

# Towards a Scalable Digital Twin Framework Architecture for Port Resilience: Leveraging IoT, Edge AI, and Data-Driven Streaming for Seamless Physical-Virtual Convergence

Alireza Rahimi<sup>†</sup>, Amirhossein Azimyzadeh<sup>\*</sup>, Jeff Munde<sup>e</sup>, Kevin Wilcox<sup>‡</sup>, Shabnam Jabari<sup>§</sup>,  
Scott Bateman<sup>\*</sup>, Ian Church<sup>‡</sup>, Hung Cao<sup>†</sup>

{alireza.rahimi, amir.az, Jeff.Munde, kevin.wilcox, sh.jabari, scottb, Ian.Church, hcao3}@unb.ca

<sup>†</sup>*Analytics Everywhere Lab, University of New Brunswick, Canada*

<sup>‡</sup>*Ocean Mapping Group, University of New Brunswick, Canada*

<sup>§</sup>*ASIL, University of New Brunswick, Canada*

<sup>\*</sup>*SPECTRAL & RIDSAI, University of New Brunswick, Canada*

**Abstract**—Digital twin technologies are increasingly adopted in smart port initiatives; however, most existing implementations focus on terminal logistics and landside optimization while giving limited attention to hydrodynamic and underwater processes. This late-breaking paper presents an ongoing research and development of a scalable, water-centric digital twin framework designed to enhance port resilience through the integration of IoT sensing, edge computing, AI-driven analytics, and cloud-based data streaming. The architecture adopts a distributed, edge-enabled design that combines real-time environmental sensing with containerized edge services and centralized visualization. A modular prototype consisting of underwater and ground-edge units was developed to validate sensing, communication, and data management pipelines. Preliminary laboratory testing demonstrates reliable real-time data acquisition, edge processing, and cloud integration. The framework supports application domains including dredging optimization, vessel maneuvering assistance, and water-level prediction for crane scheduling. The proposed approach aims to contribute toward a scalable digital twins framework for port resilience.

**Index Terms**—Digital Twin, Smart Ports, Edge Computing, Internet of Things (IoT), Hydrodynamic Monitoring

## I. INTRODUCTION AND LITERATURE REVIEW

Digital Twin (DT) technology has become a central component of smart port digitalization strategies, enabling the integration of physical assets and real-time data to support sustainability and operational efficiency [1]. However, while these developments mark significant progress, the prevailing focus remains largely directed toward terminal operations, cargo flows, and landside optimization [1, 2]. Comparatively limited attention has been given to the water body and its surrounding environments, despite their direct influence on navigational safety and hydrodynamic uncertainty [3]. This reveals a structural gap concerning integrated, water-centric frameworks capable of capturing real-time flow dynamics, sediment transport, and bathymetric evolution [4, 5]. Addressing this gap is critical for port resilience, particularly regarding maintenance dredging and vessel maneuvering [6].

Recent technological advances offer new pathways to bridge these gaps. For example, the deployment of energy-efficient LoRa IoT systems has proven effective for continuous water monitoring, offering valuable lessons in maintaining reliable connectivity for long-term environmental use cases in marine settings [7]. In computer vision, the extraction of vessel hydrostatic indicators directly from 2D imagery provides a method for indirect displacement and weight estimation. Integrating this image-based estimation within an edge AI-enabled DT offers an additional decision-support layer for safe maneuver planning and tug optimization.

In Eastern Canada, many ports are the critical drivers of the Atlantic economy but face increasing demands for accurate seabed monitoring and comprehensive analysis of complex three-dimensional currents and tidal dynamics to support growing traffic and vessel size [8]. As a key piece of strategic infrastructure, the ports require proactive, data-driven approaches to enhance navigation safety, monitor and predict dredging requirements, and optimize operational capacity. Furthermore, tidal dynamics introduce operational constraints that require integrating high-resolution environmental data with terminal equipment scheduling—a linkage often overlooked in current port IoT initiatives [8].

