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A Standards-Based Digital Twin of an Experiment with a Scale Model Ship

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ABSTRACT

We propose the use of existing data standards and web technologies to modeling and development of digital twin ships. Our research provides an open framework that can be linked to services such as visualizations, simulations and remote control. The case study applies the standards-based framework to an experiment that involved a scale model ship equipped with a dynamic positioning system under artificial waves. The digital twin prototype illustrated the capability of mirroring and controlling the model's position in real-time, and predicting motion responses across wave conditions via a web application. Thus, it closes the loop between test and design in the life cycle by allowing validation of results in comparison to empirical data during operation. The results from these experiments are used to discuss an expanded version of the digital twin for validation and optimization of motion response, as well as its implications to the system's (ship) taxonomy and data management. The conclusion summarizes lessons when using the adopted standards, as well as challenges when scaling the approach to real life operations. Future research is proposed toward extending the standardization to more complex cases.

1. Digital twins in maritime applications

Digital twins were popularized in aerospace industries, based on the principle of using digital models, sensor information, and input data to mirror and predict behaviors of a corresponding physical asset [1]. This seems to be done out of need rather than choice, given the impossibilities of having a physical, wired connection with any asset in the outer space. The maritime industry shares this characteristic with the aerospace industry, as a ship can be observed as an asset that operates in the interface of two fluids, without a physical connection to the shore. Engineering analyses and simulations have been used for decades in the maritime sector to predict the operational behaviors of a system during design, with results providing insights into how to select, modify, and refine design alternatives according to their expected functional performance. However, once a ship is launched, it is tested according to a standard row of criteria during a sea trial and then handed over to the ship owner, who will, in most cases, operate it independently from the design office. This causes segmentation, in which simulations prepared during design are not used to aid operation, and behaviors that occur during operation are not used to guide design of new vessels. A digital twin might overcome this trend by centralizing data management; during design and manufacturing, it collects the product model and simulations of behaviors, and once the system goes to operation, it is animated with data streamed from sensors and connected services. Thus, the digital twin is an essential enabler to the "digital thread", a term meaning the use of software, data, and governance models to obtain a comprehensive digital view of an engineering system throughout its life cycle [1].

Given the complexity of ships as systems and the relative novelty of the digital twin concept, digital twin implementations in both maritime industry and research are still emerging [2]. They commonly occupy a narrow domain, or they have not yet attained a high degree of maturity. Challenges when implementing a comprehensive digital twin ship span several levels. At the most fundamental, there is need to identify business and governance models that take advantage of the opportunities created by digital technologies, whether based on servitization or otherwise. Regarding infrastructure, there is need to build streaming services with reliable databases, with transmission hardware and protocols capable of exchanging large amounts of data (bandwidth) between sea and land reliably. When it comes to system integration, the maritime industry has a history of fragmentation and incompatibility of digital tools during ship design and operation.

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Different hardware and software systems often adopt incompatible proprietary formats for computer aided design models, sensor measurements, engineering analyses, and simulations [3]. The tender-based approach to data management in the maritime sector opens up for several customizations tending to undermine digital interoperability, e.g., conventions imposed by different classification societies and shipyard building strategies [4]. This represents a central concern because a digital twin uses data and models generated by various stakeholders during multiple stages of the life cycle, requiring a systematic approach to development and data integration.

Development and use of data standards are central to enabling this objective, since they should allow compatibility and exchange of models developed by disparate parties who use various software [5]. We recognize that even development and adoption of technical standards are influenced by variables that are measured not only from an objective perspective of system performance, but subjective positions of the involved parties. A standard that is technically functional and apparently reasonable might be rejected if one or more prospective user perceives it as too prescriptive, cumbersome, or for any reason not advantageous. This work serves two purposes in that context. The first one is assessing use of existing standards to digital twin development, with the objective of identifying their respective advantages and limitations. This aspect of the research to some extent builds upon previous work by the authors about web-based development of maritime simulations, as will become clear throughout the paper. The second purpose is to outline methods which might inform future standardization initiatives in the maritime sector, starting from a set of design choices aimed at dealing with the stated problems.

2. Standards for digital twin data

2.1. Modeling approach

By our design choice, when selecting standards for use in this work, we prioritized standards that are open (distributed freely) and neutral (not favoring particular vendors or actors in the industry). To avoid lock-in, we choose formats which enjoy broad support across software tools rather than being tied to a particular suite. With data becoming increasingly important through the maritime value chain, it becomes necessary that it is intelligible to employees of various backgrounds besides software development. Thus, it is necessary to select formats of simple interpretation by users to allow independent data exchange and reuse. To accomplish such goals, we look to the stack of web-based technologies. The reasons for this choice are discussed in a previous publication [6], but in summary, a web-based approach is compatible across devices and operating systems, it offers access to a broad pool of reusable, open-source code for application development, and it enables nearly instantaneous access to geographically distributed users.

Table 1 summarizes the selection with a typology of standards for product information-sharing and exchange, as defined by Rachuri et al. [7]. The typology follows a hierarchy, starting with the most basic or fundamental standards and moving toward the most comprehensive and sophisticated. Type zero standards are for implementation (i.e., programming) languages. Type one standards represent information modeling standards that model information but do not impose a specific domain of discourse or schema on the data. Type two standards are content standards that model domains of discourse, subdivided into five sub-types. The three first are for product information modeling and exchange, information exchange, and product visualization. The remaining two – standards for e-business and value chain support, and standards for security – are not considered in this work. The last type of standard concerns architectural frameworks that reconcile data use during the product life cycle from various viewpoints (e.g., enterprise, technology, and engineering). We do not consider these standards because they would require implementing a digital twin with a holistic perspective of an organization, thus lying beyond the scope and stage of maturity of this research. However, they might enable integration among future digital services in maritime and to codify a data management strategy from a business perspective. See, for example, the ISO 19847 standard for shipboard data servers to share field data at sea [8].

Regarding the first two standard types, implementation languages are those used for web development, i.e., HTML and JavaScript. For the type one standard, we use JavaScript Object Notation (JSON), which offers readability to users unfamiliar with software development, thus bridging the gap between development and engineering disciplines. JSON originated from JavaScript but is now widely supported in the information technology industry, including tools for conversion to other information modeling standards such as XML.

2.2. Digital twin content

Digital twin content is here organized into: representation of the physical asset, states collected from the asset, operating context, and simulations or analyses of behavior (based on [9]). A digital twin contains asset models that are shared among all simulations. The sensor observations collected from a system and its context feed services for analysis and simulation of across ship behavior domains. Although simulations and data used to aid operation of engineering assets are not new, the digital twin applies recent developments in technologies for simulations, digital services, and industrial internet of things to centralize all relevant digital models of the physical system it represents, thus operating as a hub that a user can access to perform key activities related to the assets' data. West and Blackburn comment on the feasibility of developing a digital twin of a fighter aircraft, drawing attention to the great burden of developing high-fidelity simulation models across several domains as a single platform [10]. They conclude that piece-wise progression is advisable, in which disparate modules that cover various simulation aspects of the asset are linked to the digital twin. Every module would be developed with relative independence to achieve the necessary balance between fidelity and simplification. Erikstad discusses balancing capability with the cost of implementing digital services for ship operations [11], proposing a service maturity index to grasp the progression from simpler, but not necessarily ineffective, to advanced services using five levels—observe, measure, model, predict, and decide. Fig. 1 summarizes this framework with examples of possible digital twin services in different domains. For succinctness, we condense the maturity scale to three levels only: monitor, predict, and decide.

Asset representation. Representation is based primarily on visualization files and textual metadata, such as specifications. Given the intention of using the digital twin for real-time monitoring of ship operation, we turned to polygonal formats which are lighter than NURBS-based alternatives such as IGES or STEP. This comes at some expense for geometry accuracy, but we assume the original NURBS files will remain available in case such accuracy is eventually needed. Suitable format alternatives are JT (Jupiter Tessellation), Wavefront OBJ, STL and glTF (Graphics Library Transmission Format). We adopted glTF due to it enjoying broad support and free licensing. It can be saved as text or binary and supports entire scenes with assemblies, colors, materials, and lights [12]. The 3D models should be complemented by metadata containing coordinate positions, weight, authorship, remarks, and identification tags.

Table 1
Typology of standards adapted to digital twins (based on [7]).

