Digital twins for the sustainable maintenance of ageing waterway infrastructure

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Keywords: maritime infrastructure, structural inspection, damage detection, lifecycle management.

Abstract

A substantial part of the ageing waterway infrastructure in Europe, including locks, quay walls, and coastal protection structures, is approaching the end of its service life, necessitating either replacement or extensive repairs to prevent hazards. The integration of digital twins offers transformative opportunities for the complete digitalization of these assets, enhancing structural inspections and maintenance processes. This paper explores methods and solutions developed through the 3D HydroMapper, port_AI, and Port:Evolution research projects funded by the Federal Ministry for Digital and Transport, Germany from 2018 to 2027. By utilizing mobile platforms for geodata collection, both above and below water, and employing technologies such as sonar, photogrammetry, and laser scanning, comprehensive and precise surface scans and images of infrastructure can be achieved. These scans enable early detection of damage, facilitating timely repair measures and extending the service life of structures. The fusion of diverse georeferenced data types within a cloud portal ensures efficient sharing and lifecycle management, contributing to sustainable infrastructure maintenance.
This paper provides a full workflow from the acquisition of waterway infrastructure below and above water to the planning of its maintenance.

1. Introduction

1.1 Ageing waterway infrastructure

The aging infrastructure of ports and harbors presents significant challenges for maintaining operational efficiency and ensuring safety. As these structures deteriorate over time, the need for effective inspection and maintenance strategies becomes increasingly critical (Görler et al., 2007). Traditional inspection methods often fall short in providing comprehensive assessments due to their limited accessibility and the complexity of underwater environments.

Studies have found that 80% of locks and weirs in Germany are over 50 years old, and 30% exceed 100 years of age, despite a theoretical lifespan of 80 to 100 years. The Federal Waterways Engineering and Research Institute (BAW) reports that many these structures are in a fair to poor condition (BAW, 2021). This results in the need for regular inspections of underwater infrastructure.

In traditional structural inspections, divers examine the structure on a sampling basis. Due to poor visibility, this often involves primarily tactile methods. Consequently, only 2-3% of the whole building are inspected. Furthermore, global geometric changes cannot be detected by the diver.

Recent advancements in sonar-based systems and digital structural assessment technologies offer promising solutions to these challenges. Sonar technology enables detailed underwater imaging, facilitating the detection of structural anomalies and degradation that are otherwise difficult to identify. Coupled with digital structural assessment tools, these technologies provide a robust framework for evaluating the condition of aging harbor infrastructure. This paper explores the integration of sonar-based inspection systems and digital assessment methodologies, highlighting their potential to enhance the accuracy and efficiency of infrastructure evaluations. By leveraging these innovative approaches, stakeholders can better manage maintenance efforts, extend the lifespan of critical assets, and ensure the continued functionality of port operations.

1.2 Workflow for sustainable lifecycle management

The sustainable lifecycle management of maritime infrastructure is crucial for maintaining the integrity and functionality of underwater structures. This paper presents a full workflow:

- Data acquisition (Section 2)
- Data processing and cloud storage (Section 3)
- Damage labeling (Section 4)
- Automated planning (Section 4).

A full workflow to cover the aforementioned aspects has been developed within three research projects (Figure 1) funded by the Federal Ministry for Digital and Transport, Germany: 3D HydroMapper (2018-2021), port_AI (2021-2024), and the current project Port:Evolution (2025-2027):

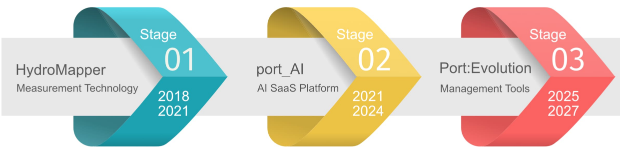

Figure 1. Timeline of the three research projects: 3D HydroMapper, port_AI, and Port:Evolution.

