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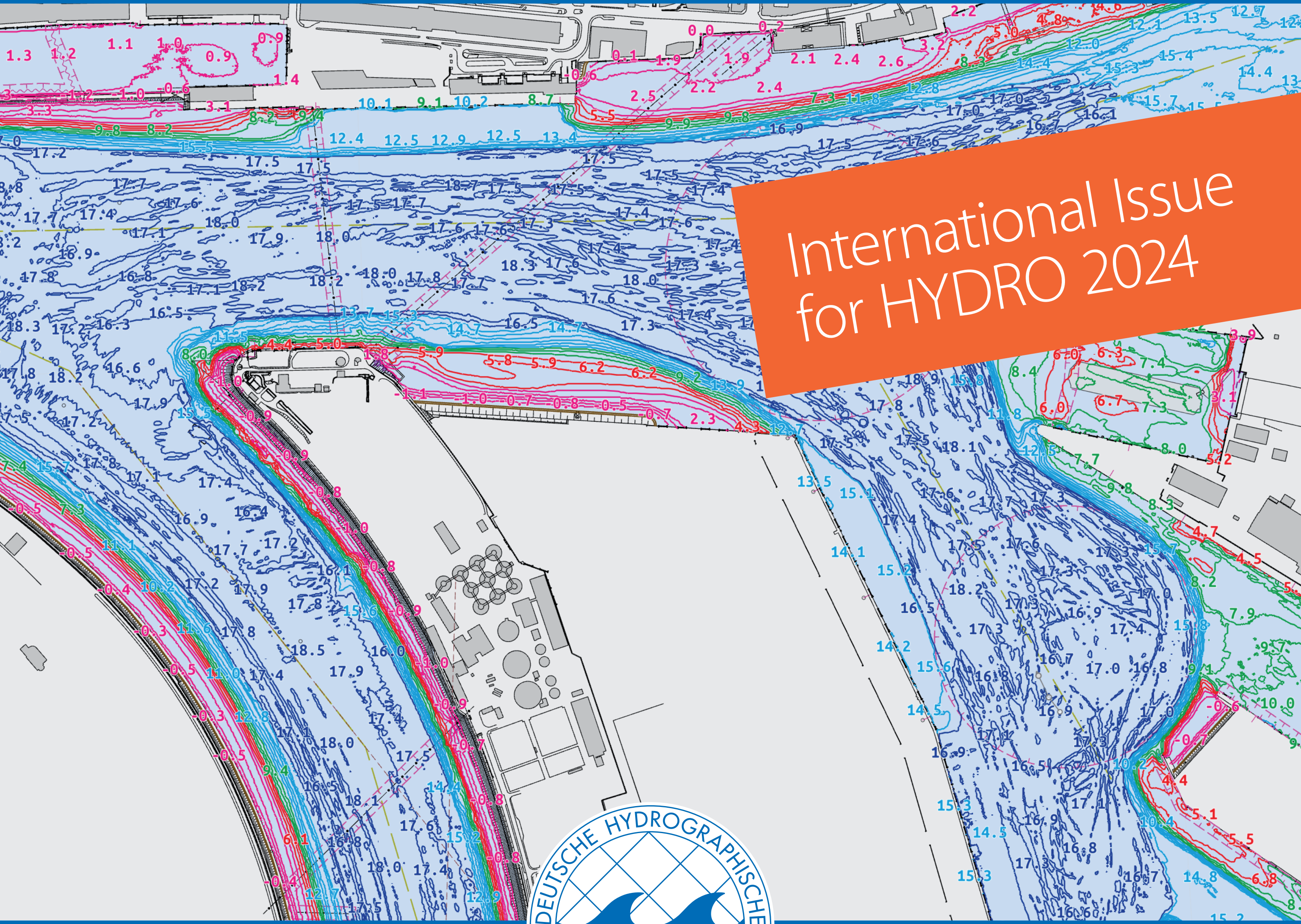

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Dear readers,


Lars Schiller

Once again, an issue of *Hydrographische Nachrichten – Journal of Applied Hydrography* – is being published entirely in English. This time, however, it is an experiment. We have offered those who are giving a presentation at HYDRO 2024 the opportunity to publish a technical article in our journal that matches their presentation. This means that the editorial team has relinquished control over the content of the magazine to a certain extent. With 59 lectures to be held in Rostock, anything between zero and 59 contributions was possible. In the end, there were seven contributions. Should we now say »only« seven contributions or »at least« seven contributions? In any case, we can say that the size of the magazine issue turned out to be quite normal. So the experiment went well.

Nevertheless, one can ask why the response was not greater. Basically, however, this fits in with what we observe elsewhere. The speakers want to be present at the events, they want to see their abstract printed in the conference handbook. But only a few authors are willing to write a detailed contribution. Consequently, most contributions come from universities or research institutions, where publications count. It is therefore all the more pleasing that we also received contributions from industry and surveying companies from the field.

We actually had a few more contributions confirmed. However, there were some cancellations shortly before the editorial deadline, for example because the measurement data could not yet be fully analysed and therefore no results could be published. The good news is that we will be printing more HYDRO 2024 articles in the next issues.

I have now told you how this magazine came about. However, organising an entire conference is much more complex. Find out what is involved in organising HYDRO 2024 in the interview with Sabine Müller. The main organiser of the event also talks about her company Innomar and her commitment to the German Hydrographic Society (DHyG).

If you are travelling to Rostock, I hope you have an interesting visit to HYDRO 2024 and that you enjoy reading the articles in this issue. And for anyone who is unable to come to Rostock, this issue may at least give you a small impression of what is happening at HYDRO 2024.

Impressum

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Interview

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Hydro Portal

Enhancing hydrographic data management in the Port of Hamburg

An article by MARYLOU GENTILHOMME, FRANK JOSUTTIS-KÖSTER, MICHAEL KOWALCZYK and JASMIN WELLNITZ

The Port of Hamburg has experienced significant modernisation in hydrographic data processing and presentation through the development of the Hydro Portal. This web-based platform, which provides an integrated view of harbour operations, is the result of collaboration between the Hamburg Port Authority (HPA) and Hamburg-based software company SenseLabs. The Hydro Portal serves as an efficient interface to Teledyne Geospatial's Caris Bathy DataBASE, providing access to HPA's more than 30,000 survey data records, expanding daily.

hydrographic data management | digital transformation in maritime operations | collaborative software development | user-centred design | GIS | cloud technology
hydrographisches Datenmanagement | digitale Transformation im maritimen Bereich | kollaborative Softwareentwicklung | nutzerzentriertes Design | GIS | Cloud-Technologie

Der Hamburger Hafen hat durch die Entwicklung des Hydro Portals eine bedeutende Modernisierung in der Verarbeitung und Darstellung hydrographischer Daten erlebt. Diese webbasierte Plattform, die einen integrierten Überblick über den Hafenbetrieb bietet, ist das Ergebnis der Zusammenarbeit zwischen der Hamburg Port Authority (HPA) und dem in Hamburg ansässigen Softwareunternehmen SenseLabs. Das Hydro Portal dient als effiziente Schnittstelle zur Caris Bathy DataBASE von Teledyne Geospatial und liefert somit den Zugang zu über 30 000 Peildatensätzen, deren Anzahl täglich wächst.

Authors

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Context and motivation – digitalisation at HPA

The Hydro Portal is a prime example of a successful digitalisation initiative at the Port of Hamburg (Fig. 1). What once began as an innovation project has now become an indispensable part of port management and is extensively used by various departments within and outside HPA in their daily operations. The success of the project is attributed to the close collaboration of experts from the fields of hydrography, navigation, geoinformation and software development. Particularly noteworthy is the consistent application of methods such as user-centred design and agile development, along with modern solutions in IT security, DevOps, cloud technology and modular architectures. The long-standing cooperation between the development team and the specialised departments has also fostered a deep understanding of hydrographic data processing within the software team.

© Photo by Christian Verheyen

Fig. 1: Hydrographic data acquisition forms the foundation of the Hydro Portal's depth data display. Five survey vessels are deployed daily in the Port of Hamburg to collect this data

To understand the success of the digitalisation, it is worthwhile to look at the path the Port of Hamburg has taken in providing depth data (Köster and Thies 2015). In 1994, the first software system for processing hydrographic data was introduced at HPA. Until 2004, both the processing software and measurement technology were supplied by the provider Atlas. Atlas already used Caris GIS for hydrographic data processing, but in 2004, the components were diversified, and HPA started to implement the whole processing and data management with Caris software like HIPS, BEAMS and HPD. This expansion increased the service capabilities of the hydrographic department, but also broadened the software landscape, including the amount of data that could be processed, which presented new challenges for HPA's IT department. Thus, the hydrographic department adopted digital practices early on, but consumers still relied on traditional hydrographic paper charts.

A major paper chart user was the Vessel Traffic Centre (Fig. 2), which used them to monitor water depths in the Port of Hamburg. This required about 200 square metres of paper. At the end of 2010, the project »AHOI – Arbeitsgerechte Neugestaltung der Nautischen Zentrale des Hamburger Hafens und Innovative Mensch-Modell-Interaktion« (User-Centred Redesign of the Vessel Traffic Centre of the Port of Hamburg and Innovative Human-Model Interaction) was launched. As part of this project, cutting-edge concepts were developed, including the use of interactive touch tables. In 2014, these ideas became a reality with the so-called »Peiltisch« (Survey Table), initially as a feasibility study. The application was precisely tailored to the needs of the Vessel Traffic Centre, allowing tasks such as planning ship manoeuvres to be performed digitally. The forms of interaction closely followed the established analog working methods of the navigators, resulting in high acceptance and gradual replacement of paper charts in the Vessel Traffic Centre.

The Peiltisch pilot project was a success and quickly sparked interest in other departments of HPA. It soon became clear that a desktop version was needed to make the application accessible to as many users as possible. The hydrographic department of HPA was responsible for developing the desktop version of the Peiltisch, known as the Peildesk. Once again, requirements for this desktop workstation were gathered, and processes were identified to be mapped into the software. The application also attracted interest beyond hydrography, extending to areas such as asset management and dredging operations.

As further requirements were implemented, it became evident that the technical foundation of the original pilot project was reaching its limits. Fundamental rework was necessary, leading to the decision for a redevelopment that would build on the extensive knowledge gained from the pilot project. At the same time, the modernisation efforts of the HPA IT department introduced new requirements for the security and operation of the application. Therefore, in 2020, the platform »Hydro Portal« was redeveloped in collaboration with the Hamburg-based software company SenseLabs, whose team had partially been involved in digitalisation initiatives since the AHOI project. This modern cloud solution was designed for efficient hydrographic data visualisation within a web interface (Fig. 3), closely integrating with Caris software.

The Hydro Portal's success over its predecessor lies in its efficient, secure provision of depth data over the internet to external HPA customers, the ability to generate the familiar PDF survey charts directly, and its support for various devices with appropriate forms of interaction like touch tables. As a result, in 2022, HPA completely phased out hydrographic paper charts.

© Photo by Julia Kück

Fig. 2: The Vessel Traffic Centre of the Port of Hamburg, a central hub for monitoring and managing maritime traffic

Data integration and visualisation – user-centred design

Feature scope of the Hydro Portal

The Hydro Portal supports users with diverse professional backgrounds in a wide range of tasks by providing integrative geo-referenced and temporal visualisation of multiple datasets. For example, the hydrographic data acquisition team plans survey operations by combining tide, depth, bridge and berth occupancy information. The visual integration of this data allows complex relationships to be easily understood, enabling efficient and reliable decisions about route planning for survey vessels, determining which areas to cover and when.