Type	Scope	Adopted
0	Implementation languages	JavaScript, HTML, CSS
1	Information modeling	JSON
2	Content standards (domains of discourse)	glTF, ISO 19848, DNV VIS
3	Architectural frameworks	None[a]

[a]Integration at enterprise-level not considered in this research.

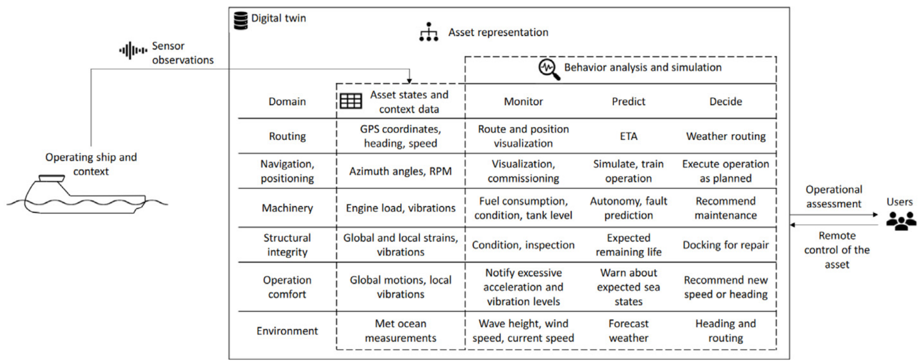


Fig. 1. Digital twin content groups with examples of simulations at different maturity levels.
Source: Updated from [2].

Ship states. A digital twin needs to gather observations from a vessel's instrumentation device in order to model the current operational situation. Measurements might be readily usable once obtained, such as in GPS coordinates showing the current vessel position, or might require further processing in order to derive a comprehensive state, such as in an exhaust temperature that gives partial insight into the functioning of an engine. This distinction depends on the digital twin's purpose and observed variable. Relevant standards within this scope are the IEC 61162 series for digital interfaces between navigation equipment [13] and the ISO 19848 standard data for shipboard machinery and equipment [14], the latter of which we adopted in this work, as schematized in Fig. 2. Ando discusses background development of the ISO 19847 and 19848 standards in Ref. [15][1]:

- Data channel list: a data channel transmits one measured variable. Depending on channel type, the variable will be classified as an instantaneous value or observation, a calculated value derived from observations, or a manual input by the crew, among others. A data channel list contains metadata describing type, purpose, update cycle, units of measure, expected range, and identification tags of one or more data channels.
- Time series data: they contain observation logs stored as one of two types: tabular or event data. Tabular data are suitable for raw numeric values or statuses sampled from sensors at regular rates, and event data model alarm information, status information, and input data at intervals not specified previously.

A user might also model data as XML, as it is fully compatible with JSON or, if a more compressed time series format is needed, CSV. The organization of shipboard data in packages provides some independence and modularity, allowing data serialization into self-contained files for exchange among parties or systems. Other than that modular structure, the standard does not prescribe any schema for organizing the packages in an overarching structure. This is not necessarily a limitation, but probably an intentional gap intended at increasing the standard's versatility for use with different database arrangements. For instance, Annexes B and C illustrate how the shipboard data can be identified according to two different naming rules provided by different vendors: the JSMEA-MAC by the Japan Ship Machinery and Equipment Association and the Vessel Information System (VIS) by DNV [16]. Because ISO sells PDF copies of the standard to users, it is reasonable not to consider it "open" [17]. If much, it might be considered "neutral" for not prioritizing the necessities of any one company in particular. Still, given the lack of competitors sharing its scope, we see the standard as one of the few viable alternatives for adoption.

Operating context. This includes representation of the surrounding environment (e.g., topographic maps) and its states (e.g., wave state, temperature, currents, and winds). The obstacles to effectively manage environmental data in digital twins are slightly different from those of ship data. From one side, metocean data has been more standardized than ship data with formats such as the Network Common Data Form for various meteorological conditions [18]. For instance, in 2013 the Norwegian Mapping Authority released free topographic data sets in the Digital Elevation Model standard by the U.S. Geological Survey, a legacy and still used format. These files provide a useful resource for automating the creation of 3D environments inside which vessel operations can be simulated [19]. On the other hand, most ship owners do not own or control weather monitoring infrastructure, so even if quality data from a certain region is available, access to it may not be straightforward. ISO 19901-1 on metocean design and operating considerations for offshore structures provides an overview of data collection infrastructure for different seas in Annexes A to G, showing that it is owned by several public and private entities around the world [20]. The challenge then becomes first to acquire access to data in the operating region of the vessel, often through external suppliers, and then link it to the digital twin. The existence of projects to document and harmonize existing metocean databases might make this process smoother [21].

[1] Fig. 2: Diagram representation of ISO 19848 data structures is reproduced by Ícaro Fonseca in A Standards-Based Digital Twin of an Experiment with a Scale Model Ship under license from Standard Online AS November 2021.

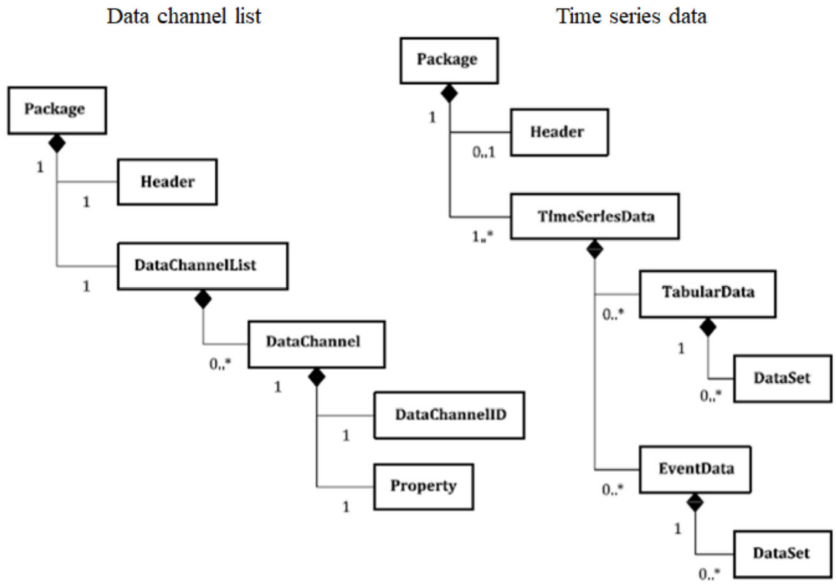


Fig. 2. Diagram representation of ISO 19848 data structures [14].

Simulations of behavior and other analyses. Recent work introduce a few considerations regarding this aspect of digital twin ships. For instance, the Functional Mock-up Interface (FMI) is a relevant alternative for simulation of dynamic systems, allowing exchange and co-simulation of cyber–physical models contained in modular units. It has been applied across different engineering domains, including maritime [22]. The authors have previously presented web-based simulations for ship operations, where geometries and weights are used to calculate hydrostatic, stability, resistance, motion response and fuel consumption, among others [23]. The simulation code does not have the formal rigor expected from a technical standard, but it outlines an approach we aim to continue exploring in the future. Finally, ship states give a data pool for training and testing of machine learning models, e.g., those targeted at predictive maintenance. Standardized schemas and metadata should simplify model reuse by allowing automation of data access and parsing during calibration.

2.3. Establishing a coherent taxonomy of a digital twin ship

Appropriate choices of views and hierarchies play a central role during management of engineering data, including a digital twin; one must first choose an adequate view to describe the system digitally and then model a hierarchical schema that organizes data according to those views, i.e., establish a taxonomy of the system. During early design stage, cargo vessels are traditionally described in lightweight groups for structure, machinery, outfitting and accommodation. Alternatively, methods for design of specialized vessels such as the Design Building Block Approach and System Based Ship Design prefer to emphasize architectural concerns by describing the vessel in terms of spaces with corresponding properties such as volumes and areas [24,25]. Such spaces are arranged in a hierarchy of systems or functions so they can be roughly traced to the tasks a ship is required to perform. During the construction phase, yards commonly adopt a physical view of the ship decomposed into blocks, assemblies, panels, and so on.