3D HydroMapper: This project focuses on creating a robust measurement system designed to accurately capture the condition of underwater infrastructure. Utilizing advanced sonar and imaging technologies, the system aims to provide detailed assessments of structural integrity, identifying areas of concern that require maintenance. The development of this measurement system is essential for ensuring precise and reliable data collection, which forms the foundation for informed decision-making in infrastructure management.

port_AI: The second project involves the creation of a comprehensive data portal that hosts and displays diverse types of data related to underwater infrastructure. This portal is designed to facilitate the identification and classification of damages by integrating data from multiple sources, including sonar imaging, environmental sensors, and historical maintenance records. By providing a centralized platform for data visualization and analysis, the portal enhances the ability to monitor infrastructure health and prioritize maintenance activities effectively.

Port:Evolution: Building on the capabilities of the data portal, this project aims to develop a holistic damage management system. The enhanced portal will link identified damage with appropriate remedial actions, generating maintenance plans and tender documents. This integrated approach ensures that all aspects of damage management are addressed, from detection to intervention, streamlining the maintenance process and improving the efficiency of infrastructure management. By automating the generation of maintenance plans and tender documents, the system supports proactive and strategic planning, ultimately extending the lifespan of maritime infrastructure.

These research projects collectively contribute to a comprehensive workflow for sustainable lifecycle management, emphasizing the importance of accurate measurement, effective data integration, and holistic damage management. By leveraging these innovative solutions, stakeholders can ensure the resilience and sustainability of underwater infrastructure, safeguarding the operational efficiency of maritime activities.

2. Data acquisition

The collection of geodata using mobile platforms in urban and rural areas is widespread. This data collection with vehicles or drones has become much easier in recent years so that users can access continuously updated maps or 3D models of cities via well-known free data platforms. In contrast, the geodata acquisition of maritime and rural infrastructure is still in its infancy. Until today, only 5-10% of the surface area of the underwater structures have been randomly scanned by divers, while the condition above water has been documented photographically. Since as much as 50-60% of the structure's surface is under water, almost 50% of the structure remains unchecked (Holste, 2025).

Due to the ageing of structures and the associated operational limitations, infrastructure operators are keen to complete their database in order to obtain a comprehensive overview of their structures (e.g. with a 3D as-built survey) and make informed decisions about the remaining service life and necessary investments. For this reason, a measurement platform (HydroMapping system) has been developed (Figure 1) using various recording technologies, such as sonar for recording linear port infrastructure under water and photogrammetry and laser scanning above water. These technologies ensure the entire acquisition of waterway infrastructure by scanning their geometries but also by providing high resolution images to resolve smallest damages. Depending on the velocity of the vessel and the water depth, around 1,5 km length of quay wall can be acquired in one day (Hesse et al., 2019).

The measurement system consists of two different methods that will be elaborated in the following: HydroScanning (Section 2.1) and HD Mapping (Section 2.2).

Figure 1. Measurement system developed within the research project 3D HydroMapper

2.1 HydroScanning

To make the condition of the underwater infrastructure visible, a survey called HydroScanning is carried out using a specialized measurement platform. This ensures optimal alignment of the sensors with the parts of the structure to be captured, thereby achieving high resolution of the objects.

To create high-resolution and precise models of underwater structural components, two main tasks must be accomplished. First, the geodetic positioning of the measurement platform, i.e. the survey vessel, and second, the actual acquisition of the water structure.

Positioning of large-scale kinematic multi-sensor systems typically involves a combination of an Inertial Measurement Unit (IMU) and satellite measurement methods. The IMU provides relative spatial orientation and a relative 3D position of the entire measurement system with several hundred measurements per second. However, due to physical limitations, it exhibits sensor drift over time. This drift is compensated by long-term stable satellite measurement methods. In the case of the 3D HydroMapper system, all four major Global Navigation Satellite Systems (GNSS) are used in combination to ensure the highest possible accuracy: GPS, GLONASS, GALILEO, and Beidou (Hesse et al., 2021).