Recent scholarship [1] confirms that DT technologies offer substantial promise for port modernization, yet a comprehensive, scalable framework remains insufficiently developed. Building on advances in AI-driven analytics, hydrodynamic simulation, and sensor integration, this research proposes an integrated approach combining ocean observation, Computational Fluid Dynamics, IoT, Edge AI, photogrammetry/LiDAR, data analytics, and 3D visualization within a hydrosatial-focused Maritime Digital Twin framework. Through structured consultations with our collaborators (Port of Saint John and the Port of Belledune, Canada) operational challenges related to dredging optimization, vessel maneuvering, and tide-dependent crane operations were systematically

translated into functional requirements. The proposed framework integrates real-time sensing infrastructure with predictive modeling and scenario-based simulation to enhance decision reliability and risk mitigation, offering seamless physical-virtual convergence.

Recent literature emphasizes the growing maturity of AI-enabled DT in marine and ocean environments [9, 10], while simultaneously highlighting persistent challenges related to real-time data assimilation, computational scalability, and edge integration [9, 11]. Although several frameworks propose hybrid physics-AI coupling and distributed architectures for maritime applications, many contributions remain at the level of simulation environments or conceptual prototypes without validated port-scale deployment [12]. In response to this gap, our work focuses on developing an edge-centric prototype to support continuous environmental sensing, localized data processing, and real-time AI inference within a port water system context. Rather than presenting a fully operational DT, this late-breaking paper describes the progressive development of a deployable demonstrator integrating data-acquisition pipelines, preliminary real-time data stream models, and a web-based visualization interface. The following section, therefore, transitions from theoretical framing to the technical architecture and initial results of the prototype, highlighting both achieved milestones and ongoing developments toward a comprehensive, proactive, data-driven DT.

## II. PROPOSED SYSTEM ARCHITECTURE

The proposed DT architecture is designed as a distributed, edge-enabled system that integrates real-time environmental sensing, data processing, AI-driven analytics, and interactive visualization within a unified framework. The architecture follows a layered yet interoperable design in which physical port water processes are continuously mirrored by computational models. Unlike purely cloud-based DT systems, the proposed framework distributes computation across edge nodes and centralized services to ensure low-latency processing, resilience to network instability, and scalable integration of predictive modules. Figure 1 presents the high-level architecture of the proposed system. The key components of this system are the Sensing Layer, Edge Layer, Cloud Layer, User Layer, and Communication Pipeline, which will be described as follows:

(i) **Sensing Layer:** serves as the primary interface for context-enriched data collection, capturing a multi-modal representation of the physical port environment. To achieve seamless physical-virtual convergence, this layer integrates a diverse array of sensors, including Underwater & Surveillance Cameras for visual monitoring and Sonar Ping & Hydrophone arrays for acoustic anomaly detection. Hydrodynamic and atmospheric states are continuously monitored through Acoustic Doppler Current Profilers (ADCP) for current velocity mapping, Weather & Air Quality sensors for meteorological context, and Multi Probe Water Quality instruments that track essential parameters like salinity and turbidity. Precise spatial-temporal alignment of these data streams is maintained

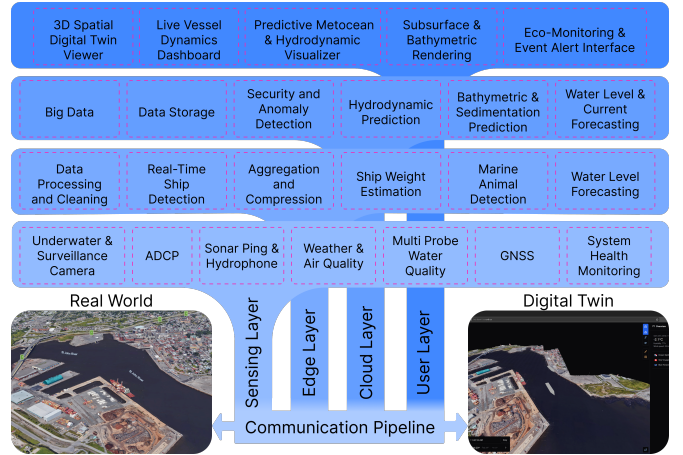


Fig. 1. High-level architecture of the proposed edge-enabled water-centric digital twin system.

via GNSS modules, while System Health Monitoring sensors—such as leak detection and power diagnostics—ensure the operational resilience of the edge hardware in harsh maritime conditions.