A digital twin should provide a meaningful structure to support data management during asset operation. Given this scope, it should be based in a functional taxonomy that can be studied and evaluated in comparison to desired or expected performance. This makes organization based on a systems-oriented view of the vessel desirable. In addition, ship states can be collected from very specific vessel components (e.g., the shaft of a pump that controls flow toward a tank), and thus the taxonomy must provide an adequate level of detail. Unfortunately, we did not find many alternatives which fulfilled these requirements. For instance, the Expanded Ship Work Breakdown Structure by the U.S. Navy is targeted at military vessels [26]. We identified two alternatives, incidentally both from the Norwegian context: the SFI Group System by SpecTec [27] and VIS [16]. We adopted VIS as the primary taxonomy for ship data for two main reasons: it is maintained with open documentation on the web (while SFI is distributed under payment) and it is being positioned to also manage sensor logs (in contrast to purely static product data). VIS is a code scheme that uses a functional view of a vessel, prioritizing a description of functions that can be assigned to the correct component. The coding scheme is aimed at clustering ship data in corresponding systems, and the ISO 19848 Annex C specifies how it can be used to identify data logs collected during operation. Thus, it can be used to map asset representation and sensor observations in a digital twin.

This choice still leaves open the task of finding suitable taxonomies for remaining digital twin content, namely operating context, and models of behavior. ISO 19901-1 puts forth a list of relevant metocean parameters to be included in databases. The parameters are organized in six main categories, which we adopt as a preliminary schema [20]: waves, currents, winds, ice, water levels and others. We see two alternative paradigms to organize simulations of behavior in a digital twin. The first one is illustrated by modern app stores, which place software in categories defined by the store owner or maintainer. The second is the tag system used in package managers and source hosting services, where publishers are allowed to define one or more keywords for each project. We judge the latter is more suitable to an open digital twin platform, as it avoids the prescription of categories and provides flexibility for a service to be described according to more than one taxonomy, such as behavior domain, simulation method and purpose in the ship value-chain.

3. Digital twin development

3.1. Standardization framework

Given the prospect of digital twins increasing in scope and importance in the maritime value chain, we put forth a modeling approach supporting gradual addition of content to the digital twin as new functionalities are implemented. We aim to achieve flexibility for adaptation to different data taxonomies while making use of the discussed standards to allow data exchange and interoperability among software tools. In terms of content, the standards establish a framework for asset representation and states, with methods for simulation of behavior to be approached in a future work. Digital twin data is arranged into individual packages, each storing textual descriptions about their purposes and characteristics (i.e., JSON metadata) and links to binary files if needed. Packages are stored in a flat hierarchy, but they contain identification tags that map them to the desired taxonomy for organizing and browsing digital twin content. We expect such modularization to maintain independence among resources, facilitating data exchange among digital twin stakeholders. We apply a standardization approach based on the principles outlined above to a simplified case study intended as starting point to future applications of greater complexity. We developed a digital twin of an experiment with a scale model platform supply vessel (PSV) in a wave basin. The digital twin data is linked to an algorithm developed on a proprietary platform to monitor and control the scale model PSV while accounting for motion response, navigation, and station keeping on waves. Thus, it offers a higher degree of service maturity compared to a simple online monitoring tool. The following steps describe the framework applied to the case study:

1. Identify the existing physical setup and installed sensors (Section 3.2).
2. Define the digital twin's intended purpose 3.3.
3. Map the data required to develop the digital twin 3.4.
4. Prepare the digital asset representation 3.5:
   (a) Write overall ship specification (JSON).
   (b) Convert necessary 3D models to standard format (glTF) and prepare corresponding metadata.
5. Prepare templates (ISO 19848) for storage of PSV states during the experiments 3.6:
   (a) Write data channel list.
   (b) Write time series data templates.
6. Model the operational environment, i.e., wave basin 3.7:
   (a) Create a digital model accounting for relevant features of the basin.
   (b) Prepare templates to store a log of wave conditions encountered by the PSV during operation.
7. Develop models for simulation of behavior 3.8:
   (a) Convert existing results from motion response analyses to self-standing JSON files.
   (b) Develop simulation models and graphical user interfaces (as web applications).
8. List the digital twin content according to the chosen taxonomies 3.9.
9. Aggregate individual components into a functional web-based system 3.10.

3.2. Experimental facility and instrumentation

The experiment was conducted using a PSV scale model in the Numerical Offshore Tank laboratory at the University of São Paulo (TPN-USP). In terms of experimental equipment and data-gathering infrastructure, the digital twin followed a bottom-up approach by linking to systems used already in the laboratory workflow. The tank itself measures 14 meters on each side and is 4.1 meters deep (Fig. 3). It is equipped with flaps that are capable of generating regular and irregular wave states from virtually any direction of propagation. The flaps also operate as wave absorbers that minimize wave reflection to avoid interference with desired wave characteristics [28]. A commercial solution for test and measurement reads the water elevation using several probes installed in the tank. To simplify identification of the wave state that occurred in the basin with the digital twin, the experiment was conducted with only regular waves that approached from a single, previously known direction, allowing extraction of wave amplitude and period using a single wave probe.

The hull used during the experiment was a 1:70 scale model of a PSV that measured 1.24 meters in length, 0.345 of beam, and 0.082 of draft (Fig. 4). It was actuated with a dynamic positioning (DP) system for navigation and station keeping that comprised two azimuth systems on the stern and a tunnel thruster on the bow. A commercial solution tracked motion of the PSV in 6 DOF (degrees of freedom) using a stereoscopic camera setup. The DP control module developed at TPN connects with that solution to operate the propulsion remotely by transmitting commands to the PSV model over radio (further details in Appendix A.1).

3.3. Digital twin purpose

The digital twin platform was developed to offer monitoring and control capabilities during experiments, with the following objectives:

- Display the operational situation in real-time:
  - The vessel's DP parameters (position in 6 DOF, propeller rotation rates and azimuth angles).
  - Physical characteristics of surrounding waves.
- Allow capabilities to access the data and control the physical asset (ship model) remotely via a web-based app.
- Provide complementary functions for assessment of motion response during operation:
  - Validation of stored response operators based on actual measurements.
  - Automatic maneuvering to minimize motion response according to stored operators.

3.4. Data content and schema

The schema clusters the digital twin's content into four groups, based on the categories discussed in Section 2.2—asset representation, sensor observations, environment observations, and behavior models. A fifth group in the data schema then stores the taxonomies that were used to map the digital twin content by referring to the identification tags stored in the individual data packages. Fig. 5 shows an overview of the digital twin schema.

3.5. Digital ship

Ship specification. The PSV specification was stored as a JSON file that contained primary dimensions and weight distribution (Fig. 6, left). Besides serving as a reference about the PSV model, the specification was used to extract the draft and overall length when rendering the 3D ship visualization.

Components and 3D models. The other packages in the asset representation described the ship's components, providing coordinate positions, VIS identification tags, and links to files with the respective 3D models (Fig. 6, right). Since the objective of the study was to monitor global motion response, the hull was modeled as a single part, without further divisions (e.g., sides and bottom). As intended, glTF allowed modeling of system assemblies with articulations for movements, illustrated by the local coordinate axes for propeller rotation in relation to the nozzle.

Fig. 3. Wave tank facilities at TPN-USP [29].

Fig. 4. Scale model PSV used during the experiments [30]. Six reflective, spherical markers for motion tracking were attached to the model.

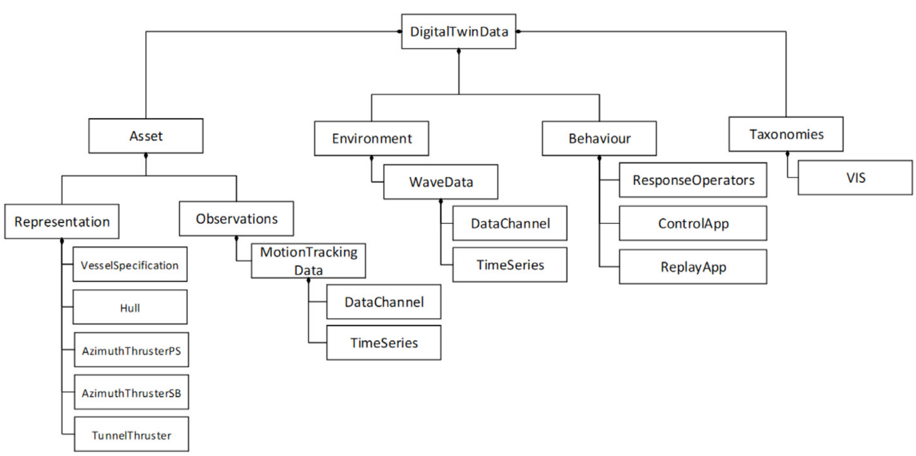


Fig. 5. Case study content schema.