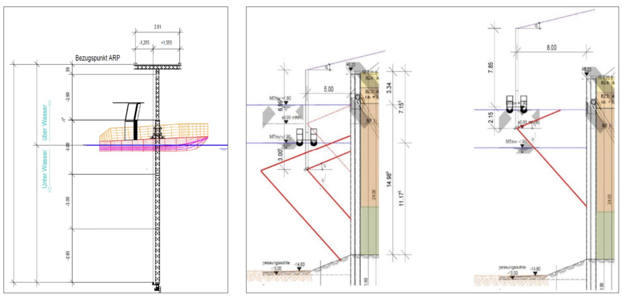

Figure 2. Measurements in multiple stripes: height variable HydroScanning (Borchers et al., 2023).

The underwater data acquisition is carried out using a high-resolution acoustic scanning system. To ensure high resolution data, the distance between sensor and object, if possible, should be less than 5m, a measurement frequency of 400 kHz or higher is used and the angles of incidence are kept as small as possible by a height-adaptive system (Figure 2). This allows the structure to be recorded at different heights with several strips.

The systems can be extended by several modular elements to put the sensor in the best position possible. Depending on the construction's height and water depth, the object is surveyed in multiple strips to reduce the measurement distance and to avoid large incidence angles.

Above water, data from a profile laser scanner, GNSS and a fiber-optic IMU are fusioned. Further cameras can texture the point cloud in real colors. Figure 3 shows an example of a quay wall. The seabed is colored according to its height to make scouring visible. The sheet piling is colored in vertical direction according to the mean position of the wall. This makes local and global deformations of the object visible. The above water point cloud is textured with real-world colors, i.e. rgb values.

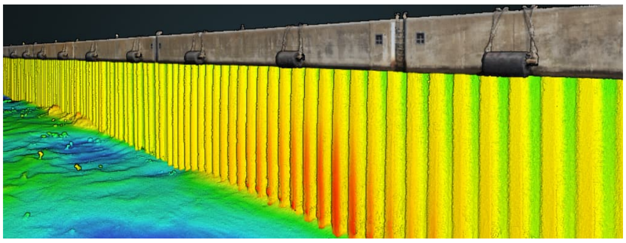

Figure 3 Under water point cloud with a global deformation indicated in red.

A true innovation in the 3D HydroMapper is the patented active quality-assuring object alignment of the imaging sensors by rotating the sensor adaptively to the object's surface. This allows both the above-water and underwater sensors to address three key challenges crucial for data quality:

1. Object shadowing, especially in cascaded pile constructions, can be effectively eliminated through active sensor alignment (Figure 4).
2. Ensuring an optimal angle of incidence on the respective object surfaces reduces both measurement noise and systematic effects in the data, providing better data quality compared to a static system.
3. When the measurement system moves slowly, which is crucial for achieving high object resolution, wind and cross currents can cause the ship or measurement platform to drift unintentionally. These effects can be fully compensated for by using active sensor detection.

Due to the adaptive alignment and control of the sensors, common pile constructions with small pile spacings can also be accurately captured. Therefore, HydroScanning is suitable for the high-precision recording and creation of as-built models for historical quay walls and storage foundations, which typically feature up to six rows of wooden piles and a recessed wooden sheet pile wall beneath the quay wall head (Figure 4).

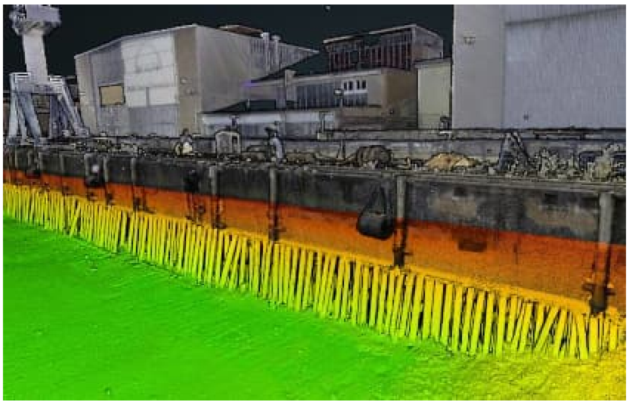

Figure 4. Under water point cloud of pile dwellings and above water laser scan.