Another user group, the Vessel Traffic Centre, receives daily updates on the depths throughout the Port of Hamburg and is informed about areas where the data has changed. This data, coupled with additional information such as tide, enables ship manoeuvres to be planned collaboratively, with the visualisation of ship silhouettes providing additional support. Dredging operations also benefit from the comprehensive data integration for planning operational activities, for example volume calculations based on comparison with target depth models. These examples illustrate

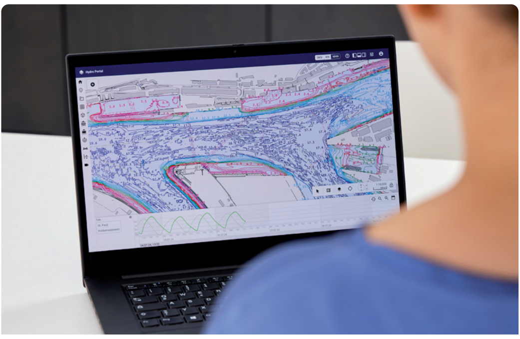

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Fig. 3: The Hydro Portal, a modern cloud solution for hydrographic data visualisation and integration, supporting various professional tasks

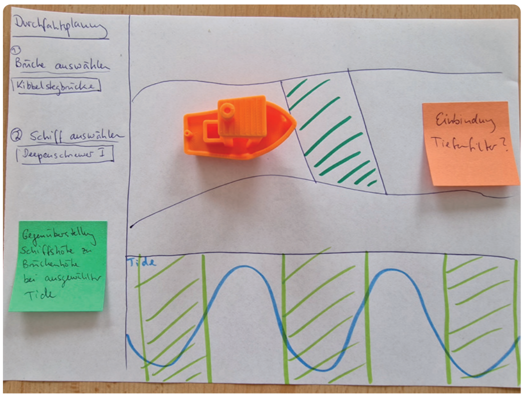


Fig. 4: Paper mock-up used in the early stages of bridge passage planning development, serving as an informal tool to align user requirements

only a part of the potential applications – the Hydro Portal offers many more features that support various professional fields.

User-centred design and agile development

A key factor in the Hydro Portal's success is the consistent application of user-centred design principles. Users are involved from the very beginning in the agile, iterative development process. Requirements are gathered collaboratively using methods like user interviews. The development team then creates paper mock-ups (Fig. 4) as informal discussion tools to present initial solutions to identified problems. This early alignment ensures the development team truly understands the domain and its key aspects and can implement the requirements correctly. Any change requests from the department can be optimally integrated at this stage.

Once the mock-ups are reviewed, implementation begins. In the next iteration, the feature is introduced in a test version. Because customers are involved from the outset, they build a deep understanding of the software, significantly reducing the need for extensive onboarding or training.

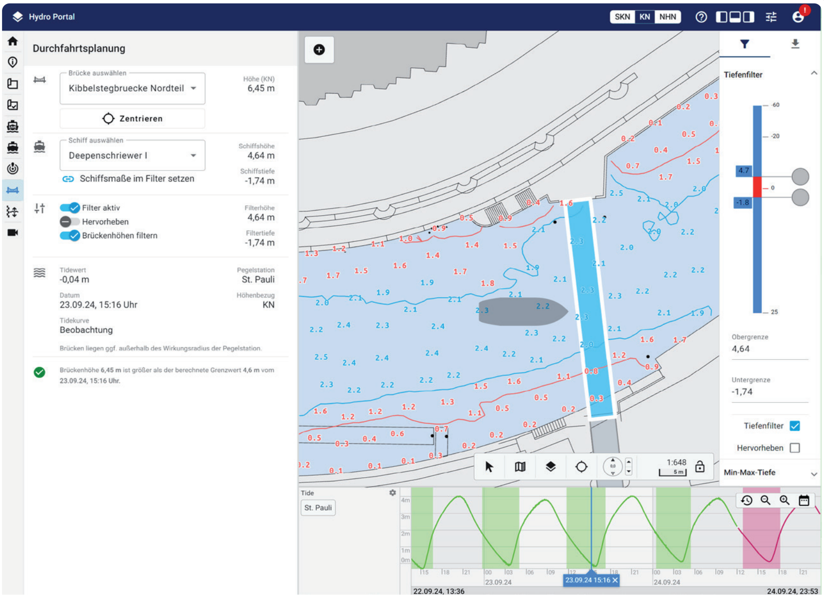
Use case: Bridge passage planning

An example of user-centred design is the redevelopment of the bridge passage planning feature, which was implemented in 2022 for survey vessel operation planning. In the Port of Hamburg, ship traffic is heavily dependent on the tides, making bridge passages possible only at specific times. The implementation of this software feature was closely coordinated with the relevant department and precisely executed following a feedback loop (Fig. 5).

The bridge passage planning feature is a prime example of the integrative functionality of the Hydro Portal. While the web interface can be operated with just a few clicks, the back end queries various existing services of HPA to link the necessary information – including depth information, water level data and bridge details from the ArcGIS Enterprise Server. The visualisation of this data is achieved through the close integration of several foundational UI components of the Hydro Portal: the map, the timeline, the browsing area and the depth filter.

The harbour map, based on ArcGIS Maps SDK for JavaScript, provides a geo-referenced visualisation of port data and, in this case, displays the position of bridges and their availability for passages at specific times. The map integrates seamlessly with the timeline, a proprietary SenseLabs development, which shows time-dependent data such as tides or ship movements. The depth filter is used to identify shallow water sections in the port, which are crucial for safe navigation and ship manoeuvre planning. Information about the survey vessels, such as ship height and draft, is stored in the department's collaborative workspace and can be easily adjusted by users when changes to reference data are needed.

The bridge passage planning feature was embedded into the extensible application framework of the Hydro Portal, specifically into one of the so-called browsing areas. The browsing area, a section of the Hydro Portal designed for data navigation, is typically used to display data in a table format, providing users with detailed insights and filtering options. Interestingly, in bridge passage planning, the browsing area offers a customised, interactive assembly of relevant information about bridges and survey vessels instead of its usual tabular structure, demonstrating its flexibility to support both general and specialised application scenarios.



Durchfahrtsplanung

Brücke auswählen: Kibbelstegbruecke Nordteil
Höhe (KN): 6,45 m

Schiff auswählen: Deepenschriewer I
Schiffshöhe: 4,64 m
Schiffstiefe: -1,74 m
Schiffsmaße im Filter setzen

☑ Filter aktiv
☐ Hervorheben
☑ Brückenhöhen filtern
Filterhöhe: 4,64 m
Filtertiefe: -1,74 m

Tidewert: -0,04 m
Pegelstation: St. Pauli
Datum: 23.09.24, 15:16 Uhr
Höhenbezug: KN
Tidekurve: Beobachtung

Brücken liegen ggf. außerhalb des Wirkungsradius der Pegelstation.

✓ Brückenhöhe 6,45 m ist größer als der berechnete Grenzwert 4,6 m vom 23.09.24, 15:16 Uhr.

Obergrenze: 4,64
Untergrenze: -1,74
☑ Tiefenfilter
☐ Hervorheben

Tide: St. Pauli

Fig. 5: Final implementation of the bridge passage planning feature in the Hydro Portal, visualising bridge passages based on tide, depth and survey vessel information

Custom access control for different user groups

The bridge passage planning tool is essential for the hydrographic department but is not needed by other HPA departments. To ensure user-friendliness and manage access to sensitive information on a departmental basis, the Hydro Portal features a sophisticated role and permission system. A user from dredging operations, for example, has access to different software tools upon logging into the portal than a user from the hydrographic department. This is particularly important for external HPA users, like terminal operators, who are granted limited access to depth data.

Flexible front end architectures: From desktop to touchscreen

When customisation through role and permission management is not sufficient, developing additional user interfaces is necessary. An example is the replacement of the Peiltisch application with a web version optimised for touchscreens. The Hydro Portal Touch was specifically developed for the Vessel Traffic Centre and designed for use on a 4K 55-inch touch table, but it can also be used by other HPA departments on portable tablets. A highlight is the development of touch-enabled web tools. Thanks to the use of monorepo technologies, the infrastructure is shared and reused across front ends, all connected to the same back ends.

Technical foundation – hydrographic data processing within the Hydro Portal

Hydrographic data management at HPA

Accurate and continuous depth data acquisition is crucial for safe port operations. The hydrographic department of HPA provides up-to-date depth information for nautical assessments, maintenance and construction projects through hydrographic survey charts, as well as additional products like volume calculations and difference maps.

A core system supporting these activities is the Teledyne Caris Bathy DataBASE solution (BDB), which manages large volumes of hydrographic data and serves as the backbone for data collection and provision in various HPA applications.

Data management and services in Bathy DataBASE

Caris Bathy DataBASE (BDB) is a proven, secure and reliable software for storing and managing bathymetric data, ideal for organisations that manage large amounts of bathymetric surveys, including ports like HPA, and for instance also have to comply with open data policies and marine spatial data infrastructure (MSDI) initiatives. In this context, data interoperability between different (GIS) systems is essential. This project with HPA showcases how BDB has evolved into a data-centric and service-based solution powered by automation and leveraging cloud-native technology.

Furthermore, through workflow analysis and discussions with HPA, this project was used to further enhance the BDB solution. The result is a commercial off-the-shelf (COTS) solution which, thanks to its REST API approach, allows a direct access to data stored in a BDB database using relational database management system (RDBMS) technology such as PostgreSQL. The solution provides REST services to publish, discover, consume and process coverage and feature data. Open Geospatial Consortium (OGC) web services are also available, for example Web Coverage Service (WCS), Web Map Service (WMS) or Web Feature Service (WFS).

Several benefits are worth mentioning, including scalability and responsiveness through containerisation and load balancing, a microservices architecture ensuring that each service is responsible for each type of data request and can be scaled as needed by the business layer, and data security and integrity through robust authentication. Besides a cloud deployment of the REST-based services, the solution can also be deployed on premise, which was done in collaboration with SenseLabs for this project.

Together through several consulting phases Teledyne Geospatial and HPA implemented this new solution and migrated data. New automated workflows were also developed, and existing ones migrated. Caris processes and Python scripts can indeed be assembled and configured into custom automated workflows, allowing HPA technical experts to focus on work truly requiring their experience, input and skills.

Visualising hydrographic data in the Hydro Portal

The Hydro Portal utilises the Caris Bathy DataBASE solution as a data source to display depth data alongside other relevant port information. Depth data is presented as soundings and contours (Fig. 6)

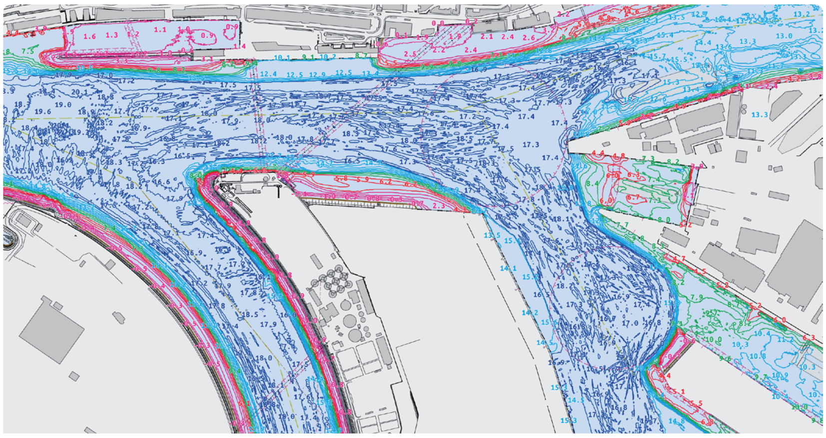


Fig. 6: Vector data visualisation in the Hydro Portal, showing soundings and contours for the harbour area

using standardised geoservices on the Hydro Portal's web interface. These services, developed by SenseLabs, include authenticated access controls for secure data provision to various user groups. Interfaces are optimised for both vector and raster data, enabling a smooth, tiled display of depth data in the front end. Soundings adjust in detail based on the map's zoom level, with back end filtering ensuring a clear and nautically safe display.

The Hydro Portal also supports raster data display (Fig. 7) in COG format (Cloud Optimised GeoTIFF) for efficient front end use.