3.6. PSV operational states

All ship states were transmitted in a single data channel list when communicating with the DP system, following the format defined by ISO 8601 as presented in 2. A data channel file was prepared with the metadata to describe the meaning of each value in the logs (Fig. 7, left). The digital twin received a stream of operational states at 100 Hz, modeled as tabular data. Commands that defined the DP setpoint were modeled as events triggered by the user. Results were stored in a time-series file for posterior use, e.g., during an experiment rewind. The file listed the time and corresponding measurements (Fig. 7, right).

3.7. Operating environment

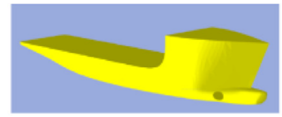
Wave basin model. The digital twin must identify incident waves that the vessel encounters during operation to evaluate its motion response, so a digital model was created to display the wave basin

Asset Representation
Specification


```
Remarks: "A ship
specification draft.",
Author: "Employee_1",
ShipID: "IM01234567",
MainDimensions: {
  LOA: 1.24,
  B: 0.3450,
  DesignDraft: 0.0820,
   UnitSymbol: "m"
},
Weight: {…},
CG: {…},
AssetID: {
  LocalID: "/dnv_vis/071",
  …
}
```


Components


```
Remarks: "High level description of the hull.",
Author: "Employee_1",
Topology: {
  Visualization: {
    STL: "hull.stl",
    GLB: "hull.glb"
  },
  Position: {…},
  UnitSymbol: "mm"
 },
AssetID: {
  LocalID: "/dnv_vis/111(mm)",
  …
}
```

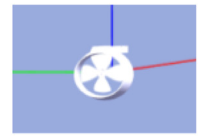


Fig. 6. Excerpt of the ship representation metadata with corresponding 3D models.

Dynamic Positioning States
Data channel list


```
DataChannelID: {
  LocalID: "/dnv_vis/453+I101/
  ShipHeave+d(mm)",
  ShortID: "PosZ",
  …
  }
},
Property: {
  DataChannelType: {
    Type: "Inst",
    UpdateCycle: "0.01"
  },
  Format: {
    Type: "Decimal"
  },
  Unit: {
    UnitSymbol: "mm",
    QuantityName: "Heave Displacement"
  },
  Name: "Ship Heave Displacement"
  }
}
…
```


Tabular data


```
DataChannelID: ["PosX","PosY","PosZ",…],
DataSet: [{
    TimeStamp: "2020-01-22T17:47:17.52Z",
    Value: ["-194.91974","2.24150",…]
  },{
    TimeStamp: "2020-01-22T17:47:17.53Z",
    Value: ["-195.64748","1.62077",…]
  },{
    TimeStamp: "2020-01-22T17:47:17.54Z",
    Value: ["-194.95781","2.21758",…]
  },{
    TimeStamp: "2020-01-22T17:47:17.55Z",
    Value: ["-198.62386","1.71179",…]
  },{
    TimeStamp: "2020-01-22T17:47:17.56Z",
    Value: ["-198.67555","1.70286",…]
  },
  …
]
```


Fig. 7. Excerpt from DP state data.

area and experiment waves in proportion to the PSV. The visualization is based on an open source example provided with the Three.js library, so it can be reused during development of web applications. It displays a water surface which can be configured to render a regular wave according to its height, period and phase. The wave length is automatically derived from the dispersion relation for deep waters and the direction is fixed during the experiments.

Environment states. Despite the scope of ISO 19848 being data for shipboard machinery and equipment, we chose to also use it to model wave characteristics. This was possible because the experiment environment is simple and controlled. Should the approach be scaled to real life operations, it would be necessary to account for the geographic perspective, so that a metocean condition can be assigned to an operating region. The instrumentation system installed in the wave basin measured water elevation at a 100 Hz frequency. Since we simplified the experiment to assess regular waves, it was sufficient to store only the wave characteristics as post-processed from the water elevation log, allowing reduction of the data footprint. Each time the algorithm that processed water elevations identified new characteristics of regular waves, it triggered a new event and saved the values to the data log (see Appendix A.2).

3.8. Behavioral models

Motion response operators. The motion response operators for amplitude and phase were obtained using a commercial boundary element method software [31] and converted to a JSON file. The file organized results using one of six motion modes, then 60 periods and 25 wave headings, starting from 0° and with an interval of 15°, up to 360°. Periods were defined at a real-life scale, so they had to be converted when applied to responses of the PSV model. The definition of JSON schema for storage of the results required a choice among alternatives which, though syntactically different, are equivalent in meaning. This observation applies to a large variety of results that can be stored in the digital twin. To minimize the effect of syntactic differences, a descriptive header was included in the package describing the results' meaning, units, and conventions. Although this is not

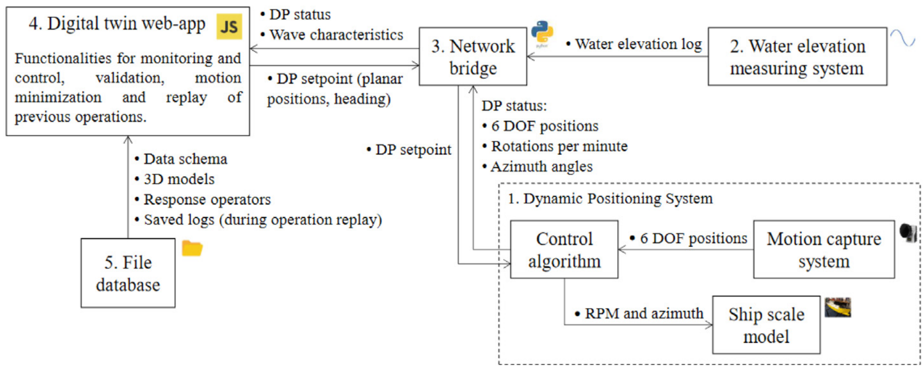


Fig. 8. Communication diagram of the digital twin system during experiment streaming.

as effective as having a common schema across the industry, it allows clear interpretation by those who use it.

Monitoring and control. Two web applications were created for the digital twin, one is a dashboard for monitoring and controlling an experiment while it occurs and another to rewind a previous experiment based on stored data. The monitoring dashboard also includes functionalities for validation of scale model motion and optimization for minimal motion response (see A.3 for details about the algorithms). During the experiment, the dashboard connects to the wave measurement and DP control systems over a local network. The DP control algorithm is handled as an external, self-contained module, and communication with it occurred only through exchanges of inputs and outputs. The DP module received as input from the user the desired setpoint on the navigation plane (i.e., coordinates and heading), and the control system automatically maneuvered the model to attain the desired position. In return, the module outputs logs containing vessel positions in 6 DOF and propulsion states. This arrangement was planned to allow for remote vessel control with the web-based application, an interaction discussed in more detail in Section 3.10.

3.9. Data taxonomies

Once all digital twin content had been collected and modeled using the appropriate metadata, they were mapped using taxonomies to allow a structured overview of the data by referring to an element's unique identification tag. We used VIS as the primary data taxonomy for ship representation and states. The schema were firstly created manually by reading the JSON files and searching for necessary information, but in the future, an algorithm could be created to assemble the hierarchies automatically from the identification tags contained in each data package. Since the digital twin contained only a few packages, the content did not span many groups modeled in VIS. In addition, VIS documentation provides flexibility when deciding the level in the hierarchy to which a sensor should be allocated. The hull model was mapped to a high level because it is not decomposable into component parts, but the thrusters were assigned to lower levels in the propulsion hierarchy. State logs were also assigned to corresponding systems—positions in 6 DOF to the navigation systems and the azimuth angles and RPMs to the thruster arrangements. The remaining digital twin contents were sparse to justify use of full-fledged taxonomies, so they were identified with suitable tags/labels. This applies to environment states, which consists only in wave data. Similarly, response operator files and web applications were identified as "motion response" and "maneuvering", respectively.