2.2 HD Mapping

However, as shown in Schmitz et al. (2020), small damages, such as cracks, cannot be resolved in the point cloud due to the limited resolution capability. They are better visible in photos having a small ground sampling distance (GSD). For this reason, a camera array with three cameras arranged one above the other, directed into three different directions. It is further equipped with an GNSS antenna to get georeferenced images. This compensates for the weather-dependent use of drones. From these images a detailed vertical orthophoto is calculated, which can resolve small details. Figure 5 shows a section of the orthophoto of a concrete lock chamber. One can recognize the pores of the concrete as well as the vertical crack in the middle of the orthophoto. This opens up the opportunity to determine damage in a very detailed manner directly from the office.

Figure 5. Section of the orthophoto of a concrete lock chamber with a vertical crack.

3. Data fusion and provision

After data acquisition, the provision and fusion of georeferenced point clouds, photogrammetry data, meshes and 360° panoramas poses a particular challenge. As part of the research project port_AI, a framework has been developed that fuses different types of data in a digital twin and provides it with the metadata required for lifecycle management. All data types are made available in a cloud portal called InfraCloud© (Figure 6). As a basis, all data types must be adequately georeferenced.

Figure 6. Different data types are all combined in the InfraCloud©.

Several tests have shown that especially the combination of point clouds and orthophoto delivers high resolution meshes in which an inspection of the infrastructure can be performed from the office.

Figure 7 shows the overview on a quay wall of a harbour. Multiple data sources are shown in this figure: the bright colors indicate the under-water point cloud acquired with the HydroScanning system. All points that belong to the seabed are indicated in blue. The greenish/yellowish colors indicate the sheet pile walls. The real-world colors represent the meshes gained from the fusion between point cloud and orthophotos. Further icons demonstrate the position of 360° panoramic images, labelled damages, previous inspection reports or as-completed drawings. Additionally, georeferenced photos or further sensor data, such as inclinometer measurements, for example, can be assigned to the asset.

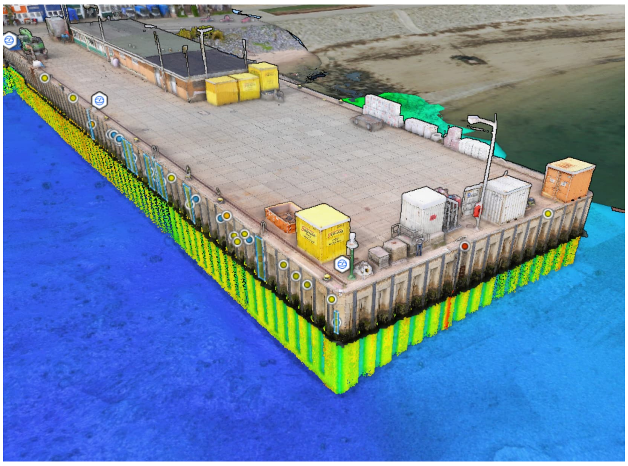

Figure 7. Fusion of all data sources: underwater scans, above water scans, orthophoto, 360° panoramic image with indicated damages.

What is visible here can be used as a digital twin, for example due to the integration of real time sensor data with integrated alarms if defined thresholds are exceeded. This is why the project is also focused on the georeferenced consideration of stationary sensor data and local measurements, such as residual wall thickness or concrete cover measurements, which contribute significantly to the assessment of the state of preservation. It is intended to provide infrastructure operators, consultants and construction companies with low-threshold access to the construction data over the entire operating period. To this end, innovative methods and procedures were developed regarding IoT-based (IoT - Internet of Things) measurement technology to be able to use scanning data in the fully digitalized process for the operation of a smart infrastructure.

4. Lifecycle management

This digitized representation of the infrastructure can be used for lifecycle management. One main application is the indication of damages and their management (Hake et al., 2022; Almouri et al., 2024). These include, for example, cracks, spalling and corrosion. Exact damage categories can be taken from damage catalogues, such as provided in Görler et al. (2007). The management of those damages is part of the third research project Port:Evolution. The digital infrastructure inspections allow for a better damage management by classifying, categorizing and prioritizing damages, and furthermore, giving suggestions and plans for maintenance measures. The following sections present the features of damage management (Section 4.1), financial planning and scheduling (Section 4.2), and lifetime extension (Section 4.3)

4.1 Damage management

Damage detection under water and above differ due to the different data sources. Since the underwater point clouds do not have such a high resolution as the laser scanner point clouds, geometric anomalies are indicated as points-of-interest (POI).

