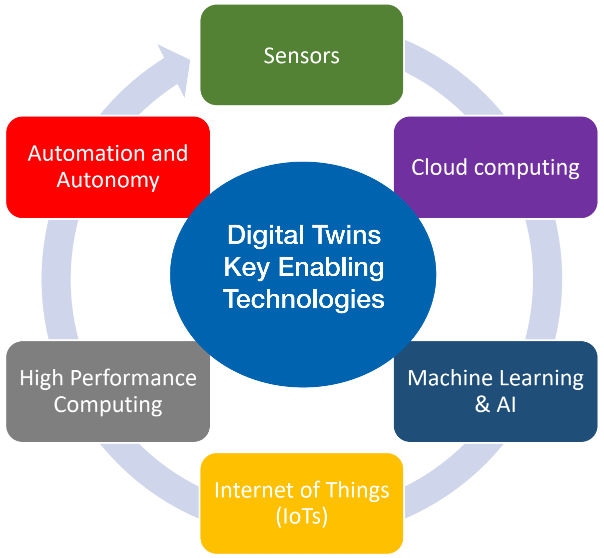
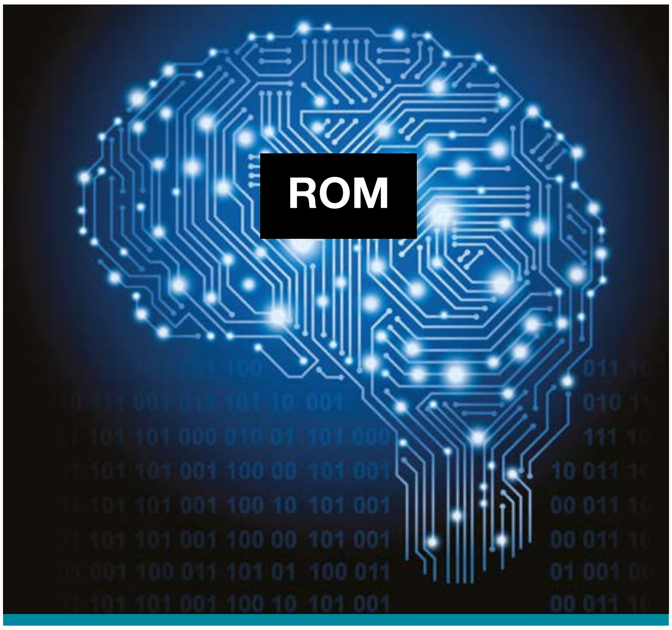


FIGURE 6.1:
Key enabling technologies for digital twins

6.1 REDUCED-ORDER MODELS

Limitations in communication and the low computing resources of underwater vehicles are the main challenge of underwater applications of digital twins. Reduced Order Models (ROM) refer to a variety of techniques used to reduce the computational complexity of mathematical models in numerical simulations [21].

ROMs are developed based on a mathematical description of a system that has been trained, verified and validated to match known real-world behaviours within a specific set of bounding or operating criteria. ROM invests computational time during an offline operational phase to select reduced-models, which can best represent the full-order models while reducing the computation for real-time or near real-time execution; these reduced models then can be verified and validated rapidly during an online operational phase. Typically, ROMs are low fidelity approximations, or reductions, of a system, usually used to predict specific behaviour of a system, or parts of a system in real-time [22].



6.2 HIGH-PERFORMANCE COMPUTING

To enable real-time execution of digital twin, high performance computing (HPC) serves a vital role. HPC supports the distributed computing pipeline that goes into creating digital twins, ingesting and processing sensor data, merging it with diverse sources of enterprise data, analysing it to deliver actionable insights, and visualising it to promote rapid responses [23].