(ii) **Edge Layer:** Edge nodes handle the collected data, starting with preprocessing and validating the incoming data. Then, each edge device stores data locally and transfers data using various communication methods to ensure a reliable system. These nodes can operate for an adequate period without a direct power connection, relying solely on the battery. Also, the edge executes lightweight AI models and performs inference to provide real-time insights and decision support while reducing bandwidth requirements. In particular, our Edge AI models can be leveraged for the following tasks: (1) short-term water-level forecasting to address the crane optimization challenge; (2) trend prediction of sediment accumulation to help with the dredging challenge; (3) vessel displacement approximation based on draft and AIS data; (4) AI ship-detection model that processes the real-time camera feed and classifies 10 ship categories, toward vessel weight estimation; and edge live camera stream analytics for other analytical purposes.

(iii) **Cloud Layer:** engineered to ingest and process the massive volumes of high-frequency data streaming from the distributed edge nodes. Recognizing that maritime environmental data constitutes a big data challenge, this layer moves beyond simple archival storage to become a platform for extracting high-value insights and operational intelligence. The cloud infrastructure utilizes a containerized environment to host several specialized AI-integrated modules designed for intensive computation. Key functional modules include Hydrodynamic Prediction and Bathymetric & Sedimentation Prediction for long-term resilience planning, alongside Marine Animal Detection for environmental monitoring. Additionally, the layer performs complex Fluid Dynamic Computation and generates real-time Water Level and Current Forecasting to support berthing and navigation. By centralizing these

resource-heavy tasks, the Cloud Layer ensures a seamless transition from raw physical measurements to the sophisticated virtual simulations required for a proactive DT.

(iv) **User Layer:** The User Layer serves as the top-most tier of the architecture, providing a unified human-in-the-loop web-based interface for direct stakeholder interaction with the maritime DT. This layer integrates several specialized modules designed to translate complex data streams into actionable insights, starting with a 3D Spatial DT Viewer that offers an immersive, interactive representation of the port environment. Real-time operational awareness is facilitated through a Live Vessel Dynamics Dashboard, while environmental conditions are managed via a Predictive Metocean & Hydrodynamic Visualizer. To support critical decision-making regarding dredging and underwater safety, the interface includes Subsurface & Bathymetric Rendering, which highlights sediment patterns and shoaling zones. Furthermore, the layer incorporates an Eco-Monitoring module and an Event Alert Interface, ensuring that port operators can receive immediate notifications regarding anomalous activities or environmental threshold violations. As shown in the high-level architecture, these components work cohesively to provide a comprehensive “proactive, data-driven” view of the port’s physical and virtual states.

(v) **Communication Pipeline:** To ensure seamless physical-virtual convergence across underwater, ground, air, and water surface domains, the proposed architecture incorporates robust heterogeneous communication components working as the “nervous system” of the DT, bridging the gap between the physical sensing layer and the virtual analytical layer. Recognizing the physical limitations of wireless signals in aquatic environments, the framework utilizes two collaborating modules: an underwater unit for direct sensor interfacing and a ground-based unit equipped with an extensive communication stack. This stack integrates Wi-Fi, Satellite, Cellular, and LoRa technologies, providing the flexibility required to handle diverse data types and operational ranges—including the potential for long-distance communication with Autonomous Underwater Vehicles (AUVs) via LoRa. By facilitating a continuous data pipeline from submerged sensors to cloud-based visualization tools, these modules enable the real-time “hydrospatial” awareness required for port resilience. To mitigate the risks of signal attenuation and environmental interference common in sea-level operations, the system implements an intelligent fallback mechanism. If primary high-bandwidth links—such as Satellite or Wi-Fi—suffer degradation due to harsh weather or obstruction, the architecture automatically transitions to cellular or LoRa protocols. This multi-layered redundancy ensures that critical telemetry and AI-processed edge insights remain accessible, preventing data loss and ensuring the digital twin remains a reliable “live” representation of the port environment even under extreme conditions.