Figure 8 gives an example where a geometric anomaly occurs. Two planes have been placed in front of the sheet piling. Most probably, the wall has already been repaired. The POIs can be introduced as suspected cases of damage in the data portal.

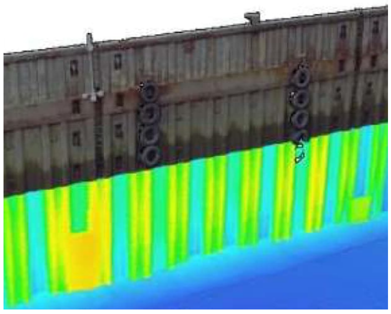

Figure 8 Points-of-interest in the sonar point cloud.

Above water, damages are much better to see. Figure 9 illustrates an example of a damaged quay wall. In the high-resolution mesh, edge damage, cracks, and rust marks are visible. Each asset has a defined object structure that outlines all components. All damages can be classified according to a standardized damage catalog and assigned to a specific component. The color of the icons indicates the damage class, ranging from 1 (minor damage) to 4 (severe damage).

In addition to the damage classes, the boundaries and dimensions of the damage can be defined, as shown in Figure 10. This allows for the determination of the entire area that needs repair. Since repair measures are standardized for all damages in Germany, the classification combined with the damaged area enables the prioritization of repair measures as well as financial planning and scheduling.

Figure 9. Obvious damages at a quay wall.

Figure 11 shows the labelling of different damages with different classifications. Hence, a great overview on georeferenced damages is given, which shows the hotspots of damages. This overview is an enormous help considering the planning of repair measures.

Figure 10. Labelled damage with polygon.

Further advances will follow in the further development of the platform. To make work more efficient, first promising research has been done for the automatic detection of damages in the research projects 3D HydroMapper (Hake et al., 2022) and port_AI (Alamouri et al., 2024). Integrating AI into damage labelling will reduce the amount of work enormously.

4.2 Financial planning and scheduling

Given the area of damages, the costs for repairs can be estimated. Figure 12 presents an example of such a cost calculation for a support wall. Cracks and spalling are assigned to the object. By knowing the repair costs, the total expense for the relevant area can be calculated. Additional costs, such as those for building site facilities or taxes, can be incorporated into the pricing. This provides a concrete price that can be used for resource planning.

Furthermore, the overview of damage hotspots combined with the damage classification show which parts of the object should be renewed and which parts are in good condition. This allows for a sustainable and cost-efficient planning of repair measures before damages get worse and more expensive. Integrating costs and time in the planning process, the tools provides a 4D and 5D planning automation to support infrastructure operators in their facility management.

4.3 Lifetime extension

Since the underwater condition of waterway infrastructure is largely unknown and only partially understood, their lifespan is often estimated using models. However, sheet pilings, for example, are significantly affected by corrosion, particularly in splash water and low water areas.

Knowing the true geometry of infrastructure such as sheet pile walls allows for accurate modeling of their load and service life. The HydroMapping system can globally acquire the geometry of the wall, enabling the true shape of the wall to be modeled using a spline approximation developed in the research project 3D-HydroMapper (Borchers et al., 2023). This information, combined with data from other external sensors (such as inclinometers and residual wall thickness measurements), provides well-founded insights into the actual load on the structure. Integrating such knowledge service lifetime can be updated using the digital twin.

As the modelled service lifetime is often pessimistic to prevent hazards, these calculations can extend the service life of sheet pilings. Consequently, this leads to substantial financial savings as well as significant reductions in CO_2 emissions (Holste, 2025).