Some commercial HPC platforms are available for users to design digital twins. The accelerated digital twin platform for scientific computing consists of the NVIDIA Modulus AI framework for developing physics-ML neural network models, and the NVIDIA Omniverse 3D virtual world simulation platform [24]. According to the company, the platform can create interactive AI simulations in real time that are physics-informed to accurately reflect the real world, for example, accelerating simulations involving computational fluid dynamics up to 10,000x faster than traditional methods for engineering simulation and design optimization workflows. It enables researchers to model complex systems, such as extreme water events, with higher speed and accuracy when compared to previous AI models.

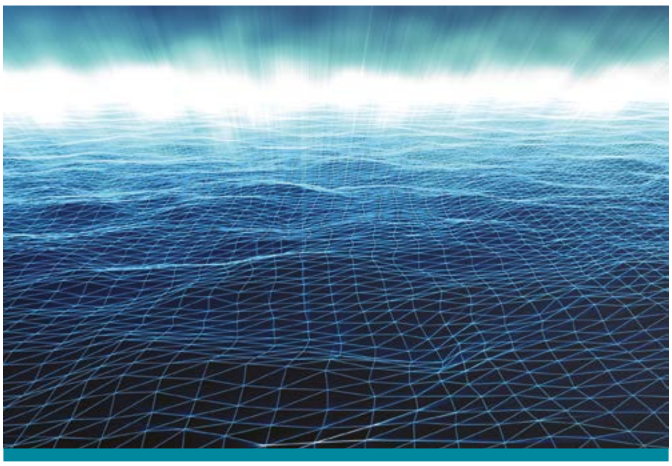
6.3 INTERNET OF THINGS (IOTS)

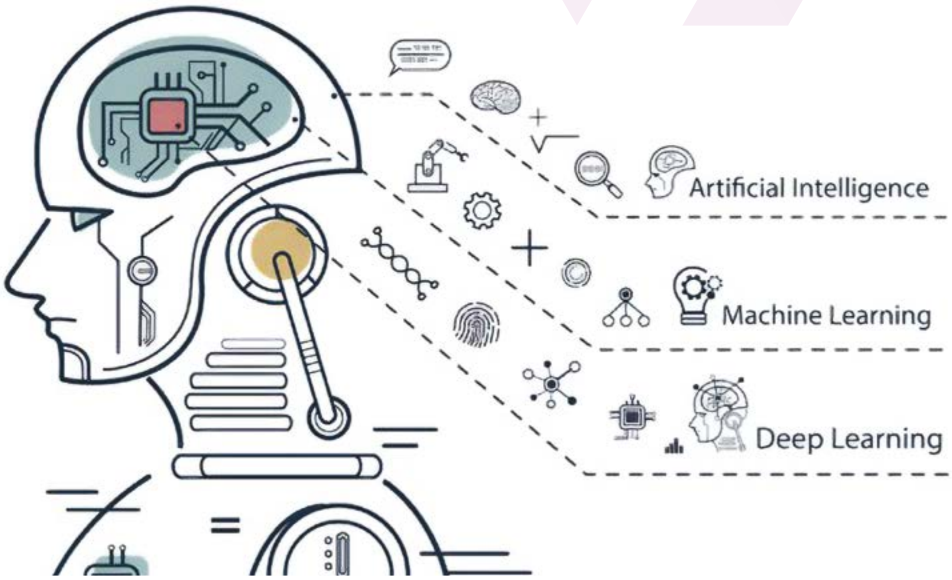
DTs aim to model every aspect of a target physical asset and its surrounding environments. This requires a lot of data to be collected for building the DT models, which, however, is a challenging task. IoT sensors can help to solve this problem. By collecting data from multiple sensors and devices, IoT can provide rich and updated information about the physical assets and its surrounding environment. Data collected by IoT devices is then standardised and delivered to the central server or cloud, where it can be decoded for utilising in different use cases including digital twins. The Internet of Underwater Things (IoUT) is an emerging communication ecosystem developed for connecting underwater objects in maritime and underwater environments. The IoUT technology is intricately linked with intelligent boats and ships, underwater vehicles/robotics, monitoring sensor networks, automatic marine transportation, positioning and navigation, underwater exploration, disaster prediction and prevention, as well as intelligent monitoring and security [25].