### III. PROTOTYPE IMPLEMENTATION

We provide details of our first prototype, which implements some of the features of the architecture described in Section II. We start by explaining the modular-designed of the prototype

at the sensing and edge layer, following by the description of the extendable hardware configuration, the Service-Oriented Architecture (SOA) software design patterns, the DT user interaction, and the connectivity pipeline implementation.

#### A. Modular-designed at Sensing & Edge Layer for Low Latency and Resilience

Given the harsh port conditions constraint, we designed our prototype to tolerate submersion up to 20m in salt water and withstand high water flow. Other constraints, such as sensor installation location and limitations, were considered, including ADCP installation location and communication protocols, as well as underwater cameras and hydrophones. On the other hand, wireless communication protocols like WiFi and LoRa cannot operate underwater due to their physical properties; therefore, we decided to use two modules: one underwater and one on the ground.

These two modules collaborate and communicate with each other. Figure 2a presents the 3D model of the underwater module that can connect to multiple underwater sensors, including ADCP, an underwater camera and light, multi-probe water quality, a hydrophone, and a depth sensor. This module can power these sensors and collect data on a Raspberry Pi 5 board. It is also equipped with leak detection sensors and monitoring capabilities. It is connected to the ground module for transferring the collected data. Figure 2b illustrates the 3D model of the ground module. Unlike the underwater module, this box is equipped with more communication modules for data transfer. It also has sensors to collect weather and location data.

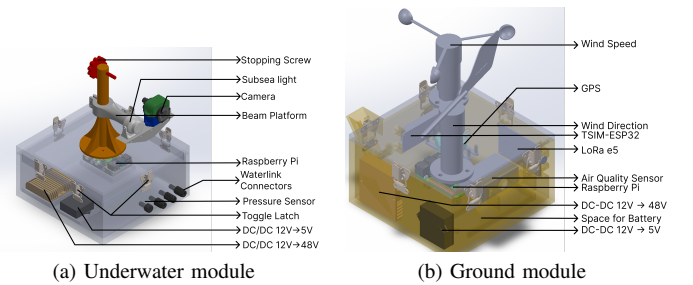


Fig. 2. The 3D designs of modules and their components in Sensing & Edge Layer.

#### B. Extendable Hardware Configuration

Our prototype integrates commercial-off-the-shelf embedded processors, multimodal environmental sensors, and heterogeneous communication modules in a modular edge platform. A key engineering challenge was ensuring robust connectivity between the sensor array and the central processing unit, given their differing environmental protection requirements: the sensors are inherently waterproof, while the core electronics are not. To address this, the underwater module was designed for structural integrity under hydrostatic pressure, employing WetLink Penetrators to create reliable high-pressure waterproof seals between external sensors and internal circuitry.

In contrast, the ground module housing the communication stack requires no extreme waterproofing but was engineered to withstand prolonged exposure to ultraviolet radiation, high humidity, and heavy precipitation in a marine atmosphere. This dual-tier hardware approach ensures system functionality in the corrosive and variable conditions of both subsurface and surface maritime environments. To support the iterative nature of the project, the hardware architecture was designed to be highly modular and expandable. Every component, including the central processing unit, was selected for easy replacement or extension. The system primarily uses development boards rather than fixed integrated circuits to maximize configuration flexibility. The Raspberry Pi 5 (RPi5) serves as the current central processor due to its extensive ecosystem, high computational performance, and wide range of extension modules that accelerate prototyping. As the system evolves to run multiple edge-based AI models concurrently, the architecture supports upgrades such as AI HATs for the RPi5 or a transition to NVIDIA Jetson modules for superior real-time AI inference performance. This adaptable strategy ensures the prototype’s long-term viability as it scales to meet the growing demands of the maritime DT.