Back end strategies for flexible and high-performance data processes

Efficient back end data processing is crucial for real-time or near-real-time data availability, ensuring a smooth user experience. The Hydro Portal's back end supports real-time calculations, precomputed data for immediate access and processes with acceptable wait times. For instance, generating a PDF survey chart takes about two minutes in the background, allowing users to continue working. Fast sounding filtering algorithms eliminate the need for precomputing individual datasets; for large, combined datasets, precomputed values are cached. The software architecture allows easy swapping of processing workflows without major changes, facilitating the implementation of faster methods as they become available.

Modular architecture, microservices and containerisation

The modular architecture of the Hydro Portal allows for a seamless integration of external systems and processes from various vendors. For example, this enables the use of processes from Caris COTS products, which can be assembled into custom workflows by hydrographers from HPA using the software Caris Process Designer.

The modular architecture of the Hydro Portal is implemented using various microservices. These microservices are designed, segmented and containerised in a way that allows them to be easily scaled. For instance, if the number of users increases, additional containers with a highly demanded microservice can be spun up. The automatic scaling is orchestrated by Kubernetes. This orchestration and containerisation allow new software versions to be deployed without downtime and prevent outages through redundancy management. To meet the high security requirements of critical infrastructure, extensive security measures are implemented within operations.

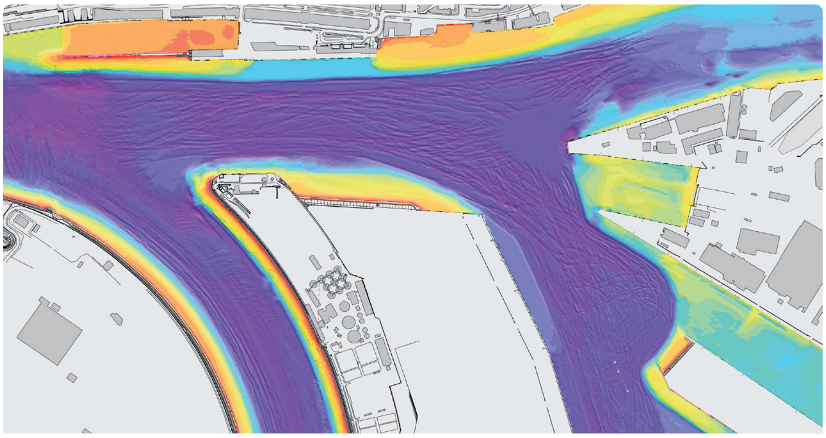


Fig. 7: Visualisation of raster data in the Hydro Portal, depicting the same harbour area

Strong partners – a success story through collaboration

The successful development of the Hydro Portal for HPA is based on a combination of proven technologies and custom-developed software components. A key success factor was the consideration of HPA's existing applications, as well as close collaboration with partners who provide central elements of this infrastructure, such as Teledyne Geospatial with Caris Bathy DataBASE and Esri ArcGIS solutions.

A crucial aspect of the project was understanding that HPA already had extensive experience in using these established systems. The solutions from Esri and Teledyne Geospatial were already deeply integrated into HPA's workflows, were technologically mature and offered advantages in terms of training and operating costs. The development of the Hydro Portal was not intended to replace any of the existing legacy systems, but rather to optimally integrate the various solutions.

For this, it was necessary to recognise the strengths of the existing systems and incorporate them strategically into the design process of the Hydro Portal. Where there were requirements not addressable by existing systems, the integration of open-source tools was beneficial. At the same time, the custom development of software components was essential to address the specific needs of HPA. The development of a high-performance component for securely filtering depth values across various zoom levels illustrates this approach. In this case, custom development was chosen to meet certain specific requirements that were not fully covered by existing systems or open-source tools. This functionality enables efficient and precise representation of depth data at different scales, which is crucial for the daily operations of HPA.

In addition to the ongoing collaboration with HPA, close coordination with partners like Teledyne Geospatial ensured seamless system integration. APIs were directly coordinated between SenseLabs and Teledyne Geospatial teams, facilitating tasks like migrating to a new Caris Bathy DataBASE version.

This project demonstrates how successful collaboration and the targeted use of proven technologies, combined with tailored solutions, can lead to flexible and efficient system integration. Custom development bridged specific functional gaps and complemented existing systems, contributing to a sustainable and economically viable implementation.

A glimpse into the future – integration in other ports through cloud solutions and user-centred approaches

The Hydro Portal's success at HPA offers valuable insights for other ports. However, a test system at the Port of Bremerhaven showed that features considered intuitive for HPA did not achieve the same acceptance in this new context. This experience highlights the importance of a user-centred design approach: workflows and requirements vary significantly from port to port, even within the same domain.

The Hydro Portal incorporates a comprehensive set of proven components, adapters and methods that were developed by SenseLabs, based on the experiences gained at HPA. This flexible toolkit enables the rapid development of customised Hydro Portals for various ports, tailored to meet the specific needs of each customer. The modular design allows efficient reuse of key UI components and back end infrastructure, while specific adjustments are made through a user-centred design process.

Cloud support is another critical factor in success. It enables rapid and seamless deployment of the system by allowing the infrastructure to scale flexibly and adapt to local conditions. Additionally, it ensures future-proofing by supporting continuous development and straightforward maintenance of the system.

Overall, the combination of a flexible architecture, modular components and a user-centred design approach enables the successful adaptation of the Hydro Portal to the specific needs of other ports, laying the groundwork for future projects. //

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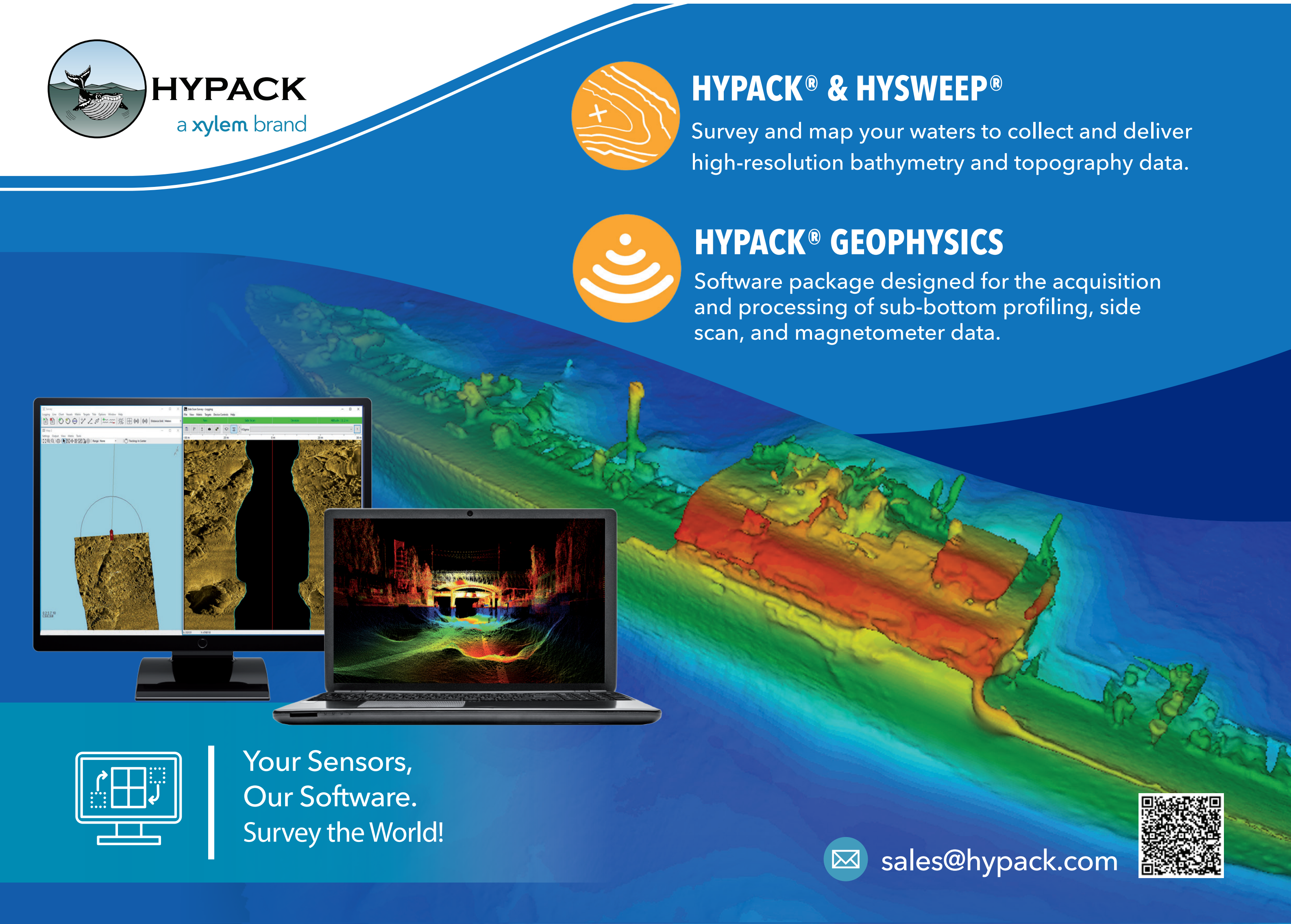

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HyFiVe: hydrography on fishing vessels

A new monitoring system enables cost effective and scalable ocean monitoring

An article by ANDREAS HERMANN, FREDERIK FURKERT, MATHIS BJÖRNER, MICHAEL NAUMANN, DANIEL STEPPUTTIS, MARTIN GAG and STANISLAS KLEIN

Whether for modelling climate change or understanding fish stocks, ocean data is essential across many disciplines. Traditionally, such data has been collected by research vessels, which are costly and limited in scope. To enhance data resolution, the concept of ships-of-opportunity presents a scalable alternative, utilising vessels originally financed for non-scientific purposes. Fishing vessels, in particular, offer unique advantages as they operate in deep waters, allowing access to the entire water column for attached measuring systems. We developed a highly flexible, autonomous measuring system within the HyFiVe project over the past three years. This system comprises three main components: a sensor carrier mounted on fishing gear for underwater data collection, a deck unit for geo-referencing and data transfer, and an onshore server for automatic quality control and data storage. In this article, we provide an overview of the HyFiVe measuring system, summarise the results of measurement campaigns to date, and discuss the system's benefits to the community.

hydrography | monitoring system | ships of opportunity | open source | citizen science | future fishery
Hydrographie | Überwachungssystem | Nicht-Forschungsschiffe | Open Source | Bürgerwissenschaft | Fischerei der Zukunft

Ob für die Modellierung des Klimawandels oder das Verständnis von Fischbeständen – Meeresdaten sind für viele Disziplinen unerlässlich. Traditionell werden solche Daten von Forschungsschiffen gesammelt, die kostspielig und in ihrer Reichweite begrenzt sind. Um die Datenauflösung zu verbessern, stellt das Konzept der Ships of Opportunity eine skalierbare Alternative dar, bei der Schiffe eingesetzt werden, die ursprünglich für nicht-wissenschaftliche Zwecke finanziert wurden. Insbesondere Fischereifahrzeuge bieten einzigartige Vorteile, da sie in tiefen Gewässern operieren und den Zugang zur gesamten Wassersäule für die angebrachten Messsysteme ermöglichen. Im Rahmen des HyFiVe-Projekts haben wir in den vergangenen drei Jahren ein hochflexibles, autonomes Messsystem entwickelt. Dieses System besteht aus drei Hauptkomponenten: einem Sensorträger, der an einem Fanggerät für die Datenerfassung unter Wasser angebracht ist, einer Deckseinheit für die Georeferenzierung und Datenübertragung sowie einem Server an Land für die automatische Qualitätskontrolle und Datenspeicherung. In diesem Artikel geben wir einen Überblick über das HyFiVe-Messsystem, fassen die Ergebnisse der bisherigen Messkampagnen zusammen und diskutieren den Nutzen des Systems für die Gemeinschaft.

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1 Introduction

The ocean is a crucial resource for humanity, serving various purposes such as transportation, food supply, and recreation. However, human activities have increasingly exerted anthropogenic pressure on marine ecosystems, a situation exacerbated by climate change. This is particularly true for sensitive ecosystems like those in coastal and marginal seas with limited water exchange, such as the Baltic Sea. The Baltic Sea is a unique but fragile environment where the impacts of pollution, fishery pressure and climate change are more pronounced (HELCOM 2018; ICES Advice 2024).