6.4 CLOUD, FOG AND EDGE COMPUTING

Cloud, fog, and edge computing can be an ideal platform for sharing and distributing data for digital twins [26]. Cloud computing provides a scalable and cost-efficient platform for data storage and processing, where the users around the world can have access into it from servers, via the internet. Fog and edge computing are the extensions of cloud computing. Fog nodes are distributed computing entities, formed by at least one networked physical processing device, able to execute distributed tasks. Edge computing moves processing nearest to where it is needed, allowing computation closer to the source, reducing cloud traffic and service latency, improving response times [27].

Implementing digital twins using cloud, fog and edge computing can reduce connectivity and latency issues in networks. This enables more collaborations and data sharing between multiple stakeholders in the maritime industry in a cybersecure setting.





6.5 MACHINE LEARNING AND ARTIFICIAL INTELLIGENCE

Digital twins require a high-volume of data to be exchanged between digital and physical twins. Machine learning and AI will be very important for analysing the data. Machine learning can be used to learn the simulation model and compensate the mismatch between the physical twin and digital twin. The predictability of machine learning techniques such as neural networks can be employed in the digital twin to improve the prediction capacity [28]. AI can enhance digital twins in many ways. It can merge the sensor data with physical model to construct the digital twin model. When the system does not have enough data for training, the digital twin model can generate a new training dataset, and machine learning can be applied to combine it with sensor data for application purposes.

6.6 AUTOMATION AND AUTONOMY

The underwater environment poses a high risk for humans to collect data for building a DT model. Robotics and autonomous system technologies can replace humans for such dangerous tasks in harsh environments. Multiple collaborative and connected robotics or devices or underwater vehicles can improve the performance of underwater inspection and surveying. Digital twin marine vehicles will be essential to understand, train, certify and maintain such autonomous systems, where large-scale simulations of complex operational scenarios will be needed [29]. The use of the digital twins to certify systems/modifications to systems, will require the inclusion of regulatory committees in the design, validation, and utilisation in a trustworthy collaboration.

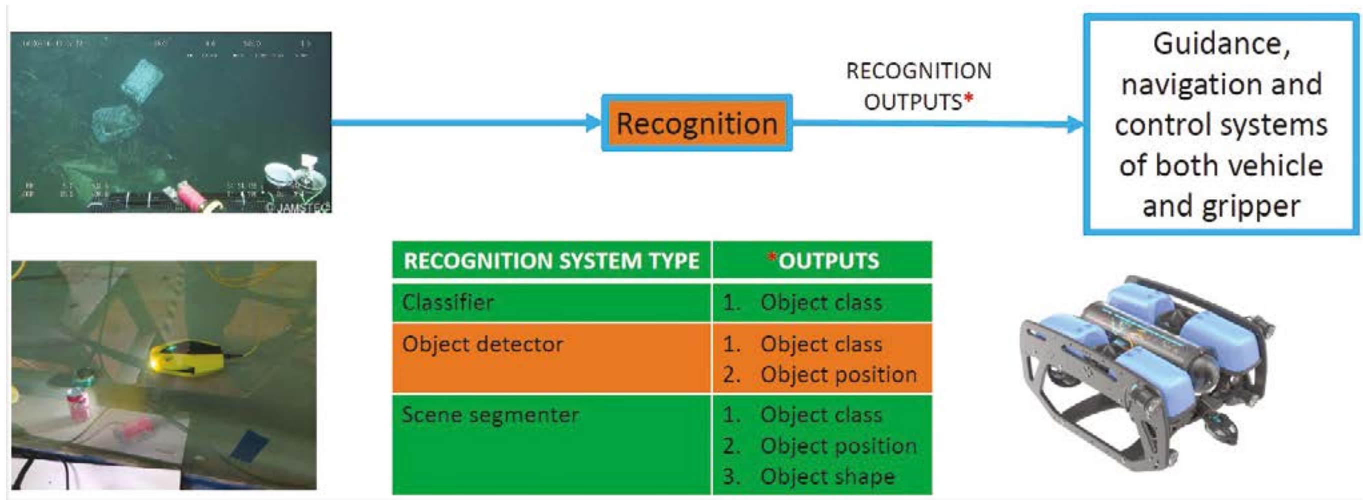


FIGURE 6.6:
Marine debris detection and cleaning using autonomous underwater vehicle.