3.10. Aggregation into a web-based system

Fig. 8 schematizes the data architecture for execution of experiments, aggregating various subsystems into 5 (five) main components. Component 1 represents the DP system, including the motion capture and the controlled PSV model. Component 2 shows the water elevation measuring system. We developed a network bridge in Python (Component 3) to centralize communication between the measuring systems and the digital twin web application (Component 4) in both directions. The bridge performs two functions in the first direction—one to receive the motion and propulsion logs from the DP system to repass them to the web app, and the other to receive the water elevation signal, calculate the wave characteristics from it, and repass them to the web application. In the reverse direction, it communicates by receiving the DP setpoint that the user defined on the app and repassing it to the control system. When transmitting packets among systems, the bridge also establishes compatibility between transmission protocols. The web interface uses WebSocket, a protocol broadly used by modern streaming applications, and other systems use the older User Datagram Protocol. The last digital twin component is the database (5), which stores the digital twin files in a local computer folder. The web application can access the folder and retrieve relevant files during simulations. We did not include a specialized database system in the digital twin architecture to simplify development and deployment. The file-based approach was sufficient for this case study, which generated only a few megabytes of digital twin and experimental data. For operations with a large amount of data, a solution would be to include a robust commercial alternative such as Amazon Web Services into the data loop. The streaming architecture was later adapted to rewind experiments based on stored data. In practice, this greatly simplifies setup by removing the need for communication with the measuring systems, since the web application retrieves all relevant data from the database folder.

4. Digital twin functionalities

4.1. Web-based control dashboard

The web application (Fig. 8, Component 5) provides a user with a graphical interface during operation of the digital twin, as well as allowing remote access of the data and control of the physical asset. The interface displays four elements—a 3D scene at the center, a set of 2D plots at the bottom, a monitoring panel on the left and controls at the top right (Fig. 9). The 3D visualization shows wave states, ship position in 6 DOF, and propeller rotations in nearly real-time. All such states are listed on the leftmost panel. The 2D dashboard shows time-series for various motion modes, exemplified as heave and pitch in the figure. Top-right

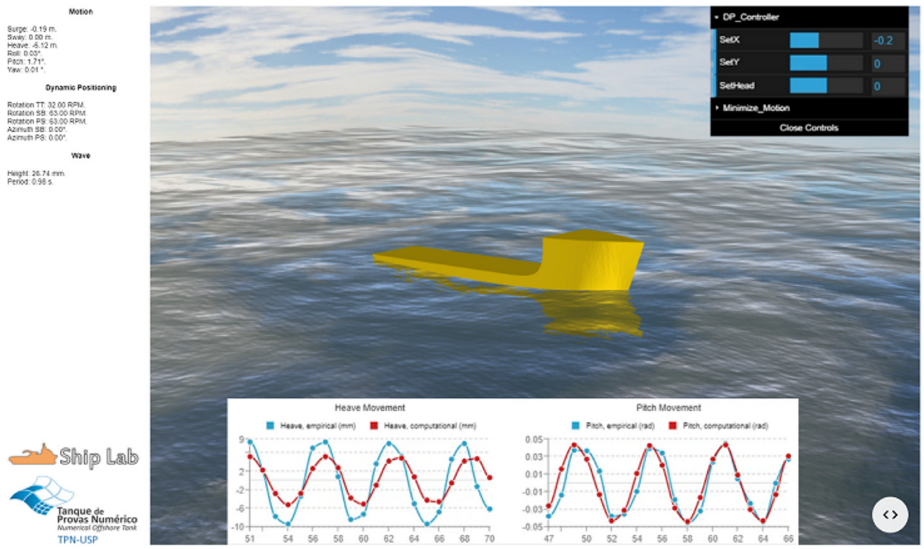


Fig. 9. Screenshot of the web-based digital twin dashboard.

elements provide DP controllers for the PSV model. The three graphic sliders allow a user to control the setpoint (i.e., two planar coordinates and the heading). A drop-down menu contains a list of the model's six motion modes so that a user can select one that he/she wants to minimize.

4.2. Digital twin use cases

Monitoring and control. The most fundamental functionality of the digital twin is monitoring and control of the experiment (Fig. 10). This capability was useful during the experiments by allowing debugging and testing of the experimental setup. For example, it was used frequently to verify propulsion system functionality, especially when the model was inside the tank. It also helped to identify whether the model was drifting toward an undesired position, out of the field of view of the motion tracking system, and thus risking getting out of control by breaking the DP feedback loop. Such situations could be addressed quickly using the digital twin interface itself.

Motion validation. The app allows validation of motion responses that are estimated during design in comparison to those measured during the experiment. The 2D plots compare ship coordinates as measured during the experiment in real-time and expected coordinates as reconstructed from response operators; respectively, blue and red lines in Fig. 9. In practice, the application allows quick qualitative evaluation of the difference between expected and measured amplitude responses. Further development is needed to provide indicators at the level of detail that is required by a wave basin facility, namely quantitative comparisons of amplitude and phase for all 6 DOF.

Motion optimization. This functionality allows a user to adapt a response to waves for one decoupled motion mode. The application uses stored responses to minimize ship motion during station keeping by controlling its heading relative to the wave direction. While the PSV is floating during a wave condition, a user can select one of the six motion modes from a drop-down list, and once selected, the optimization algorithm searches for a heading that minimizes that motion mode and sends a command for the DP module to maneuver the vessel toward the specified heading. This type of optimization offers basic and self-evident results. For example, if the PSV is floating during head waves and the user selects an algorithm to minimize pitch motion, it automatically turns the model in the position of beam waves (Fig. 11). Although the maneuver minimizes pitch, the new heading also maximizes roll response. Using an advanced optimization algorithm, operators can minimize the coupled motion response on a strategic point of the vessel, e.g., the location on deck where a crane is performing a lifting operation.

5. Discussion

5.1. Digital twin as support to experiments

Robust remote control technologies are an essential enabler to a shore control center and thus a necessary step toward autonomous ship operations, especially when combined with algorithms for situational awareness and decision making [32]. The monitoring use case illustrates the potential of a digital twin to aid ship operation by allowing easier interpretation of states in comparison to traditional means, such as displaying logs and charts, or triggering alarms. This type of responsive interaction was enabled by a communication system that exchanged data with the physical setup at high frequency and low latency. We used a modular approach to link the DP control system to the digital twin. From one side, it reduced development effort and increased flexibility in comparison to the digital twin as a single integrated system. From the other, even for a simple digital twin compared to full-scale applications, it created unforeseen interactions during operation of distributed subsystems. This might happen, for example, if operators are unfamiliar with assumptions made during development of the modules, or if an operator overrides simulation parameters in a module and the system does not propagate new values to remaining ones. In our experience, these problems can be ameliorated by communicating assumptions clearly among operators and developers, either in the form of written software documentation or spoken instructions. At the industrial scale, these measures might be complemented by access permission management that suits each user's level of knowledge about the systems they are developing or operating.

5.2. Application of the standards

ISO 19848 standard was simple to understand and implement, and demonstrated a good degree of flexibility, being able to accommodate all data involved in the case study, including