Hydrographic parameters, which include salinity, temperature and dissolved oxygen levels, are critical indicators for assessing the health of such marine environments. Traditionally, these data are collected by research vessels or moored platforms. To acquire more extensive data from the open oceans, gliders and floats are also utilised (Freeland et al. 2020; Queste et al. 2012). While these methods provide high-quality data, their high operational costs limit their spatial and temporal coverage.

To overcome these limitations and enhance data resolution, the concept of »ships of opportunity« (SoO) has been proposed. SoO leverages vessels not primarily intended for scientific research to collect valuable environmental data. This approach is particularly promising for increasing the frequency and coverage of data collection, especially in regions like the Baltic Sea, where extensive monitoring is crucial.

However, SoO systems are usually limited to surface water monitoring (Rosa 2021). In this context, fishing vessels offer a unique advantage as they deploy gear in deep water, making them ideal platforms for deploying hydrographic sensors that can collect data throughout the entire water column. Recognising the absence of suitable commercial systems for this purpose, we initiated the HyFiVe (Hydrography on Fishing Vessels) project in 2021 to develop a flexible and autonomous monitoring system.

2 HyFiVe in the Baltic Sea

The HyFiVe system was initially intended for use in trawl fisheries. However, the situation in the Baltic Sea has deteriorated dramatically in recent years, with key fish stocks, such as cod and herring, collapsing. This decline has led to the closure of significant portions of the fishery, with little hope of recovery in the near future due to persistent adverse water conditions that hinder reproduction (HELCOM 2018; ICES Advice 2024; Lewin et al. 2023). The collapse of these stocks has placed traditional coastal fishing, recognised as an intangible cultural heritage, under severe threat (Lasner and Barz 2023).

With the fishery largely closed, the HyFiVe system cannot currently contribute to increasing data density through trawl fisheries. Yet, paradoxically, more data is now needed than ever to develop and justify appropriate conservation measures. In response, the HyFiVe system has been adapted for use in small-scale fisheries. This adaptation aligns with efforts to provide fishermen with alternative sources of income by involving them in environmental monitoring and the protection of the Baltic Sea ecosystem. Initiatives like the Sea Rangers programme exemplify this approach, where fishermen contribute to citizen science and environmental stewardship (de Graaf et al. 2023).

3 HyFiVe system overview

3.1 System design and modularity

The HyFiVe system is designed with a focus on flexibility, modularity and ease of use. Its autonomous nature is underpinned by three core components: a data logger, a deck unit and an onshore server (Fig. 1).

- Data logger: The data logger is mounted on fishing gear, such as trawls or nets, and collects essential hydrographic data, including salinity, temperature and dissolved oxygen levels. Designed for autonomous operation, the system requires minimal interaction from the vessel's crew.
- Deck unit: The deck unit is responsible for georeferencing the data and facilitating its transfer to the onshore server. It ensures that the data is accurately associated with its geographical location and time of collection.
- Onshore server: The onshore server manages the automatic quality control, visualisation and storage of the data. It also makes the data accessible to users via a web server and integrates it into international databases.

The modularity of the HyFiVe system allows it to be easily adapted to measure different chemical and physical ocean parameters, making it suitable for a variety of vessels and fishing operations. The system's design incorporates process routines and bidirectional communication capabilities, enabling seamless data acquisition, transfer, post-processing, visualisation, remote servicing and reconfiguration of devices. All components and developments are published at GitHub under open-source licenses, allowing the public to use and modify the system according to their needs (https://github.com/HyFiVeUser/HyFiVe).

The system operates in three distinct phases and employs established Internet of Things (IoT) protocols for wireless communication:

Preparation: Configurations for loggers are prepared on the server and transferred to all deck boxes, allowing for remote maintenance and reconfiguration. The loggers synchronise their configuration parameters and clocks with the deck box at regular intervals.

Acquisition: The deck box collects GPS data and stores it for later geo-referencing. While submerged, the logger controls the attached sensors and collects measurement data throughout the deployment.

Transmission: After each deployment, the logger wirelessly transmits the stored data to the deck unit, which geo-references and visualises it. The complete datasets are then transmitted to the onshore server, where they are processed for further applications.

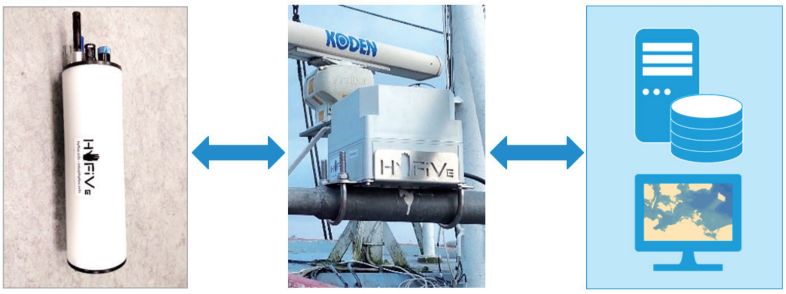


Fig. 1: HyFiVe system components (from left to right): data logger, deck unit and onshore server

3.2 The sensors

The data logger is designed with one interface board that connects to the mainboard for each integrated sensor, allowing for the integration of nearly any OEM sensor into the system. The current system, optimised for the Baltic Sea, measures conductivity (C), temperature (T), depth (D), and dissolved oxygen (DO) levels. The complex selection process for the chosen OEM sensors will be described in detail soon. Finally we use an Atlas Scientific K1.0 conductivity probe, a BlueRobotics Celsius Fast Response temperature probe, a Keller PAA-20D pressure sensor and a Pyroscience Pico-O2-Sub oxygen sensor.

3.3 The data logger

The data logger is a self-sufficient measuring system that controls the sensors via a mainboard based on an ESP32 controller (Espressif Systems Co. Ltd). Interface boards are available for various communication protocols, including I2C, UART, RS232, RS485, and analog input signals. The interface boards allow power supply programming for each sensor to values of 3.3 V, 5 V and 12 V. The logger uses WiFi for communication with the deck unit and features a battery management system (BMS) with external contacts for fast recharge. The battery with a capacity of 133 Wh uses twelve Li-Ion cells aggregated to a 4S3P cylinder block with a diameter that fits inside the housing tube and provides power for continuous measurement of parameters at 1 Hz for 30 days. In commercial fishery operations, where the logger predominantly operates in power-saving mode, this battery life can extend to several months. The underwater housing is made from polyoxymethylene (POM) and can accommodate up to six sensors. It has a depth rating of 300 metres at a diameter of 90 mm and a length of 285 mm without sensor heads. In the current sensor configuration the total length is 340 mm. An optional steel mounting bracket provides additional mechanical protection for installation on trawl doors. Fig. 2 illustrates the latest version of the data logger.

The logger's firmware manages all internal tasks and applies SD card settings, including sensor data, network credentials and thresholds. To extend deployment time, the microcontroller stays mostly in deep-sleep mode, with sensors either off or in power-saving mode. At regular intervals, a Real Time Clock RTC wakes the microcontroller to take a sensor reading (e.g. conductivity or pressure) and checks if the logger is submerged. If not in water, the system stays in standby mode, periodically checking the wireless connection to sync the RTC and the configuration from the deck unit.

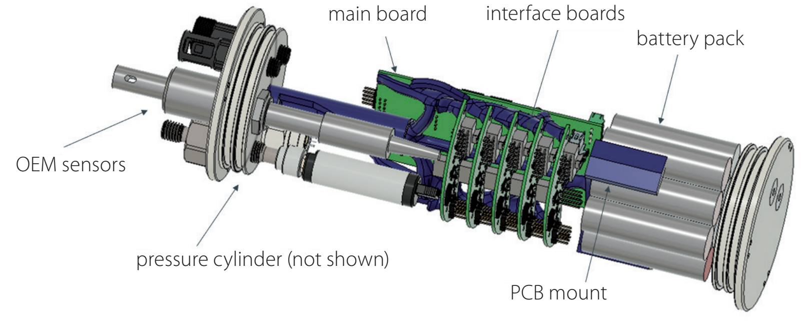


Fig. 2: Inside view of the latest data logger with its modular system components

3.4 The deck unit

The deck unit serves as the communication hub for all subsystems, providing a local wireless network, mobile connectivity and GPS reception. The main components include a Teltonika RUT955 router and a Raspberry Pi 4B single-board computer (SBC). The SBC processes measurement data and geo-references it using the visual programming tool Node-RED, storing it locally in an InfluxDB time series database. Additionally, it provides a webserver to visualise the local measurement data. The deck unit is powered externally and can operate on either 230 VAC or 9 to 30 VDC.

The router provides a wireless LAN for the Raspberry Pi, the logger and other field devices. It also offers a network time protocol (NTP) server for time synchronisation, an MQTT broker for data transmission, a GPS receiver and a gateway to the onshore server via LTE. Regularly, a Node-RED application reads the InfluxDB deployments, adds scientific metadata and creates NetCDF files for transmission to the onshore server.

A standard IP67-rated housing (180 mm × 180 mm × 150 mm) was selected for weather protection. Antennas for GPS, WiFi and LTE are placed inside to avoid cable feed-throughs. Components are secured with 3D-printed mountings. The box can be attached on deck (Fig. 3) using a steel plate mount, water-cut, and clamped to the vessel's railing with U-shaped bolts of different sizes.

3.5 The onshore server

The onshore server is the central component for data management and transfer, featuring a relational database (MariaDB), a VPN server and a web interface for data visualisation and remote configuration. It stores all relevant metadata and configuration data for the subsystems in operation, their integrated sensors and the respective fishery vessels. The database also maintains sensor specifications and calibration histories, ensuring the traceability of measured values – an important feature for autonomously acquired data with no manual editing. The system automatically checks all stored measurements for outliers, incorrect coordinates and irregular timestamps.

A configuration interface allows for remote management of the loggers and deck boxes in

Fig. 3: Mounting of the data logger on the trawl doors and the deck unit of the roof

the field. It visualises the last known position of the systems, their state of charge and memory capacity. New configuration files can be created remotely and automatically picked up by the deck units in the field.

Currently, the system interfaces with the Beluga Navigator of Geomar Helmholtz Centre for Ocean Research Kiel (https://beluga.geomar.de/hyfive), with plans to integrate additional databases in the future.

4 Field deployments: Trawling and coastal gillnet fishery

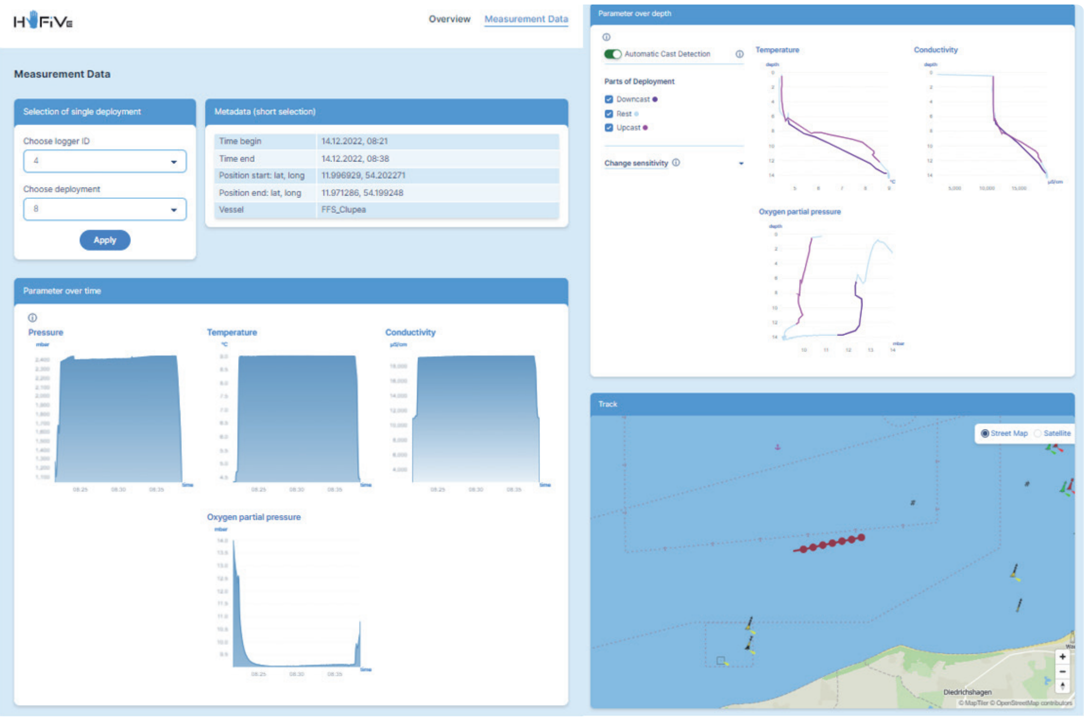
So far, the existing systems have been tested in over 150 deployments in fisheries and various citizen science applications. The results for two important use cases are presented in more detail below.