7. A BRIEF OVERVIEW OF DIGITAL TWINS RESEARCH ACROSS THE UK

In the UK, the research on Digital Twins has just started recently, and is mainly applied to manufacturing. The National Digital Twin programme (NDTp) was run by the Centre for Digital Built Britain, a partnership between the University of Cambridge and the Department for Business, Energy and Industrial Strategy. Launched by HM Treasury in July 2018, the NDTp was set up to deliver the key recommendations of the National Infrastructure Commission's 2017 'Data for the Public Good Report' [30]. The Digital Twin Hub was created in 2020 by the centre for digital Britain at the University of Cambridge [31]. It is a place for learning and sharing experiences; for driving innovation, developing expertise and advancing the state of the art for digital twins. It identifies good practice, develops guidance and shapes standards on data sharing as well as showcasing the benefits of collaborative, connected digital twin endeavours.

The Digital Twin methodologies have been applied for optimizing critical parameters of a complex maritime site, Her Majesty's Naval Base (HMNB) Devonport, by the University of Plymouth [32]. To realise the potential of digital twins there is the need to understand their essential underpinning infrastructures and capacities. A consortium of experts, led by the UK's National Oceanography Centre (NOC), have published 'An Information Management Framework for Environmental Digital Twins (IMFe)' which outlines the building blocks to allow the digital twin community to realise the potential of environmental digital twins. A recently funded EPSRC programme 'Digital Twins for Improved Dynamic Design' led by the University of Sheffield, aims to deliver the transformative new science required to generate digital twin technology for key sections of UK-industry: specifically, power generation, automotive and aerospace [33]. The Alan Turing Institute has initiated a digital twin program for AI in digital twins, namely 'The Turing Research and Innovation Cluster in Digital Twins' [34]. Digital twins have been extensively developed for robotics in the UK, but mainly for manufacturing robotics: for example, research from the University of Sheffield [35]. Developments of digital twins for underwater robots have received attention recently, from the groups from Queen's University Belfast, University of Manchester and ORCA [36].

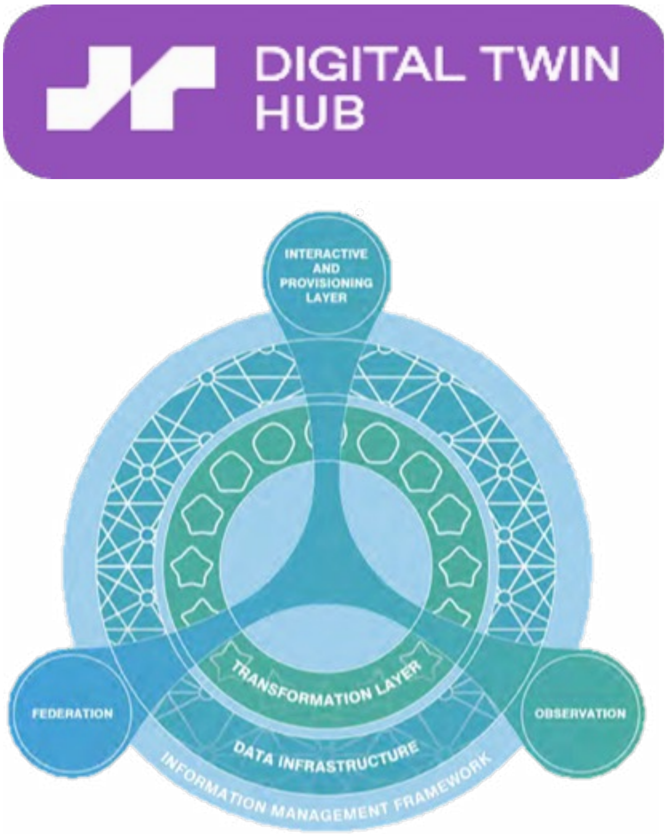


FIGURE 7.1:
Digital Twin Hub

8. USE CASES

To illustrate the concepts and applications of digital twins for marine operation, in this paper, we will describe the uses of digital twin for three use cases:

- Use case 1: Control of launch and recovery in enhanced sea-states
- Use case 2: Distributed resilient control of multiple collaborative AUVs via Digital Twins
- Use case 3: Trust Aware Digital Twins for Marine Engineering

8.1. USE CASE 1: CONTROL OF LAUNCH AND RECOVERY IN ENHANCED SEA-STATES

The goal of the "Launch and Recovery Co-Creation Initiative" funded by EPSRC is to extend the range of sea states in which existing wave limited maritime operations can be safely carried out. Important examples of these operations are the launch and recovery (L&R) from a mother-ship of small craft, manned and unmanned air vehicles and submersibles [37].

In the L&R task, the small craft is launched and connected to the mother-ship by a cable, and the hoisting process is achieved by a crane fixed on the mother-ship. The movements of both the mother-ship and the small boat are subject to wave forces. Once the two crafts are physically connected, the operator is committed to wait for a proper time instant to initiate the hoisting process. Key constraints applying to the proposed system are as follows. First, collisions between the mother-ship and the small boat should be avoided. Second, the terminal cable velocity of the hoist cable should be zero for safety reasons and the hoisting time should be short to ensure fast recovery. Finally, overlarge swing angular velocities should be avoided for comfort and safety concerns.

In this project, a digital twin is used to model and predict the collision between mother-ship and small craft. The DT will take the inputs of the enabling technologies of: (i) predictive wave environmental data; (ii) the associated predicted wave driven vessel motion information; and (iii) a real time decision support system for vessel operators responsible for L&R.