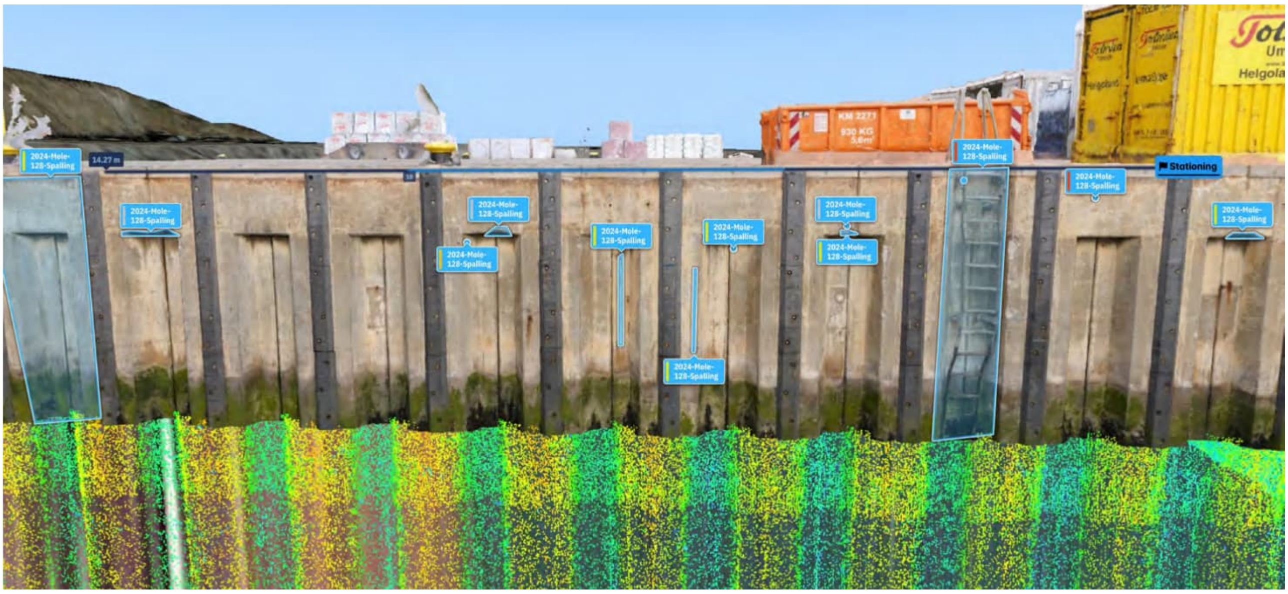

Figure 11. Quay wall with indicated damages (Holste, 2025).

Support wall

#	Description	Quantity	Unit	Price (€)	Total (€)
01	Concrete repair				2.486
01/**01**	Crack	21,3	m	75	1.598
01/**02**	Spalling	8,08	m²	110	889
	Subtotal				2.486
	building site facilities	10	%	249	
	Subtotal				2.735
	Access equipment	1700	€		1.700
	SUM (Netto)				4.435
	Additional costs	0	%		0
	Subtotal				4.435
	Sales tax	19	%		843
	SUM (Brutto)				**5.278**

Figure 12. Cost calculator of repair measures.

5. Conclusions and outlook

This paper presents the results of the three research projects 3D HydroMapper, port_AI, and the ongoing project Port:Evolution funded by the Federal Ministry for Digital and Transport, Germany. The goal of these projects is to develop a complete framework for the sustainable maintenance of ageing waterway infrastructure. Important steps have been:

- The development of a measurement system that delivers high resolution points clouds and images above and below water,
- The development of a data platform to combine all data sources in a digital twin, which allows for digital infrastructure inspection,
- The management of infrastructure by implementing measures for repairing infrastructure, financial planning, and scheduling.

These results form the basis for digital infrastructure inspection and digital maintenance planning. First pilot projects show an increase in efficiency of 50% while inspecting infrastructure.

The ongoing project Port:Evolution deals with the planning automation as mentioned in Section 4 to improve the process of sustainable maintenance of ageing waterway infrastructure. Therefore, the project focuses on the automated detection of damages, especially under water, the automation of planning processes, and the integration of high-resolution laser scans under water to build a solid data base for reliable infrastructure inspection.

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