### C. Service-Oriented Architecture (SOA) Software Stack across DT Layers

Figure 3 illustrates the SOA-based software stack designed and deployed across the different DT layers. We developed a service-based architecture in which each service performs a single task at the sensing and edge layers. In the underwater module, sensor and storage services are deployed, while the ground module hosts network, queue, storage, and remote debugging services. All services are designed to be scalable and reusable, and are executed in Docker containers to enable parallel operation.

The sensor service is a parallel data acquisition and streaming service that interfaces with hardware, collects data, and forwards it to a queue. It is built on a generic base sensor class that simplifies inheritance, allowing new sensors to be added easily. The storage service retrieves data from the queue and saves a local copy. The underwater storage serves as a backup during communication outages with the ground station, while the ground storage persistently records all events and data. The queue service, implemented as a Redis instance in Docker, provides a reliable data pipeline between services. Each service can define and publish to a queue or subscribe to existing ones through a global configuration system. The network service, designed similarly to the sensor service for extensibility, incorporates a priority-based fallback mechanism. It uses a configuration file to manage data types and supported transfer protocols, selecting the highest-priority available protocol and falling back to alternatives if needed. In case of total outage, local storage ensures data preservation. Finally, the remote debugging service, deployed in the cloud, enables SSH access to the edge nodes over Wi-Fi or the Internet and provides system health monitoring via a local web-based application.

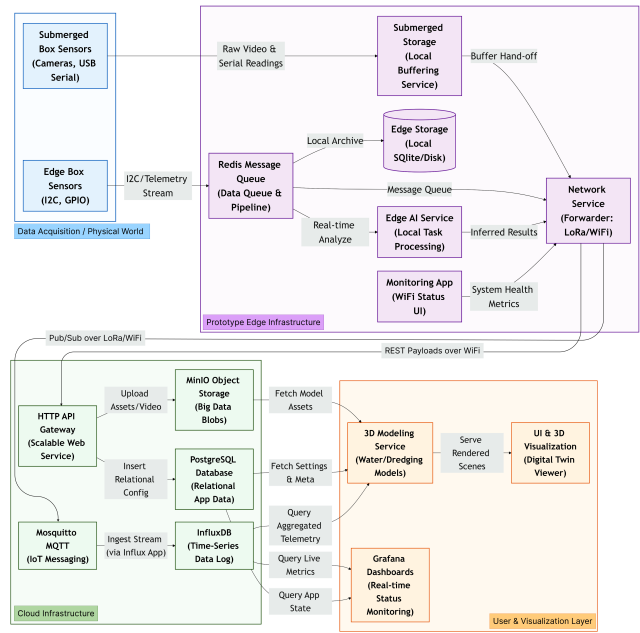


Fig. 3. Overview of SOA Design Pattern across DT Layers

### D. Web-based DT User Interaction

At user layer, the frontend employs the WebGPU API for hardware-accelerated rendering within the 3D Spatial Digital Twin Viewer. An adaptive timeline controls temporal navigation to visualize historical events retrospectively alongside projected predictive model outputs. To handle computationally demanding environmental datasets (e.g., water currents, tidal variations, salinity), large multidimensional arrays are encoded into texture data. This circumvents standard web rendering limitations by loading data directly into GPU memory. Furthermore, data retrieval adapts to payload and latency constraints. Time-sensitive telemetry relies on WebSockets, and bulk requests depend on HTTP servers. To maintain spatial accuracy, a custom conversion module maps global geospatial coordinates into the local 3D scene space. Finally, dynamic role-based access toggles specific views and analytical tools to match the authenticated user’s operational scope.