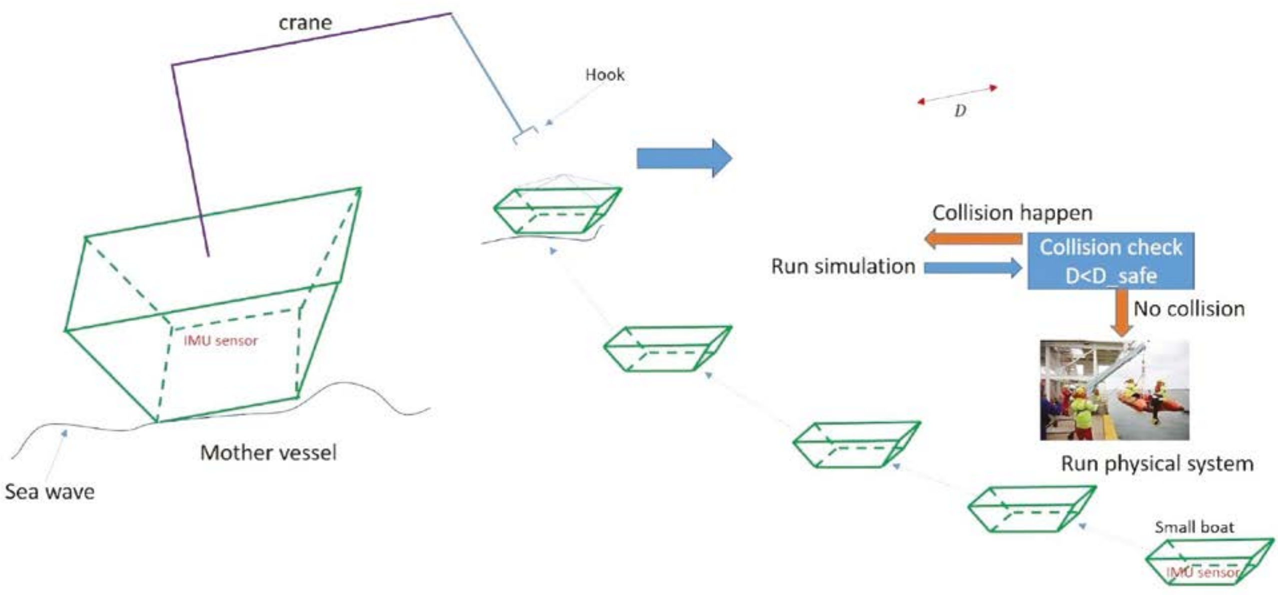


Figure 8.1
Illustrating the launch and recovery process

8.2. USE CASE 2: DISTRIBUTED RESILIENT CONTROL OF MULTIPLE COLLABORATIVE AUVS VIA DIGITAL TWINS

This case study was investigated as part of the project 'AI-Enhanced Digital Twin for Multiple Collaborative Underwater Vehicles' funded by The Royal Society, and the project 'NERC-MOST: Development of Homogeneous Unmanned Marine Vehicles for Monitoring and Removing Marine Debris' funded by NERC (UKRI), led by Queen's University Belfast.

The aim of the distributed resilient control is to identify a decision-making strategy that enables vulnerable mission capabilities to be extended beyond mission targets to meet the real-time requirement, whilst maintaining the safety requirements of the system. Given the mission profile and the inputs of the predicted system's life cycle obtained from a digital twin, the overall long-term system performance is simulated, and used to optimise the control effort allocation strategy. The human-machine interaction model through the digital twin is developed to characterise how human operators determine their behaviour when encountering faults/failures of the autonomous systems.

In this model, the situation and health condition and the corresponding mitigation approach can be taken as the inputs of a simulation. The DT will provide an insight into the future that predicts the propagation of faults/failures and estimates the remaining useful life (RUL) of the system. Through this mechanism, at run time, the systems have a preview of what lies near and far ahead. Leveraging this information will improve the performance of AUVs while providing strong guarantees on their safety.

Based on the estimated RUL, an optimal task allocation strategy can be designed to assign tasks for the healthy components and faulty components in the system so that the mission can be extended to meet the requirement of timeliness. The operator can interact with the underwater robot's team through the DT, where they can observe the operation and the health condition of the autonomous agents. Acknowledging the health condition of autonomous agents online allows the operator to guide safety decision making, to guarantee the safety of the system when a failure occurs in the system.

FIGURE 8.2:
Case use of digital twin for Distributed resilient control of multiple collaborative AUVs

> Digital twin could assist the operational commander in better understanding the situation of unmanned assets, particularly in the presence of faults, failures or reduced or no communications.

8.3. USE CASE 3: TRUST AWARE DIGITAL TWINS FOR MARINE ENGINEERING

This use case was studied as an extension to the outcomes of the EPSRC funded project ‘Digital Twins for Improved Dynamic Design’ led by the University of Sheffield.

The goal of creating trust aware digital twins for marine applications is to provide accurate and understandable information used for decision making. For critical marine applications, such as submersible infrastructure repair robots, submarines, and submersible communication devices, the reliability of the information regarding the systems is paramount. This is particularly true for the examination of “what if” scenarios used for decision making, such as trajectory planning, repair scheduling, and energy management, due to the amplification of uncertainty. The decisions regarding these scenarios typically require a multidisciplinary approach with multiple experts. For example, determining where the repair robot will go next involves the evaluation of the internal energy/battery, prioritising locations based on damage, and if there are any other robots deployed and their trajectories.