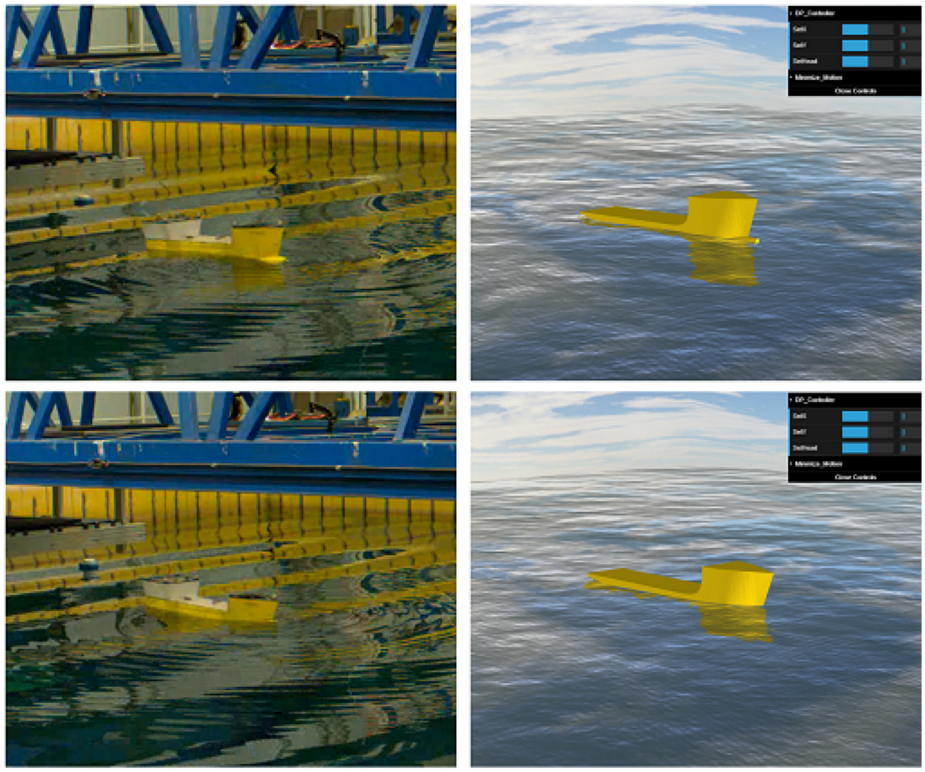


Fig. 10. Screenshots of the monitoring application in comparison to the physical experiment.

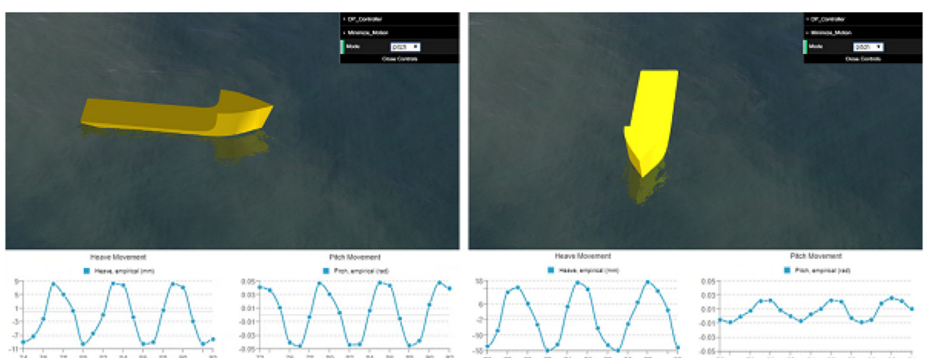


Fig. 11. Motion minimization function maneuvering the model toward a heading that minimizes pitch motion (beam waves).

setpoints and values calculated from raw observations. The document ensures consistency between descriptive metadata and the corresponding log, making sure they can be correctly interpreted by users. As a consequence of the document's scope, its application does not per se guarantee data cross consistency among different vessels. For those looking to automate creation of digital twins for a fleet of vessels, it is necessary first to verify every ship is doted with the necessary sensor setup (obviously) and then confirm they adopt the same naming rules with identical names for equivalent data channels. I.e., the ISO standard specifies a Local ID which should in principle be identical for the same kind of sensor in different ships, though in practice this parity depends on how strictly the adopted taxonomy constructs this ID. Although the document specifies that regular measurement intervals are expected for consecutive readings in tabular data, the data structure can accommodate readings at variable time steps without modification. A few problems arose when trying to reinforce the standard time format across measuring systems. ISO uses the convention defined by document 8601, which gives an unambiguous format for storage of date that can be interpreted regardless of variations due to, for instance, time zones or summertime [33]. Commercial instruments commonly follow internal conventions for time labels, sometimes by marking the time in seconds since measurements started during the current execution (i.e., zero seconds at the beginning of the experiment), complicating synchronization of time among distributed systems. However, this is a problem encountered when using instruments designed for a wave basin; the time conventions used by actual shipboard logs might be different.

VIS provided an adequate degree of detailing to map the ship representation inside a digital twin. The functional perspective has, so far, been consistent with the digital twin purpose by grouping components according to ship systems. Surveying the taxonomy during application suggested that it is expansive in terms of modeling variations of physical systems (e.g., mechanical or electrical propulsion). VIS also offers a good base in terms of mapping sensor logs, whether they are taken from a vessel component or navigation system, such as headings and positions.

Instead of opting for a stricter standardization, VIS provides flexibility when choosing the level in the hierarchy to which a sensor should be allocated and when creating a Local ID for a sensor, leaving margin to the creation of various alternatives with the same meaning. E.g., the document requires users to construct a suffix describing the quantity being measured. As the suffix is not standardized, an exhaust gas inlet could be denoted by "ExhaustGasIn" or "EXH_G_IN". The glTF format was considered as an alternative for storing geometric models as articulated assemblies that would simplify inclusion on a digital twin visualization. The format supports highly sophisticated structures with assemblies, sub-assemblies, etc. From one perspective, such sophistication is promising in allowing exchanges of models with articulations for movement; from the other, the hierarchies contained in a single file might conflict with or become redundant over the taxonomy chosen for the ship representation as a whole. For this reason, use of intricate glTF models needs to be guided by clear understanding of whether they suit a chosen taxonomy for asset representation.

5.3. Toward full-scale digital twin ships

There are several challenges to extending this early case study toward a full-scale digital twin. In terms of data management, if the approach outlined here is to be developed into a standard, it will be necessary to define templates for asset metadata and taxonomies (such as VIS) more formally, specifying all mandatory and optional fields the data structures should contain. There are also concerns about the capability of handling large amounts of content with the proposed framework. A related project is investigating development of platforms with support to multiple users and integration with databases, allowing digital twin content to be transmitted to the client on demand [34]. As the scope and complexity of a web-based project increases, it becomes challenging to manage and propagate changes on the code base. Technologies such as the TypeScript language (for static checking of variable types) and automated testing might alleviate this issue.

In terms of functionality, the use of a test basin made identification of wave characteristics much simpler compared to estimation of real ocean states. Ideally, a full-scale digital twin would be connected to external services providing weather conditions derived from *in situ* measurements or estimation models in various operational regions. Once the digital twin receives the vessel's geographic position, it would automatically search for the service covering the corresponding region and use the data (in this case, wave direction, significant period, and height) in the simulation. In practice, such architecture would require overcoming the challenges in data availability and access discussed earlier. At this stage, the use cases with motion validation and optimization serve as proofs of concept for showing how a digital twin can help close the data loop toward using design analyses during ship operation. In real situations, a vessel could have accelerations measured with sensors and linked to a decision aiding system, i.e., a reactive decision aiding system, rather than a proactive one. This could be done locally on the bridge or remotely on an onshore control center, though the later would require much work to ensure secure data exchange with controlled vessels. While we are not approaching these issues, current research on autonomous vessels may provide insights into the topic [35].

5.4. Open source approach and reuse of source code

From its beginning, the study aimed at an open-source approach to digital twin development, so most of the source code is publicly available on an online repository. There were however a few compromises. The control module for dynamic positioning, can be found in extant work [30], but was developed in Matlab, a proprietary platform. The motivation for using an open approach was the possibility of reusing source code to develop other projects, and such reuse can occur in various ways (Fig. 12). For example, a user can adapt the entire digital twin by linking it to an alternative wave basin with similar instruments to achieve the functionalities discussed in this paper. Once adapted, the digital twin can then be extended with new functionalities added to the original source code (Fig. 12, case 1). In another context, it might be useful to extract an excerpt of the source code, such as a function, visualization, or standard template, to develop a project with a different purpose (case 2). The open approach enables verification and reproduction of results, including access to data collected during experiments. To illustrate this, an application for experiment rewind is available on the public repository (case 3). From an engineering perspective, the application demonstrates how a digital twin can be used to review a previously executed operation and study the behaviors of the systems involved. From a research perspective, it illustrates how results can be reproduced from source code and data that are publicly available.