4.1 Trawling test deployment

The HyFiVe system was used during trawling operation on the FFS *Clupea* in the Warnemünde area. The mounting of the deck unit and the data loggers is shown in Fig. 3. The system successfully collected and transmitted data on salinity, temperature and dissolved oxygen while the vessel engaged in routine fishing activities (three trawls on December 6, 2022 and four trawls on December 14, 2022).

All data were transmitted to the onshore server, where they can be accessed at the webserver http://hyfive.info:4001. Within this measurement campaign, 140 minutes of underwater data were collected at a 1 Hz measurement frequency (>18,000 parameter sets) over a period of eight days in a coastal area extending three nautical miles along the coast. This underscores the potential of this measurement method to significantly enhance the spatial and temporal resolution of data density.

Fig. 4 illustrates screenshots from one selected deployment showing a table with metadata, graphs with measurement data for each parameter and the underwater track in a map.



Measurement Data

Choose logger ID: 4

Choose deployment: 8

Metadata (short selection)

Time begin	14.12.2022, 08:21
Time end	14.12.2022, 08:38
Position start: lat, long	11.996929, 54.202271
Position end: lat, long	11.971286, 54.199248
Vessel	FFS_Clupea

☑ Downcast ●
☑ Rest ●
☑ Upcast ●

Fig. 4: Screenshots from one selected deployment at December 6, 2022, showing a table with metadata, graphs with measurement data for each parameter and the underwater track on a map

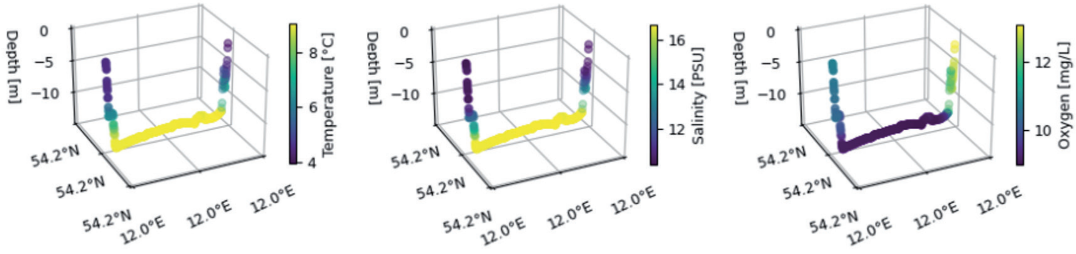


Fig. 5: Processed values by depth: temperature, salinity and dissolved oxygen (left to right)

Upon submersion, the logger successfully detected the start of each deployment and measured all parameters at a frequency of 1 Hz until the deployment's conclusion. After surfacing the logger automatically transmitted the data to the deck box where the corresponding coordinates were added. The 3D plots of latitude, longitude and depth in Fig. 5 display the processed values for temperature, oxygen and salinity from the selected trawl in Fig. 4.

Temperature and salinity increase with depth, while dissolved oxygen slightly decreases, which is typical for this region in winter. Even near the bottom, with approximately 10 mg/l of dissolved oxygen, there is sufficient oxygen for fish to survive, making this information also valuable for fisheries.

4.2 Coastal gillnet fishery deployment

The system was also deployed in coastal gillnet fisheries, demonstrating its versatility in nearshore environments. Over the past year, two systems were tested by coastal fishermen from Travemünde and Kühlungsborn area. These fishermen, who typically operate gillnets on their own vessels, used the system to measure profiles from the surface to the seafloor at specific positions along transects (Fig. 6). The transects which start in deep waters and extend towards shallow waters close to shore are about 2 km long and provide valuable data on the water column's hydrographic properties. For the Kühlungsborn transect a zoom is integrated in Fig. 6 as well as a picture showing the fisherman monitoring one station. This is done by slowly lowering the data logger by hand on a rope from the surface to the ground and back.

The mission of this campaign is to conduct regular transect measurements (weekly), particularly during periods when oxygen deficiency zones are expected (June to November), in order to obtain meaningful data for observing this phenomenon. The future plan is to define similar transects along the entire German Baltic Sea coast and have them sampled by fishermen.

A closer examination of the monitoring results in Fig. 7 reveals the presence of two distinct water masses separated by a halocline at a depth of

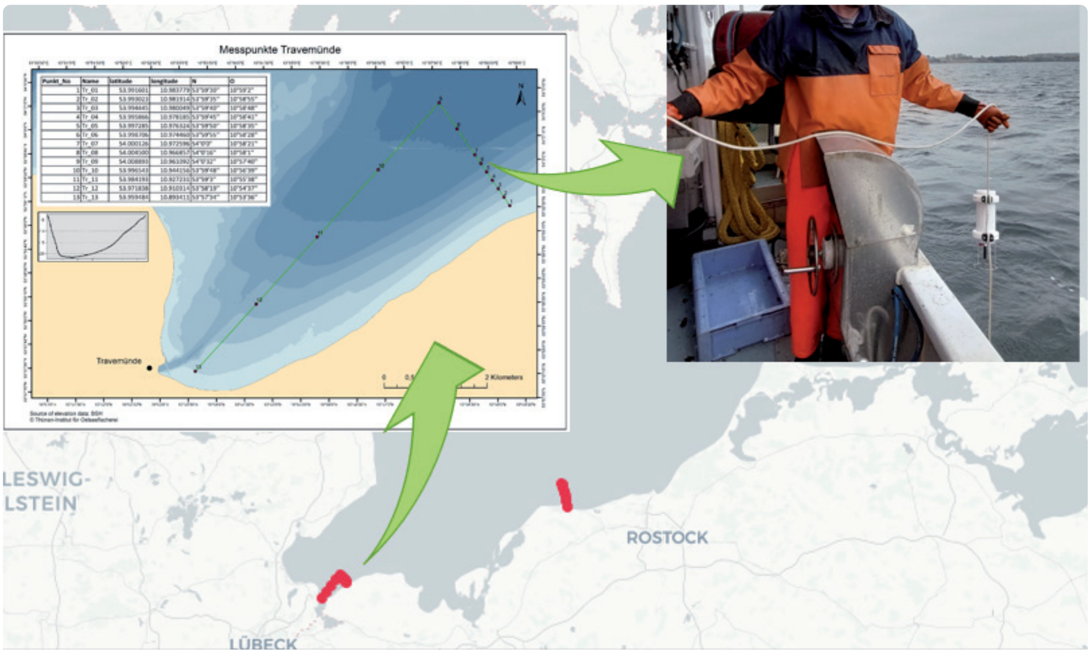


Fig. 6: Small scale fishery monitoring campaign

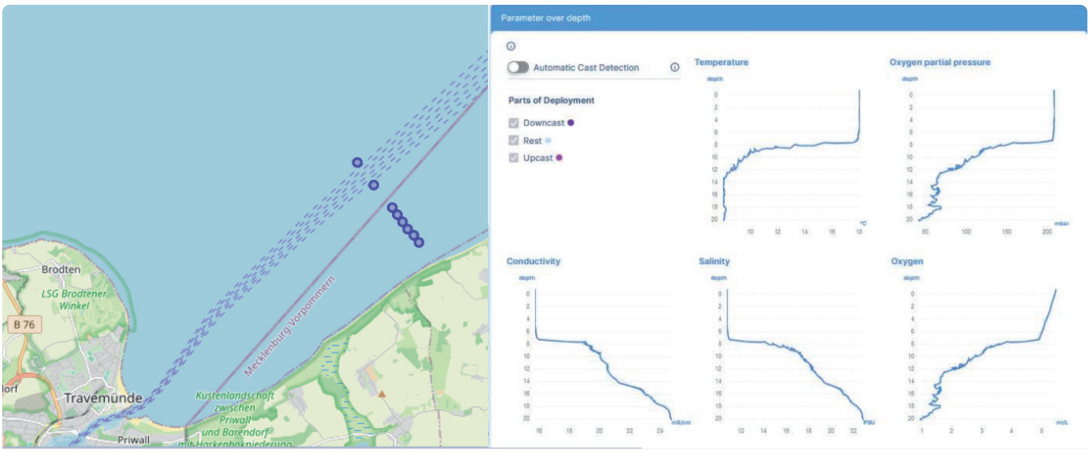


Fig. 7: Measuring results (4.7.24, 12:50) close to Travemünde indicate hypoxia below 11 m depth

approximately 9 metres. The lower water mass exhibits higher salinity and lower oxygen levels, with oxygen concentrations dropping below 2 mg/l at depths greater than 11 metres which indicates hypoxic conditions (Rosa et al. 2021) in which fish could not stay. Setting a gillnet here would have no chance of success.

5 Discussions and limitations

The HyFiVe system represents a significant advancement in autonomous hydrographic monitoring, but its current limitations need addressing to achieve full potential. The primary issue is that only ten systems have been deployed so far, restricting extensive testing across varied environments. This limited deployment hampers the identification and correction of weaknesses or hidden errors that may affect system robustness.

Limited deployment and testing

With the current systems primarily tested in the Baltic Sea, broader deployments are needed to evaluate performance in different geographic locations and conditions. Without this, potential issues in sensor integration, data processing and hardware durability might remain undetected, which could compromise the system's reliability over time.

Hidden errors and system robustness

The system's modular design introduces flexibility but also risks hidden errors, particularly in integrating various sensors and maintaining long-term operational stability. These issues must be identified and resolved to ensure consistent performance across diverse conditions.

Scaling and continuous improvement

To overcome these limitations, expanding the number of deployed systems is essential. More extensive use would provide valuable data for rigorous testing and iterative improvement, helping to eliminate persistent issues. Feedback from users will be crucial in guiding these enhancements.

Long-term reliability

The long-term reliability of HyFiVe must be validated through extended use. This includes assessing the durability of components, the stability of data transmissions, and the consistency of sensor performance. Developing effective maintenance strategies and field repair options, will be critical.

In summary, while HyFiVe is a promising tool for oceanographic monitoring, addressing these limitations through broader deployment, ongoing testing and continuous refinement is essential to fully realise its potential.

6 Perspective and conclusion

The HyFiVe system marks a significant advancement in autonomous hydrographic monitoring, offering exceptional flexibility and modularity that make it applicable across diverse domains, from citizen science initiatives to environmental monitoring by small-scale and commercial fisheries. By embracing an open-source approach, with all resources and documentation available on GitHub, HyFiVe not only promotes transparency but also encourages widespread adoption and adaptation, including commercial reuse. To date, ten systems have been successfully developed and deployed, contributing to small-scale fisheries like SeaRanger (de Graaf et al. 2023), contributing to citizen science projects and supporting the development of early warning systems for marine hazards such as hypoxia, blue-green algae and Vibrio bacteria through initiatives like the Prime-Prevention project (AWI 2024). We warmly invite collaboration from the scientific community and other interested parties to utilise, enhance and expand the capabilities of the HyFiVe system, with all necessary tools and resources available through our GitHub repository.