### E. Heterogeneous Connectivity Pipeline Implementation

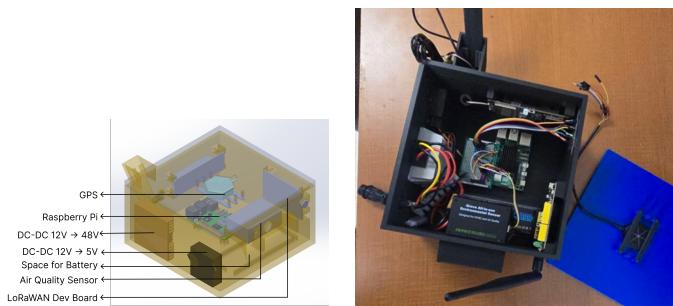
We implemented a multi-modal communication infrastructure with fallback mechanisms to enhance reliability. The prototype integrates four wireless technologies: Wi-Fi (AX210), Satellite (Starlink), Cellular (SIM7600G-H), and LoRa (E5 LoRaWAN). Telemetry data from the edge is ingested via an MQTT broker (Mosquitto) and forwarded by a subscriber service to a time-series database (InfluxDB) for storage and temporal analysis. Real-time and historical visualization is provided through Grafana dashboards connected directly to InfluxDB. For LoRa communication, The Things Stack (TTS) serves as the LoRaWAN network server, handling device registration, authentication, gateway coordination, uplink/downlink

management, and payload decoding. TTS interfaces with back-end services via MQTT or HTTP and uses PostgreSQL for device metadata, sessions, and network configuration. Image and metadata uploads are managed by a FastAPI-based HTTP service. Files are stored in MinIO object storage, while metadata is maintained in PostgreSQL. Database administration is performed via Adminer. Nginx acts as a reverse proxy for secure internal routing and HTTPS enforcement, while Cloudflare provides DNS management, traffic protection, and edge-level access control. This layered cloud architecture forms a distributed yet integrated system that securely handles heterogeneous data streams from the edge, supporting telemetry ingestion, storage, analytics, visualization, and file management.

#### IV. LABORATORY TESTINGS & PRELIMINARY RESULTS

##### A. Laboratory Prototype Testing

For the lab testing purpose, we have designed a smaller-scale version of the proposed system, which combines the features of both ground and underwater edge modules for the preliminary testing and evaluation of the equipment and software. Our short-term goal is to evaluate and refine our prototype and ensure that each developed software component and hardware component can operate in real-world conditions. The initial design and component integration are illustrated in Figure 4a. For the primary prototype, a modular, battery-powered system was engineered to aggregate data from ADCP, GNSS, meteorological, and system health-monitoring sensors. Controlled by a RPi5, the unit incorporates LoRa and cellular modules for heterogeneous communication. Power is supplied by a 12V LiFePO4 battery, regulated via DC-DC converters to provide 5V and 48V rails. To facilitate rapid iterative refinement, the testing assembly was fabricated using 3D-printed Polylactic Acid (PLA), as shown in Figure 4b.



(a) 3D model of the testing module showing included components in the first test phase. (b) Printed and assembled testing module providing

Fig. 4. Overall caption describing the four images.

Data acquisition is managed through custom Python-based services: a serial protocol interface for ADCP configuration and command execution, an I2C-based service for weather data, and a combined UART/I2C pipeline for GNSS positioning. These asynchronous data streams are ingested into a

multi-queue cache system. Finally, dedicated storage and network services manage data persistence and facilitate uplink to the cloud via cellular and LoRa protocols, ensuring operational continuity in the maritime environment.

##### B. Preliminary Results

1) *Sample data streams results from sensors:* Some sample data collected from initial lab prototype streamed to our cloud infrastructure. Figure 5 depicts the realtime data collected 3 represented sensors of our prototype, including temperature, humidity, and air quality sensors.