6. Conclusion and further research

As digital twins and other digital services increase in importance for the maritime value chain, it becomes necessary to establish frameworks and data structures to support modeling and storage while enabling data exchange and interoperability. The case study applied existing standards and web-technologies to the digital twin of a wave basin. The web app illustrated how digital twins can take advantage of dashboards and visualizations to communicate operational situations clearly, allowing effective response from operators. The approach was successful in yielding a functional digital twin web application which is compatible across digital devices and operational systems. When applying the ISO and DNV standards in practice, we found out that they have been designed to provide users with flexibility to customize their own implementations, even if this leaves room for reduced consistency among different digital twin projects. We judge this design compromise as adequate because it suits the tender-based character of data management in the maritime industry, thus increasing likelihood of adoption. It also implies that companies aiming to enable automated data processing across vessels will need to further specify their implementation approaches internally. In addition to using existing standards, the work proposed methods for modeling ship representation and handling data taxonomies. These methods require stricter formalization before they can be considered as standards, especially regarding specification of normative data structures. However, they contain principles that might inform future standardization initiatives.

The proposed framework encompassed only some of the aspects necessary to develop full-scale digital twins. It should be complemented by back-end integration with databases, standardized simulation models, access to quality metocean data, and secure infrastructure for remote operations. An important topic for future research is investigation into how the standards perform with complex digital twins, eventually scaling to a broader digital architecture. Development of a digital twin of NTNU's research vessel Gunnerus offers an opportunity to approach such issues using a case study that applies the standards to a real ship [36]. Various vessels' systems are currently instrumented with sensors, with shipboard logs streamed to a cloud platform. Thus, future research should develop a real-time monitoring application of Gunnerus, which would serve as a basis for a digital twin system of the vessel. From engineering and operation support perspectives, we investigate how taxonomies accommodate

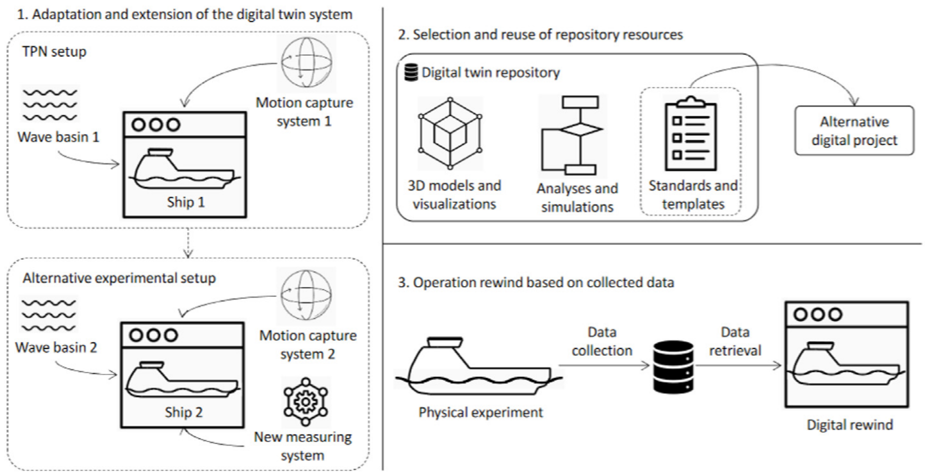


Fig. 12. Reuse cases for the digital twin system, source code, and experiment data.

a greater quantity and variety of data during ship operation. As this study did not propose standardized behavioral models, the digital twin linked various algorithms developed in different programming languages. Future work should investigate how digital twin data could be linked to simulations in a systematic manner by making use of standardized application programming interfaces.

7. Source code and open data

The digital twin source code, experiment data and documentation are available on: https://github.com/shiplab/dt_cv.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Mathematical modeling of behavior

A.1. Dynamic positioning control

The DP module was reused from work [30]. It applies robust techniques to control the ship's position while filtering disturbances from wave motions, ensuring stable performance across environmental conditions. During the current experiment, the algorithm was applied to the control of a single PSV model, but it has been also tested with consensus control of complex operations, during which vessels in a fleet moved in coordination. Fig. A.13 shows the architecture of the DP control module in connection with PSV operation. The optical motion tracking system parses PSV positions in 6 DOF, streaming them to the DP control algorithm, which estimates the propellers' rotation rates to maneuver the ship toward a user-defined setpoint and sends them as a command to the PSV over the radio frequency link (Fig. A.13, Component 1). This process operates iteratively at 100 Hz. For simplicity of the mathematical problem, the algorithm locks both azimuth angles to a neutral position, making the system of maneuvering equations determinate. This led to sub-optimal use of the propulsion system in terms of energy consumption, but it did not impair the DP functionality for the purposes of this study.

A.2. Extraction of wave characteristics

The wave model extracts wave characteristics from water elevations using a simple approach (Fig. A.14). The algorithm receives the stream of water elevations and begins storing crests and valleys through the signal using corresponding time labels (stage 1). Once the water elevation crosses the zero line, the algorithm identifies that a wave cycle ended and retrieves the last two saved values, one crest and one valley, in whichever order, to estimate the wave height, period, and phase — that is, whether the newly detected zero-crossing is an up-crossing leading to a new crest or down-crossing leading to a new valley (stage 2). After characteristics of the first wave cycle are received and saved, the algorithm updates them only when the new wave height or period has a difference of more than 2% in relation to it. This tolerance was implemented to avoid excessive identification of new waves due to light, random noise in water elevation readings.

The calculation of wave characteristics is performed by the network bridge (Fig. 8, Component 3) to reduce the necessary bandwidth and computational effort required from the web app client (Fig. 8, Component 4). To validate the algorithm, we generated a regular wave state with known characteristics in the tank and compared its values to parameters that the algorithm extracted. We set the flap system to generate a wave period of 0.978s with 28.6 mm of height. Under these conditions, the digital twin algorithm extracted from the wave signal a period of 1.020s and a wave height of 26.8 mm, a difference of 4.3% and 6.2%, respectively. We attribute these differences mainly to variations between the wave characteristics given as input to the wave generator system and the wave state that occurred in the wave tank, especially because it might suffer minor interference from the reflection on the tank's walls. The random variations in readings of the water elevation measuring system might also have contributed to a lesser extent.

A.3. Handling of response operators

Identification and retrieval. Once the web app client receives current wave characteristics, it searches and retrieves corresponding operators for validation of motion responses from the stored results (Fig. 8, Component 5) according to the following steps:

1. Scale wave period to full size.
2. Search closest period among the stored results.
3. Build time series from results.

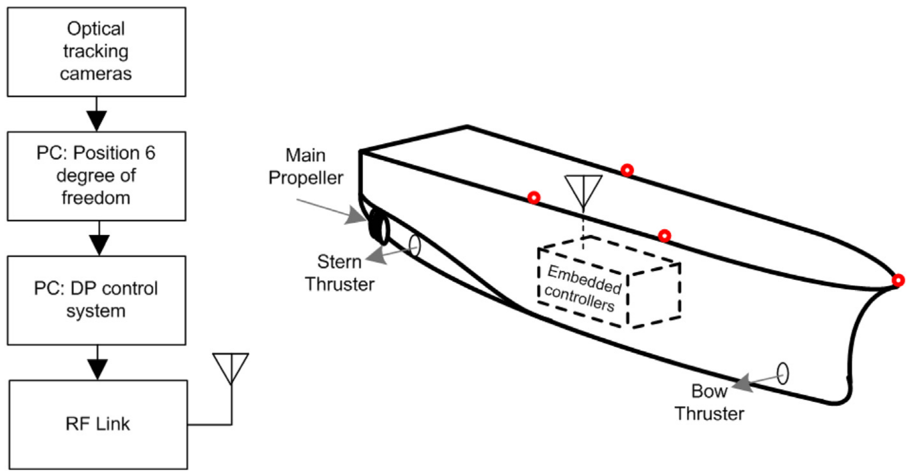


Fig. A.13. Scheme of the DP control module architecture [37].

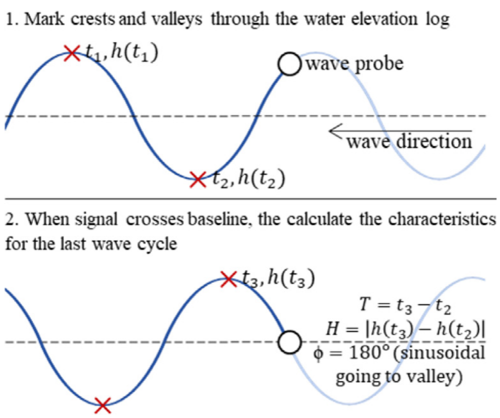


Fig. A.14. Extraction of wave characteristics from the water elevation log.