7 Funding

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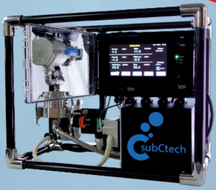

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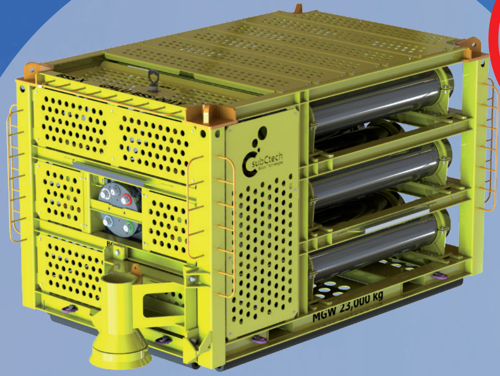

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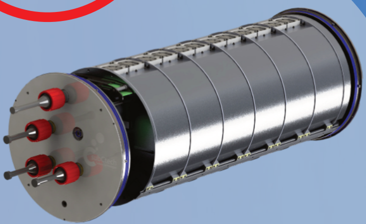

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Transfer of autonomous mapping concepts to a small uncrewed surface vehicle

An article by TOM SCHMIDT, JAN WITTE, UWE LICHTENSTEIN, ANGELIKA ZUBE and PHILIPP WOOCK

Approximately 70 % of the Earth's surface is comprised of water, yet our understanding of its rivers, lakes and especially its oceans remain surprisingly limited. By employing state-of-the-art mapping technologies, uncrewed vessels can efficiently survey underwater terrain and gather valuable data, thereby reducing operational time and costs significantly. This paper examines the adaptation of autonomous mapping principles to a compact, uncrewed autonomous surface vessel (ASV), demonstrating practical applications for aquatic data gathering. Particular emphasis is placed on the bathymetry data obtained through the use of the ASV, exemplifying its potential to offer precise underwater terrain maps, which are indispensable for comprehensive environmental monitoring, authorities and scientific research. The results demonstrate successful multi-domain mapping of various inland water environments, including harbours and lakes, using a compact ASV equipped with algorithms from Fraunhofer IOSB's Autonomy Toolbox (ATB). Additionally, the study achieved effective sensor fusion of geo-referenced LiDAR, sonar and camera data, providing a comprehensive hydrographic dataset for detailed environmental analysis. We find that autonomy functions of ASVs are already suitable for practical use; however, manual verification cannot be entirely eliminated yet.

autonomy | mapping | obstacle | sonar | autonomous surface vessel – ASV
Autonomie | Kartierung | Hindernis | Sonar | autonomes Überwasserfahrzeug

Etwa 70 % der Erdoberfläche bestehen aus Wasser, doch unser Wissen über die Flüsse, Seen und insbesondere die Ozeane ist erstaunlich begrenzt. Durch den Einsatz modernster Kartierungstechnologien können unbemannte Schiffe das Unterwassergelände effizient vermessen und wertvolle Daten sammeln, wodurch sich die Betriebszeit und -kosten erheblich verringern. In diesem Beitrag wird die Anpassung der Prinzipien der autonomen Kartierung an ein kompaktes, unbemanntes Oberflächenfahrzeug (USV) untersucht, um praktische Anwendungen für die Datenerfassung unter Wasser zu erläutern. Besonderes Augenmerk liegt dabei auf den Bathymetriedaten, die durch den Einsatz des ASV gewonnen werden, um das Potenzial für präzise Unter-Wasser-Geländekarten zu verdeutlichen, die für eine umfassende Umweltüberwachung, für Behörden und die wissenschaftliche Forschung unerlässlich sind. Die Ergebnisse zeigen, dass ein kompaktes ASV, das mit Algorithmen aus der Autonomy Toolbox (ATB) des Fraunhofer IOSB ausgestattet ist, erfolgreich eine Multidomänenkartierung verschiedener Binnengewässer, einschließlich Häfen und Seen, durchführt. Darüber hinaus wurde in der Studie eine effektive Sensorfusion von georeferenzierten LiDAR-, Sonar- und Kameradaten erreicht, die einen umfassenden hydrographischen Datensatz für detaillierte Umweltanalysen liefert. Wir stellen fest, dass die Autonomiefunktionen von ASVs bereits für den praktischen Einsatz geeignet sind; die manuelle Verifizierung kann jedoch noch nicht vollständig eliminiert werden.

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1 Introduction

Autonomous surface vessels (ASVs) are increasingly crucial for marine operations, particularly for tasks such as bathymetric surveying, environmental monitoring and inspection of underwater infrastructures. These unmanned platforms have evolved significantly over the past decades, driven by advancements in autonomous navigation, guidance, control systems and sensor integration. ASVs offer a safer, more cost-effective and more versatile solution for mapping and data acquisition in a variety of marine environments, ranging from coastal zones to open seas, as well as lakes and rivers.

State of the art

The development of ASVs has been marked by progressive technological innovations since their inception. An early comprehensive overview of ASV technologies up to 2008 highlights the initial development phases, focusing on the diversification of design and propulsion systems, as well as the incorporation of basic navigational and control capabilities (Manley 2008). By 2017, the landscape had expanded significantly, with at least 60 different ASV platforms documented, each tailored for specific applications in marine science and engineering (Schiaretti et al. 2017).

The core components of an ASV include its navigation, guidance and control systems, which are fundamental to its autonomous capabilities. Alves et al. (2006) provided a detailed exploration of these systems, emphasising the integration of sensors and algorithms for real-time decision-making and environmental adaptation.

Numerous examples demonstrate the wide-ranging applications of ASVs in marine environments. During the early stages, ASVs were mainly developed as low-cost options for tackling the challenge of hydrographic data collection and are quite diverse in their capabilities and sensor equipment. These vehicles were deployed in inaccessible shallow-water areas (Beck et al. 2008; Ferreira et al. 2009; Odetti et al. 2019) for measuring parameters for water quality (Dunbabin et al. 2009; Ferri et al. 2015), in hostile environments (Bertram et al. 2016), for geographical surveys (Stanghellini et al. 2020) and for unimpeded sensor measurements accomplished by aerial propulsion (da Silva et al. 2021; Regina et al. 2021).

Critical to ASVs used for ocean mapping or environmental monitoring is the ability to provide robust navigation with an intelligent path planning algorithm and obstacle avoidance to navigate in complex and dynamic environments. Karapetyan et al. (2019) provided a dynamic control framework for adaptive survey operations, while Clunie et al. (2021) developed software for maritime object detection and tracking. To ensure real-time obstacle avoidance, Campos et al. (2019) proposed an algorithm for navigating challenging scenarios. Dalpe et al. (2018) enhanced route planning using Potential Field Methods (PFM) and A* algorithms, and Jeong et al. (2018) introduced adaptive route planning that utilises real-time data, enabling ASVs to adjust their paths dynamically.

The mapping capabilities of ASVs have evolved significantly with advances in sensor integration and data acquisition. Early approaches for mapping the environment above the waterline, had a single omni-directional camera for shoreline mapping (Subramanian et al. 2006). Enhancing the perception capabilities of ASVs was the incorporation of LiDAR sensors for detection of the environment, inspection of surrounding structures or to automate docking to improve navigation precision (Pereira et al. 2021). Below the surface, the addition of multibeam echo sounders (MBES) enabled detailed harbour surveys (Iwen et al. 2019) and terrain-based navigation with accurate bathymetric data (Jung et al. 2019). Recent developments, like the SENSE ASV for inspecting maritime infrastructures (Campos et al. 2021) and the Nautilus ASV for offshore operation and maintenance tasks (Campos et al. 2024), have expanded ASV use to complex scenarios like inspecting offshore wind structures. The integration of multi-modal sensors now allows comprehensive mapping of offshore structures and the seafloor (Jung et al. 2023), reflecting a trend toward more sophisticated and adaptable ASV technologies.

Our approach extends the work of Zube et al. (2022) that presented the predecessor of the Otter ASV with a similar sensor setup, an improved processing pipeline and enhanced mapping capabilities. This work builds on the previously developed algorithms and the sensor configuration described in Kleiser et al. (2020) which uses the advantages of a ROS-based ASV architecture. Usage of ROS (robot operating system) for such a task was suggested by Barbier et al. (2018). The integration onto a more compact ASV platform and the robust real-world measurement and mapping stability of the platform shown by conducting surveys in practical scenarios are the key improvements illustrated in this paper.

3 Technical details of the autonomous vehicle

Several factors were taken into consideration when selecting the carrier platform. In comparison to the Fraunhofer IOSB's preceding test vehicle, the Water Strider from Zube et al. (2022), the system's open software architecture should allow for the integration of additional sensor hardware and the use of the IOSB Autonomy Toolbox (ATB) to generate comprehensive environmental representations both above and below the water surface. The previous platform's setup and dismantling times should be reduced through a more compact form factor and easier handling. We therefore chose Maritime Robotics' Otter as a base platform (Fig. 1).

Fig. 1: The Otter during its latest deployment in the »Rostocker Fracht- und Fischereihafen«

3.1 Otter platform

The Otter Pro (Fig. 1) is an unmanned surface vehicle designed for a range of maritime applications. The platform measures 2 m in length and 1.08 m in width, with a dry weight of 62 kg. It allows payloads up to 30 kg. The vehicle is powered by two electric motors, enabling it to reach a maximum speed of 6 knots in the absence of sensors. With a Norbit iWBMSe multibeam sonar (MBES) and four 915 Wh lithium-ion batteries, the vehicle is rated for up to 20 hours of operation at a speed of 2 knots.

The Otter Pro is supplied with its own vehicle control station (VCS) software for use with a dedicated PC. The system enables the user to plan simple patterns and to collect bathymetric data. The vessel is equipped with a camera and an automatic identification system (AIS) Class B, allowing for the monitoring of the surrounding environment.

The Otter is designed to accommodate a multitude of sensors, including MBES or single-beam echo sounders for bathymetric surveys.

The vessel has been designed to operate effectively in a variety of marine environments, including coastal, inland and offshore locations. It is rated for sea conditions up to Sea State 2 (waves up to 0.5 m).

3.2 Communication system

The Otter is equipped with many communication interfaces, encompassing RF, satellite communications, 4G and WiFi data transmission. Its WiFi range in the field tests covered distances up to 500 m.

The communication system enables the operator to inspect the vessel's status and trajectory while simultaneously displaying information received via AIS, thereby facilitating intervention in situations of reduced situational awareness at any time. Furthermore, the system enables the operator to view a low-resolution camera image and preview the results of bathymetric measurements.

Fig. 2: Sensor configuration. 1: GNSS bow, 2: GNSS stern, 3: LiDAR, 4: camera starboard, 5: camera port, 6: DVL (hidden), 7: MBES (hidden), 8: thruster port, 9: thruster starboard (hidden), 10: antennas

3.3 Sensors

In comparison to the Water Strider from Zube et al. (2022), modifications have been implemented with regard to the sensor configuration (Fig. 2).

Cameras

In comparison to the Water Strider platform, which was equipped with two full HD Sony SCNEB643R IP cameras, the Otter has been enhanced with the addition of two GigE Vision Sony IMX304 cameras, which offer a resolution of 4096 × 3000 pixels. These cameras are housed in a waterproof enclosure.

Both cameras are mounted on a custom-built mast, with one facing starboard and the other facing port. Additionally, the cameras are rotated slightly forward to enhance the overlap between two consecutive images as the boat progresses in a forward direction. The cameras are equipped with a 1.1" CMOS sensor and a Fujinon CF08ZA-1S lens with a focal length of 8 mm, which provides a field of view (FOV) of 85.7° horizontally and 67.5° vertically.

LiDAR

The LiDAR Ouster OS1 installed on the Otter is a further improvement compared to the Velodyne VLP-16 on the Water Strider. The LiDAR is also affixed to the mast in a horizontal position at its tip. The OS1 is capable of online overwater perception with a maximum range of about 200 m, a vertical aperture angle of 42.4° ± 1.0° (+21.2° to −21.2°), and a horizontal aperture angle of 360°. The angular sampling accuracy is ±0.01° in both the vertical and horizontal planes. The OS1 used has a vertical resolution of 64 channels, which are arranged in a fan shape and rotate at 10 Hz. The primary function of the LiDAR is to perform obstacle detection, whereby an online map of the water surface is created and, if applicable, areas in close proximity to the banks are also identified. Further details may be found in the work of Kleiser et al. (2017).