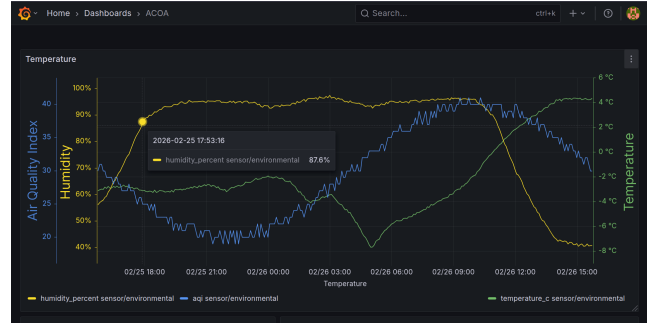


Fig. 5. Sample Data streams from sensors visualized in the cloud with Grafana

2) *DT visualization for User Interaction:* An interactive web-based visualization platform provides a virtual port environment. This visualization is based on a 3D spatial viewer that supports live vessel dynamics and can display a predictive metocean and hydrodynamic visualizer. The viewer has sub-surface and bathymetric rendering to provide useful sediment locations and patterns, which are important for decision-making. Finally, the visualization layer has an Eco-Monitoring feature and an event alert interface. The current interface functions as a demonstrator platform and will be progressively integrated with dynamic simulation services. We demo the Alpha version of our DT visualization [at this URL](#).

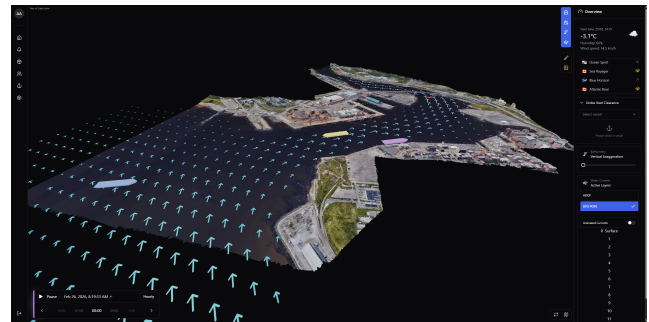


Fig. 6. Prototype web-based visualization interface displaying environmental data and predictive outputs. This prototype demo can be found [here](#).

#### V. DIGITAL TWIN USE CASES AT THE PORTS

This section describes potential application domains where our proposed DT can deliver operational and strategic value.

By integrating real-time environmental sensing, AI-driven analytics, and interactive visualization, the framework supports data-informed decision-making across hydraulic management, vessel maneuvering, water-level prediction, and port security operations.

**1. Dredging optimization:** Dredging represents a major recurring operational cost, often requiring reactive scheduling based on limited bathymetric or historical information. By continuously integrating hydrodynamic data (e.g., current velocity, turbidity, sediment trends) with predictive models, our DT can support sediment accumulation forecasting and scenario-based planning. This enables more accurate dredging scheduling, reduces unnecessary operations, and optimizes costs through condition-based intervention rather than fixed-interval maintenance.

**2. Vessel maneuvering and pilot assistance:** Our real-time DT visualization of water currents, wind conditions, and environmental parameters can be combined with AI-based vessel weight estimation and traffic data to improve navigational awareness. Pilots and port operators can use this information to better anticipate hydrodynamic forces during docking and departure, thereby improving maneuver efficiency, reducing fuel consumption, and enhancing safety margins, particularly under adverse weather or tidal conditions.

**3. Crane usage optimization:** Our proposed DT enables water-level prediction and optimization of crane operation time windows. By integrating historical tide data, real-time water-level measurements, and meteorological forecasts into predictive models, the system estimates short- and medium-term water level variations. These predictions allow port operators to identify optimal berthing windows for vessels with specific draft requirements and to schedule crane operations under safe and efficient conditions. Better synchronization of vessel arrivals, water depth availability, and crane utilization reduces idle time, prevents delays, and increases berth throughput. This improves key performance indicators (KPIs) such as turnaround time, asset utilization rate, and operational cost efficiency, delivering more reliable planning for both port authorities and customers.