The desire to create a trust aware digital twin is for multiple purposes. The first desire is the time reduction for decision making, thus saving money in operation and possible damage repair. When a decision maker requires information, they would typically require a conversation/inquiry to individual experts for information that needs to be compiled together. The time to gather this information is highly dependent on a wide variety of factors such as holiday/sick leave, personnel availability, and the difficulty of gathering the information. A trust aware digital twin can severely reduce this time by the inclusion of expertly made components that would replace the experts in the generation of the information used for decision making, allowing the experts to develop novel systems and perform more manual tasks. Another main desire, particularly for long-lived systems where the original designers and experts retire during the life of the system, is the inclusion of historical expert knowledge. When an expert is no longer available to be contacted, the trust aware digital twin can act as a knowledge base left behind by the experts. This knowledge base, along with the user-focused design of the digital twin, provides a degree of trust for the simulations, sensor data, generated information, and the digital twin as a whole.

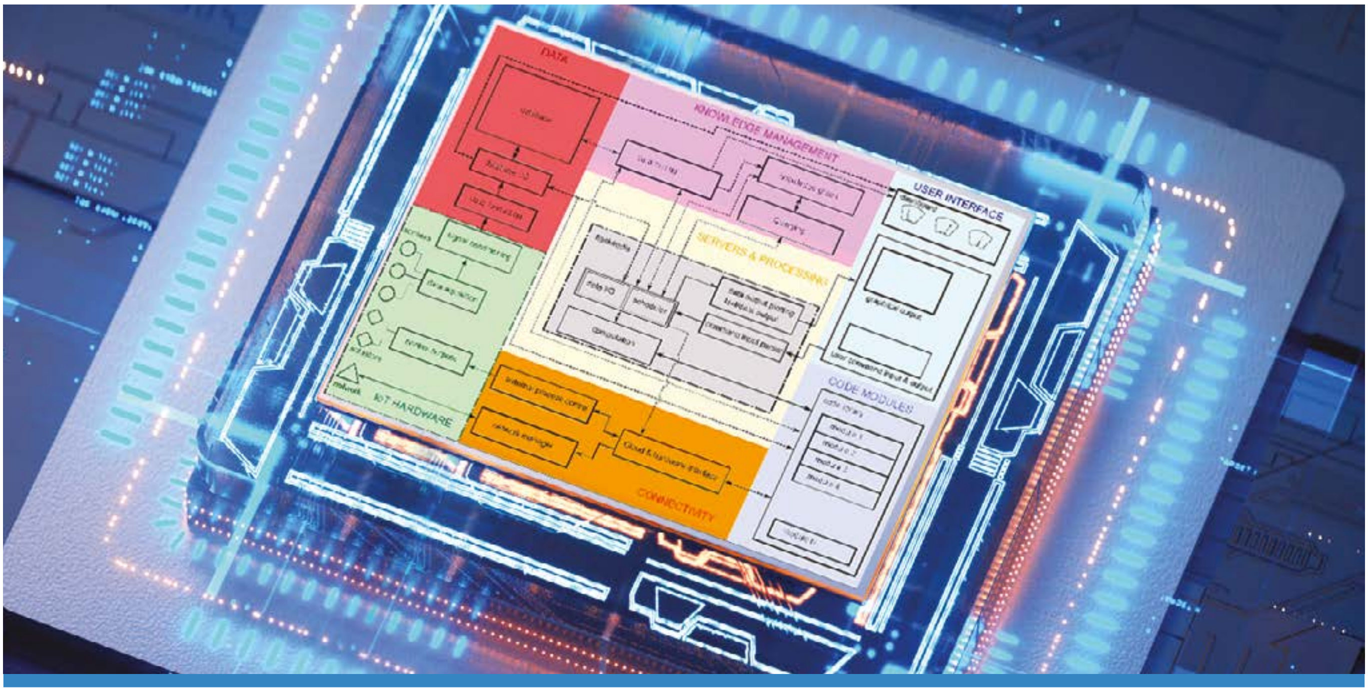


FIGURE 8.3:
A schematic diagram for trust aware digital twin design

9. FUTURE ENABLING TECHNOLOGIES OF DIGITAL TWINS

To gain full advantage from introducing common digital platforms some important factors must be in place:

Data

Digital twins require a high volume of data communication between the virtual and digital twin. Issues related to data such as trust, privacy, cybersecurity, convergence and governance, acquisition and large-scale analysis need to be addressed.