Sonar

The Otter is equipped with a Norbit iWBMSe multibeam echo sounder, capable of providing roll-stabilised bathymetric and backscatter data with up to 512 beams at depths from 0.2 m to 275 m and ping rates up to 60 Hz. In contrast, the Water Strider used an interferometric sonar system (BathySwath2) that excels in shallow water surveys and efficient area coverage. However, the multibeam echo sounder provides improved nadir accuracy, making it more suitable for its intended applications.

When utilising the MBES at a depth of 15 m, a speed of 2 kn and an opening angle of up to 160°, the system achieves a mapping capability of up to 170 m^2 per second. Consequently, the Otter platform enhances this capacity covering approximately 0.6 km^2 per hour which represents a slight improvement over the Water Strider, which surveyed an area of 0.5 km^2 per hour.

Localisation sensor

To facilitate the localisation of sensors, the Otter has been equipped with a dual-antenna GNSS from Trimble and the sonar-integrated Applanix POS MV SurfMaster inertial navigation system (INS/IMU). Furthermore, a client for Ntrip is used in conjunction with the 4G modem.

Although the localisation configuration on the Otter can provide a localisation solution, we use only the unprocessed measurements from the GNSS, including global position and velocity data, and the IMU measurements (including 3D accelerations and 3D angular rates) in our own mapping and sensor fusion algorithms.

In comparison to the Water Strider, the dual-antenna GPS also eliminates the necessity for a solid-state compass, providing global heading data.

DVL

To enhance the vessel's capabilities, a Waterlinked A125 DVL (Doppler velocity log) was installed. A DVL emits acoustic signals toward the seabed and measures the Doppler frequency shift of the reflections to determine the vehicle's velocity relative to the seabed. Using multiple acoustic beams, it calculates the three-dimensional velocity vector, providing comprehensive navigational data. The A125 is a particularly compact long-range DVL that measures the speed of the Otter relative to the seabed, thereby enhancing navigational accuracy, particularly in GNSS-denied environments. The device is capable of operating at water depths of 5 cm to 125 m, which makes it well-suited to the Otter's shallow water applications. The device is rated for a long-term accuracy of ±1.01 % and a velocity resolution of 0.1 mm/s.

4 Software and computing setup

The Otter underwent significant modifications in accordance with the requisite specifications for our intended applications, encompassing alterations to the software and computer configuration.

The system comprises three computers, the onboard system (OBS PC) in the control box from Maritime Robotics, an Intel NUC10i5FNK (Otter ROS PC, ORP) and a FleetPC-4-B car PC (Otter Vision PC). All computers are linked via an Ethernet connection to form a local network, which allows for time synchronisation and message exchange. The OBS PC serves as the primary hub for sensor data and control. The ORP was reconfigured to utilise the ATB of the Fraunhofer IOSB. The entire ATB is based on the robot operating system (ROS) middleware, where each sensor, e.g. the autopilot, obstacle avoidance and the motor actuators, feature their own ROS node. The Otter Vision PC was installed for the exclusive purpose of processing camera data by the ATB. Both, the ORP and the Otter Vision PC are operated under the Ubuntu 20.04 operating system and ROS noetic. This enables an autopilot functionality for the Otter by path planning, navigation with obstacle detection and avoidance. Further sensor data processing is carried out via the ATB toolbox.

The Otter employs a backseat driver concept which separates the vehicle hardware control from the autonomy functions: The OBS PC (frontseat) exchanges commands via a network-based API with the ORP (backseat). That way, the vehicle is commanded always with correct low-level commands by the OBS PC while the high-level autonomy situation assessment happens on the ORP by the ATB. Issued commands from the ATB are e.g. desired heading and speed. Measured heading, position, and actual speed, are data values delivered to the network by the OBS PC.

Mission planning

In the context of mission path generation in the ATB, the operator is first required to select the area to be surveyed on the map by drawing a polygon (Fig. 3). Subsequently, the system generates a mission plan containing lawnmower patterns based on the previously marked polygon. Furthermore, the system considers the required safety distances and avoids unnecessary deviations in route. The generation of the path is followed by the creation

Fig. 3: Planned path by the ATB based on the defined polygon with detected obstacles (swimmers) in black

of an online collision avoidance plan in the proximity of the pre-planned path, with the objective of circumventing any obstacles (Petereit et al. 2013; Petereit 2017; Emter et al. 2018). In this phase, both static and dynamic obstacles are considered. The optimal path is identified by minimising a cost function. A multi-layered control scheme is employed to guarantee that the vehicle will follow the planned path. The speed is regulated by a proportional-integral (PI) controller, while the direction is controlled by a proportional (P) controller. Further details are found in Zube et al. (2022).

5 Data acquisition

The conversion of the entire Otter platform to ROS offers the possibility of recording all sensor and actuator data, including camera images, point clouds derived from LiDAR, data pertaining to the vehicle's localisation, motor speeds and bathymetry data from the sonar into ROSbags. The considerable amount of data generated is stored on an SSD, thus enabling offline evaluation. The sensors that are equipped with ROS drivers are time synchronised. This is guaranteed by the incorporation of pertinent time stamps. Furthermore, it is possible to save the data processed by the algorithms in addition to the sensor data, thereby facilitating a more comprehensive understanding of the processes while developing autonomy functionality. The camera data, which is stored separately on the Otter Vision PC, plays a distinctive role in this context. To achieve time synchronisation between the Otter Vision PC and the Otter ROS PC, chrony is used, which enables the generation of time-coherent time stamps for all the ROS messages. To prevent the recording of unnecessary image data for the purpose of 3D reconstruction via offline photogrammetry, the camera is triggered by an algorithm such that only the previously specified area of interest is visible in the image, and that there is a minimum and maximum amount of overlap between consecutive images with the ground sampling distance (GSD) being maintained.

The bathymetry data can be saved and visualised/analysed as point clouds using a ROSbag and Rviz or Foxglove as well as using the Vehicle Control System (VCS) software from Maritime Robotics (Fig. 4 and Fig 5). In the latter case, the data is stored in the s7k format on a hard drive on the Otter and transferred once the mission has been completed.

The data can be imported in proprietary software like Caris but here we used the open-source software MB-System, developed by the Monterey Bay Aquarium Research Institute (Caress et al. 2008). It is utilised for the post-processing of data obtained from multibeam echo sounders. The software facilitates the processing of raw MBES data and the creation of three-dimensional bathymetric models of the seafloor. The process commences with the data being imported into the MB-System software. Subsequently, the software performs pre-processing, whereby any data errors are corrected or removed, and noise reduction is applied by an algorithmic pre-filtering technique. Following the application of the algorithmic pre-filtering, the data may then be subjected to manual processing, beam-by-beam, utilising the mbedit tool. A variety of filters may be applied to specific beams to enhance data quality. Areas that are visibly distorted or inaccurate, such as the edges of the beams, can be removed, as they may be affected by factors such as the roll angle of the Otter, waves or uneven ground conditions. This removal serves to improve the overall accuracy of the data. Furthermore, a separately recorded water sound profile can be utilised. The mbeditviz tool can then be applied to visualise the sonar recordings in a 2D representation or 3D grid, thus facilitating the development of an understanding of the recorded topology. Additionally, it is possible to visualise selected areas as a point cloud, thereby eliminating any remaining inaccurate measurements or enabling the inspection of specific areas in greater detail. Finally, processing and exporting the grid allows the recorded data to be visualised in GIS software such as QGIS, as illustrated in Fig. 4 and Fig. 5.

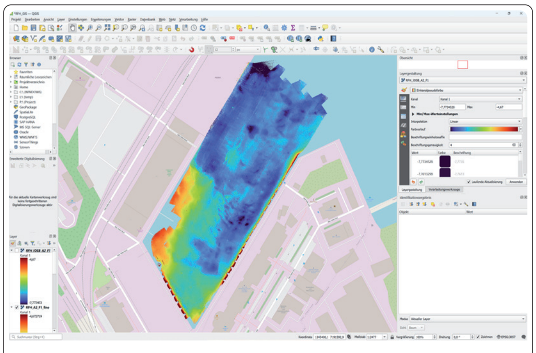


Fig. 4: Visualisation of the bathymetry data recorded at the »Rostocker Fracht- und Fischereihafen« in QGIS using the Maritime Robotics control software

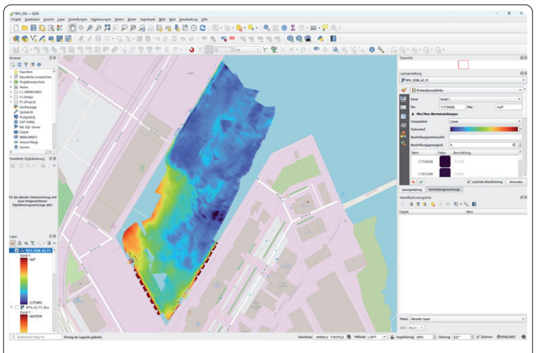


Fig. 5: Visualisation of the bathymetry data recorded at the »Rostocker Fracht- und Fischereihafen« in QGIS using the Autonomy Toolbox of the Fraunhofer IOSB

Fig. 6: Slightly overexposed image of Schwerin Castle taken by the Otter

Fig. 7: Close-up of Schwerin Castle taken by the Otter

6 Data analysis

In addition to the data collected using photogrammetry, this chapter also analyses the bathymetry data recorded by the Otter. The surveys were performed at two designated locations: in front of and in the vicinity of Schwerin Castle in Schwerin's Inner Lake and in Rostock's freight and fishing harbour.

6.1 Deployment »Schwerin Inner Lake«

As part of this deployment, high-resolution image data of Schwerin Castle was recorded using the Otter. The images were captured as part of the bathymetric survey of the Inner Lake situated in front of Schwerin Castle. It should be noted that due to the necessity of prioritising the survey of the lake bed, there are occasions when the optimal position for images cannot be attained. The images can thus be considered a by-product of the main survey. The two images presented (Fig. 6 and Fig. 7) demonstrate the diverse viewing angles and distances encountered during the data collection process. In addition, the images show the difficulties posed by fluctuating light conditions and reflections on the water surface. Furthermore, due to the positioning on the water and a rather short survey limited to a certain area in front of Schwerin Castle, not every area of the castle could be captured, resulting in partial gaps in the photogrammetric reconstruction (Fig. 8). Despite these limitations, the photogrammetric model produced a satisfactory result, providing a representation of the captured castle structure.