**4. Maritime security and anomaly detection:** By fusing hydrophone signals, AIS data streams, and camera-based monitoring, our proposed DT can detect unusual vessel behavior, unauthorized intrusion, or anomalous underwater activity. Machine learning models can identify deviations from normal traffic or acoustic patterns, enabling early warning and coordinated response. This integrated security layer enhances situational awareness and strengthens the resilience of port infrastructure against operational and security-related risks.

## VI. CONCLUSION

This study introduced a scalable DT framework to enhance port resilience by integrating IoT sensing, edge computing, AI-driven analytics, and cloud-based visualization. In contrast to many existing port digitalization efforts that primarily focus on terminal logistics and landside optimization, the proposed approach emphasizes the hydrodynamic and underwater domain.

By combining distributed edge intelligence with centralized data services, the architecture enables real-time environmental monitoring, low-latency processing, and modular scalability across heterogeneous sensing systems.

A prototype was designed to demonstrate the technical feasibility of the framework. The system integrates underwater and ground-edge modules equipped with ADCP, environmental sensors, communication subsystems, and containerized software services. Initial laboratory testing confirmed the successful integration of sensing, data streaming, storage, and cloud visualization components. The identified use cases highlight the practical relevance of the framework for improving operational efficiency and supporting data-driven decision-making in port environments.

Future work will first focus on completing the full-scale implementation of the proposed prototype as described in the system architecture and on deploying it in collaboration with the Port of Saint John and the Port of Belledune. Field deployment will enable long-term validation under real operational and environmental conditions. The subsequent phase will focus on data collection and curation to support the development and training of the dedicated AI models mentioned before. This progression from prototype deployment to data-driven model refinement will advance the framework toward a fully operational and adaptive maritime DT.

## ACKNOWLEDGMENT

This work was supported by the ACOA Project No 227444

## REFERENCES

- [1] S. M. Homayouni, J. Pinho de Sousa, and C. Moreira Marques, "Unlocking the potential of digital twins to achieve sustainability in seaports: the state of practice and future outlook," *WMU Journal of Maritime Affairs*, 2024.
- [2] M. Ayyub *et al.*, "Digital twin for resilience and sustainability assessment of port facility," *Maritime Policy & Management*, 2025, preprint available via University of Glasgow ePrints.
- [3] IHO, "The digital twin of the navigable waters: paving the way for e-navigation," [Online], 2024, accessed 2026.
- [4] R. Lepper *et al.*, "A hydrographic dataset of the wadden sea as a foundation for a digital twin of the coastal ocean," *Scientific Data*, vol. 12, p. 1746, 2025.
- [5] S. Karasu *et al.*, "Monitoring sediment transport in certain harbor launches in the southeastern black sea," *Water*, vol. 15, no. 21, p. 3860, 2023.
- [6] W. P. Fuller, R. J. Wagner, and R. E. Lewis, "U.s. hydrodynamic dredging challenges and opportunities," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2678, no. 2, 2023.
- [7] S. A. R. Azghadi *et al.*, "An energy-efficient lora iot system for water monitoring: lessons learned and use cases," in *2024 IEEE International Conference on Consumer Electronics-Asia (ICCE-Asia)*. IEEE, 2024, pp. 1–4.
- [8] S. Mali *et al.*, "Tide-induced bottom current and sediment resuspension in halifax harbour," *Water*, vol. 16, no. 22, p. 3272, 2024.
- [9] Y.-z. Li *et al.*, "A review of the applications of digital twin technology in marine research," *China Ocean Engineering*, vol. 39, pp. 383–394, 2025.
- [10] G. Chen *et al.*, "Toward digital twin of the ocean: from digitalization to cloning," *Intelligent Marine Technology and Systems*, vol. 1, no. 1, p. 3, 2023.
- [11] M. S. Dihan *et al.*, "Digital twin: Data exploration, architecture, implementation and future," *Heliyon*, vol. 10, no. 5, p. e26503, 2024.
- [12] J. Neugebauer, L. Heilig, and S. Voß, "Digital twins in the context of seaports and terminal facilities," *Flexible Services and Manufacturing Journal*, vol. 36, no. 3, pp. 821–917, 2024.