Synchronise Protocol and Standards

Digital twins involve a wide range of technologies and tools that are invented or developed by different companies/experts. Inevitably, there are different protocols and standards, for these technologies and tools. To enable these technologies and tools to work together, data and models should be standardised and delivered in common formats/languages, protocols and standards.

Consultancies

Digital twins for the marine industry will require specialised consultancy services. They will need support from industry with modelling (hydrodynamics, structures, process optimisation, machine performance, control systems and logistics), data management (storage, update, etc), visualisation (static and dynamic models) and identifying applications.

Communication Network

The enabling technologies of autonomous underwater vehicles and underwater communications are well short behind their counterparts in ground and air due to the challenges of wireless underwater communications. This is the major barrier that prevents the development of digital twins for underwater assets and operations. Therefore, there is a need to build faster and more efficient communication interfaces such as 5G, 6G for underwater environments.

Safety and Trust

Human trust in autonomous systems must be fully understood. Performance factors contribute the most to the loss or maintenance of trust in the system, and when and how to engage autonomous features during abnormal conditions and cyber-attacks will need to be investigated.

Public Acceptance

Applying digital twins for enhancing the autonomy of marine vehicles needs to demonstrate significantly higher safety levels for both humans and vehicles. How to integrate human interaction into the DT loop so that human can have access to the life-cycle model of autonomous systems and interact with autonomous systems in real-time and remotely needs to be justified not only from an efficiency point of view, but also from assuring safety and trustful interactions.

10. SUMMARY AND RECOMMENDATIONS

This white paper has outlined the potential applications and uses of digital twins for marine operations. The challenges, key enabling technologies of digital twins and an overview of research across the UK on digital twins were highlighted.

Finally, in conclusion, some recommendations for future directions and investment in digital twins for marine engineering based on an analysis of existing capabilities are:

- Autonomous systems, robotics and sensors: The design of digital twins requires a good understanding of the physical model and its environment. This is, however, difficult to obtain for an undersea environment. Therefore, more research on autonomous systems, robotics and sensors, undersea surveying technologies for marine engineering needs to be carried out to gain understanding of the undersea environment.
- Underwater communication: In contrast to their counterparts in ground and air, digital twins for underwater operations are heavily affected by environmental disturbances such as wind, waves and currents. Using artificial intelligence (AI) and different levels of automation for handling environmental disturbances should be promoted. The current wireless communication technology for underwater environment is well below the actual requirement of data transmission of the digital twins. 5G/6G technologies therefore need to be investigated further for the challenges associated with the underwater environment.
- Human Factors: Human behaviour and humans in the loop, including equality, diversity and inclusion (EDI), ethics, and trustworthiness have not been considered and addressed well when promoting digital twin research. To reach the full potential of digital twins for replacing humans in safety critical applications, human factors in digital twins and humans-in-the-loop digital twins need to be initiated and investigated further.
- Open-source industrial settings: The incorporation of digital twins in open-source industrial settings should be promoted to provide an immense amount of information for researchers on identifying how to design impactful research, and incentivise industry partners to incorporate modern technology in an agile fashion. Researching digital twins (as a whole) is reaching the apex of applicability and will only move forward through the development of key technologies (as traditional research) and system-specific issues that can only be identified through use-cases.
- Strategic planning and investment: For the UK to reach its potential in this area and to be competitive, it will be necessary to invest more on highly skilled people, research excellence, and research infrastructure across multiple disciplines and places. Strategic planning and investment from the UK government for multi-institute projects or programme grants on digital twins needs to be made for the development of infrastructure and research across the UK.
- Pushing key enabling technologies: The success of digital twins relies on the maturities of the key enabling technologies such as simulation techniques, AI/ML, high-performance computing, cloud-fog-edge computing, robotics and automation, etc. The research on the key enabling technologies needs to be pushed further and investigated together.

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