In step 1 the algorithm scales the current wave period to real-life size according to Froude relation:

$$T_{Real} = \frac{T_{Scaled}}{\sqrt{coeff}}$$

Step 2 searches for the period in the JSON schema that approaches the calculated value most closely. Taking, for example, the wave period mentioned above, 1.020s, the algorithm will scale at:

$$T_{Real} = \frac{1.020}{\sqrt{1/70}} = 8.534$$

The algorithm searches for the closest period stored in results, which in this case is 8.666s, and, considering the PSV is floating with a known heading in relation to the waves, it retrieves the corresponding amplitude and phase operators. They are used to construct a time series that is plotted graphically for visual comparison with experimental measurements in step 3. This is done with a simple sinusoidal curve:

$$\eta(t) = RAO \cdot A \cdot \sin\left(\frac{2\pi}{T}t + \phi\right)$$

where *RAO* is the response amplitude operator, *A* is the wave amplitude, and ϕ is the phase angle.

Search for minimal motion response. The optimization algorithm in the web app can be executed to minimize the vessel's decoupled motion response according to the steps:

1. The user selects as input one of the six motion modes to be minimized.
2. The algorithm searches for the heading that minimizes the response for the selected mode.
3. The algorithm sends command to the DP module to maneuver the ship toward the heading.

As verification of the algorithm, we conducted tests during which minimized results were known and which confirmed that the algorithm performed the search and selection correctly. See Section 7 for a link to the scripts the last two appendices discuss.

References

[1] Defense Acquisition University. Glossary of defense acquisition acronyms and terms. 2021, https://www.dau.edu/glossary/Pages/Glossary.aspx. (Accessed 11 June 2021).
[2] Fonseca ÍcaroA, Gaspar HM. Challenges when creating a cohesive digital twin ship: a data modelling perspective. Ship Technol Res 2020;1–14. http://dx.doi.org/10.1080/09377255.2020.1815140.
[3] Whitfield R, Duffy A, York P, Vassalos D, Kaklis P. Managing the exchange of engineering product data to support through life ship design. Comput Aided Des 2011;43(5):516–32. http://dx.doi.org/10.1016/j.cad.2010.12.002.
[4] Gaspar HM. Data-driven ship design. In: 17th Conference on computer and IT applications in the maritime industries. 2018, p. 426–39.
[5] Låg S, With SB. Standardisation as an enabler of digitalisation in the maritime industry. 2017.
[6] Gaspar HM. Javascript applied to maritime design and engineering. In: 16th Conference on computer and IT applications in the maritime industries. 2017, p. 253–69.
[7] Rachuri S, Subrahmanian E, Bouras A, Fenves SJ, Foufou S, Sriram RD. Information sharing and exchange in the context of product lifecycle management: Role of standards. Comput Aided Des 2008;40(7):789–800. http://dx.doi.org/10.1016/j.cad.2007.06.012.
[8] ISO. 19848 Ships and marine technology – standard data for shipboard machinery and equipment. Geneva, Switzerland: International Organization for Standardization (ISO); 2018.
[9] Erikstad SO. Merging physics, big data analytics and simulation for the next-generation digital twins. In: 11th Symposium On high-performance marine vehicles. 2017, p. 139–49.
[10] West TD, Blackburn M. Demonstrated benefits of a nascent digital twin. INSIGHT 2018;21(1):43–7.
[11] Erikstad SO. Designing ship digital services. In: 18th Conference on computer and IT applications in the maritime industries. 2019, p. 354–63.
[12] Robinet F, Arnaud R, Parisi T, Cozzi P. Gltf: Designing an open-standard runtime asset format. In: GPU Pro 360 guide to 3D engine design. A K Peters/CRC Press; 2018, p. 243–60. http://dx.doi.org/10.1201/9781351172486-20.
[13] IEC. Maritime navigation and radiocommunication equipment and systems – digital interfaces – part 1: single talker and multiple listeners. Geneva, Switzerland: International Electrotechnical Commission (IEC); 2016.
[14] ISO. 19847 Ships and marine technology – shipboard data servers to share field data at sea. Geneva, Switzerland: International Organization for Standardization (ISO); 2018.

[15] Ando H. Digitalization in the maritime industry. ClassNK Tech J 2019;1(1).
[16] Vindøy V. A functionally oriented vessel data model used as basis for classification. In: 7th International conference on computer and IT applications in the maritime industries, compit, Vol. 8. 2008, p. 60–9.
[17] Smith B. Against idiosyncrasy in ontology development. Front Artif Intell Appl 2006;150:15–26.
[18] Quaeghebeur E, Zaaijer MB. How to improve the state of the art in metocean measurement datasets. Wind Energy Sci 2020;5(1):285–308. http://dx.doi.org/10.5194/wes-5-285-2020.
[19] Sandvik B. three.geo: Geospatial data support in three.js. 2021, Available at https://github.com/turban/three.geo. (Accessed 11 June 2021).
[20] ISO. 19901-1 Petroleum and natural gas industries – specific requirements for offshore structures – part 1: metocean design and operating considerations. Geneva, Switzerland: International Organization for Standardization (ISO); 2015.
[21] Schaap D. SIMORC - system of industry metocean data for the offshore and research communities. In: OCEANS 2007 - Europe. IEEE; 2007, p. 1–2. http://dx.doi.org/10.1109/oceanse.2007.4302405, URL http://www.simorc.com/.
[22] Hatledal LI, Skulstad R, Li G, Styve A, Zhang H. Co-simulation as a fundamental technology for twin ships. Model Identif Control Nor Res Bull 2020;41(4):297–311. http://dx.doi.org/10.4173/mic.2020.4.2.
[23] Fonseca ÍA, Gaspar HM. A prime on web-based simulation. In: Iacono M, Palmieri F, Gribaudo M, Ficco M, editors. ECMS 2019 proceedings. ECMS; 2019, p. 23–9. http://dx.doi.org/10.7148/2019-0023.
[24] Andrews D, Dicks C. The building block design methodology applied to advanced naval ship design. In: Marine design conference. 1997, p. 1–8.
[25] Levander K. System based ship design. In: NTNU marine technology.(seakey naval architecture). 2012.
[26] Pal M. Ship work breakdown structures through different ship lifecycle stages. In: International conference on computer applications in shipbuilding. 2015.
[27] Xantic. SFI group system - a system for classification of technical and economic ship information. Product description. 2001.
[28] de Mello P, Carneiro M, Tannuri E, Kassab F, Marques R, Adamowski J, et al. A control and automation system for wave basins. Mechatronics 2013;23(1):94–107. http://dx.doi.org/10.1016/j.mechatronics.2012.11.004.
[29] Mello PCd. Sistema de automação e controle para tanques oceânicos com múltiplos atuadores (Ph.D. thesis), University of São Paulo; 2012.
[30] Ianagui ASS. Robust system design for consensus control in dynamically positioned vessel fleet (Ph.D. thesis), University of São Paulo; 2019.
[31] WAMIT. Wamit, inc. - the state of the art in wave interaction analysis. 2021, https://www.wamit.com/. (Accessed 17 December 2021).
[32] Hoem ÅS, Rødseth ØJ, Johnsen SO. Adopting the CRIOP framework as an interdisciplinary risk analysis method in the design of remote control centre for maritime autonomous systems. In: Advances in safety management and human performance. Springer International Publishing; 2021, p. 219–27. http://dx.doi.org/10.1007/978-3-030-80288-2_26.
[33] ISO. 8601 Date and time — representations for information interchange — part 1: basic rules. Geneva, Switzerland: International Organization for Standardization (ISO); 2019.
[34] de Oliveira FF. An open web platform for ship analysis and simulation. Norwegian University of Science and Technology; 2021.
[35] Kavallieratos G, Katsikas S, Gkioulos V. Cyber-attacks against the autonomous ship. In: Computer security. Springer International Publishing; 2019, p. 20–36. http://dx.doi.org/10.1007/978-3-030-12786-2_2.
[36] Fonseca ÍA, Gaspar HM. An open framework for data taxonomies in digital twin ships. 2022, (In Press).
[37] Ianagui ASS, Mello PCD, Tannuri EA. Robust output-feedback control in a dynamic positioning system via high order sliding modes: Theoretical framework and experimental evaluation. IEEE Access 2020;8:91701–24. http://dx.doi.org/10.1109/access.2020.2994515.