A subsequent survey of the Inner Lake in the vicinity of Schwerin Castle confirmed the discovery of the bow of a historic brick barge situated on the lake bed. Fig. 9 and Fig. 10 represent the outcome of a comprehensive bathymetric survey conducted in close collaboration with the State Office for Culture and Monument Preservation of Mecklenburg Western Pomerania. The location of the wreck was previously only known with a degree of uncertainty, based on observations and video recordings made by an amateur diver who had collected initial visual evidence of the barge during dives (Fig. 11). The

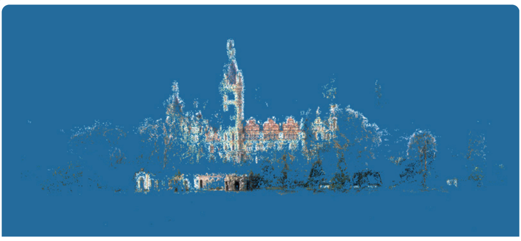


Fig. 8: Photogrammetric reconstruction of Schwerin Castle from Otter's camera data

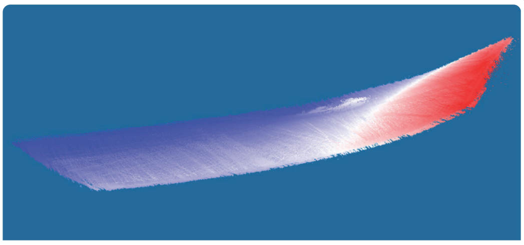


Fig. 9: Lateral view of part of the bathymetry of the Schwerin Inner Lake with the protruding bow of a brick barge

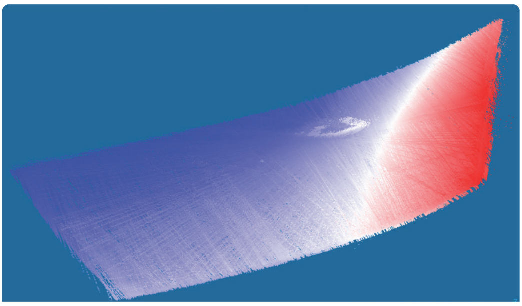
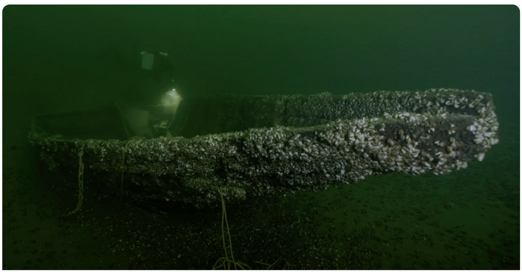


Fig. 10: Oblique top view of part of the bathymetry of the Schwerin Inner Lake with the protruding bow of a brick barge.



© Photo by Jens-Uwe Lamm, uw-film.de

Fig. 11: Underwater camera shot of the sunken brick barge

bathymetric data obtained during the mission now provides a high-resolution topographical representation of the lake bed, on which the barge can be clearly recognised. Of particular note is the bow of the ship, which is visible in the data as a white-coloured, slightly protruding object. The colour transition from blue to red illustrates the changes in depth of the lake bed, whereby the barge stands out clearly from its surroundings.

6.2 Deployment »Rostocker Fracht- und Fischereihafen«

To obtain data from a port scenario like in Iwen et al. (2019), we surveyed the »Rostocker Fracht- und Fischereihafen«. This was done to describe the methodologies and outcomes of two distinct survey operations conducted using the Otter, highlighting the integration of different technological approaches from Maritime Robotics and the Fraunhofer IOSB's ATB.

The Maritime Robotics control software necessitates a manual input of the survey path, often resembling a lawn mower pattern. This process requires the operator to meticulously plan each part of the survey area to ensure complete coverage, which can be both time-consuming and labour-intensive. In contrast, the ATB software from Fraunhofer IOSB introduces an enhanced level of automation and intelligence in planning. By merely drawing a polygon over the target area within the software interface, the system automatically generates an optimal lawn mower pattern given a certain swath width. This automated path planning not only saves significant time but also reduces the potential for human error in missing critical survey areas.

It should be noted that both methods currently have certain limitations when used in the vicinity of the harbour wall. In the case of the Maritime Robotics software, the distance to the harbour wall is determined beforehand by the operator through the configuration of paths at a specified distance from the aforementioned structure. In contrast, the ATB utilises a different approach whereby the distance to the bounding polygon is automatically determined by the software, which is defined by the operator in the map in relation to the quay edge. The ATB is currently optimised to cover surveys of larger areas. However, as each waypoint uses an individual reach distance, waypoints at the edges could be treated differently in an inspection case and static obstacles could be implemented with a reduced safety distance. Therefore, in the tests shown in Fig. 12 and Fig. 13 the Otter trajectories keep the same safety distance to the quay wall as it does to dynamic obstacles, necessitating the use of manually controlled measurement journeys in short, curved paths, to complete the map near the quay wall.

A crucial distinction between the two systems lies in their operational safety features. The Maritime Robotics software in its used release state does not include obstacle avoidance technology, thus requiring constant monitoring of the ASV to prevent po-

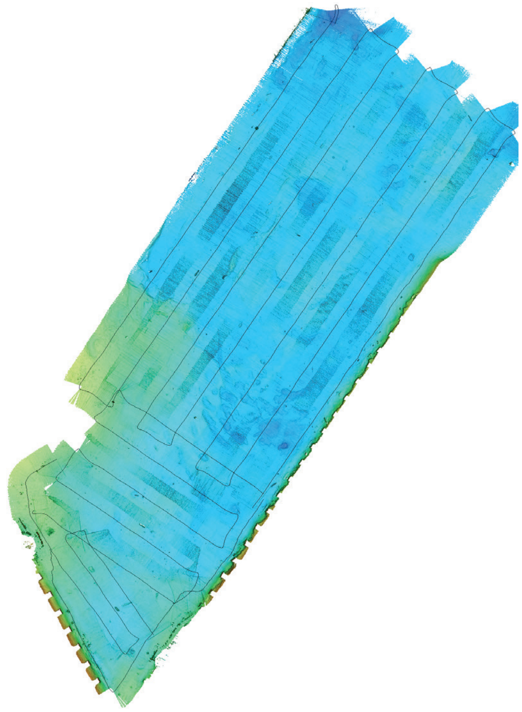


Fig. 12: Visualisation of the bathymetry data recorded at the »Rostocker Fracht- und Fischereihafen« in MB-System using the Maritime Robotics control software

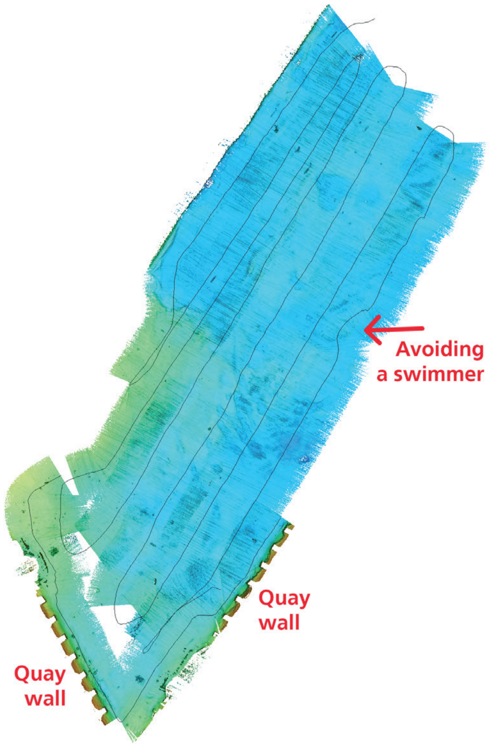


Fig. 13: Visualisation of the bathymetry data recorded at the »Rostocker Fracht- und Fischereihafen« in MB-System using the Autonomy Toolbox of the Fraunhofer IOSB

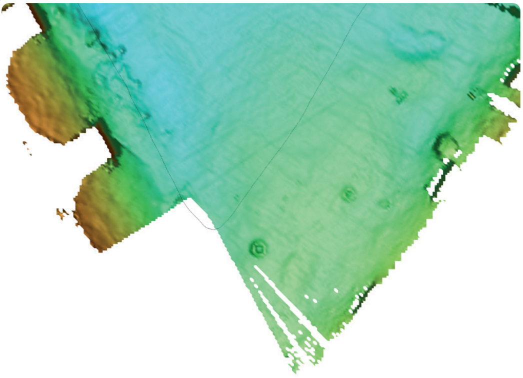


Fig. 14: Visualisation of a tyre on the seabed near the quay edge of the »Rostocker Fracht- und Fischereihafen« in an MB-System generated grid

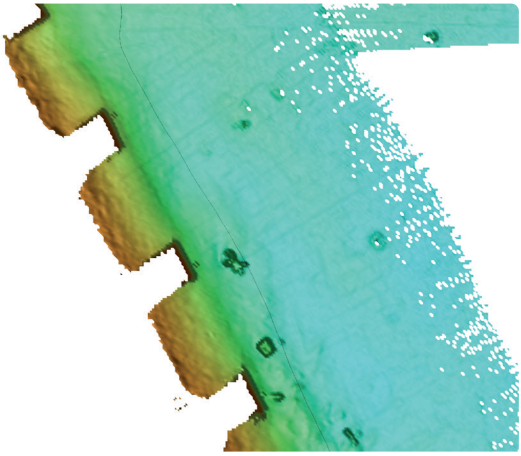


Fig. 16: Visualisation of undefined objects on the seabed near the quay edge of the »Rostocker Fracht- und Fischereihafen« in an MB-System generated grid

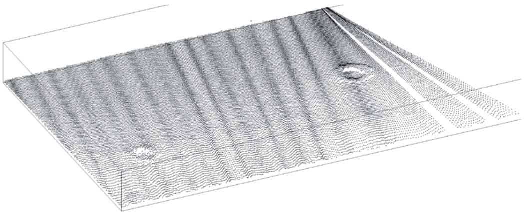


Fig. 15: Visualisation of a tyre on the seabed near the quay edge of the »Rostocker Fracht- und Fischereihafen« in an MB-System generated point cloud

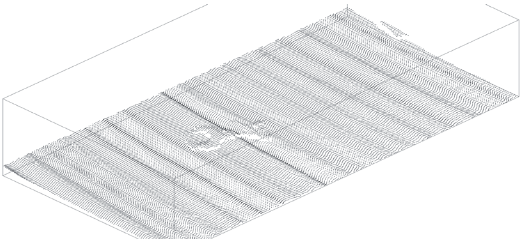


Fig. 17: Visualisation of undefined objects on the seabed near the quay edge of the »Rostocker Fracht- und Fischereihafen« in an MB-System generated point cloud

tential collisions. This can be particularly challenging in dynamic environments where unexpected dynamic obstacles or entities, such as swimmers or vessels, may enter the survey area.

The survey conducted with IOSB's ATB demonstrated an improvement in this aspect, as it comes equipped with obstacle avoidance. During the operation, the Otter autonomously altered its path to avoid swimmers, a feature indicated by a red arrow in Fig. 13, enhancing both the safety and reliability of the survey process. The data gaps in Fig. 13 arise because the cornering manoeuvres were discarded due to their inferior quality. In comparison to Fig. 12, these data gaps were not filled in order to demonstrate the superiority of the ATB. With a single run, nearly the same results were achieved that would have otherwise required three runs.

Both surveys provided high-resolution bathymetric data, revealing underwater features such as quay walls, tires and unidentifiable objects on the seabed. The MB-System software, utilised in both methodologies, effectively displayed these features in both grid and point cloud visualisations (Fig. 14 to Fig. 17). The precision of these images is of vital importance for the accurate localisation of objects, thereby facilitating a more informed assessment of the underwater environment and thus contributing to the evaluation of potential hazard zones in harbour areas. During our deployment, we set the swath of the multibeam echo sounder to 140° and recorded at a survey speed of 1.5 knots. The depth of water surveyed ranged up to 11 metres which required a rather narrow mission line spacing.

7 Conclusion and outlook

The analysis of these two deployments of the Otter demonstrates significant advancements in operational methodologies. The automation capabilities of the ATB system notably reduce the manual effort and increases the safety and efficiency of marine surveys. Furthermore, the detailed data captured and visualised through MB-System highlights the potential of autonomous survey techniques to contribute to safer and more effective marine navigation and infrastructure maintenance.

Future developments for the Otter ASV will likely focus on incorporating compliance with the International Regulations for Preventing Collisions at Sea (COLREGs) into its navigation systems to ensure safe operation in congested waters. Relevant for this incorporation are earlier efforts to include a collision avoidance system (CAS) for ASVs that adheres to COLREGs, enhancing autonomous navigation (Sun et al. 2018), the COLREGs compliance in both single-ship and complex multi-ship scenarios (Chiang et al. 2018) or the control scheme for tugboats in congested ports, indicating potential applications for ASVs (Du et al. 2021). Building on these foundations, future ASVs could integrate advanced algorithms that ensure COLREGs compliance while dynamically adapting to diverse maritime environments, enhancing safety and operational flexibility.

Future improvements to autonomous surface vessels (ASVs) will likely focus on advancing both real-time perception and comprehensive environmental mapping capabilities. One key area of development will be achieving a complete 3D representation of the environment through fully automated integrated post-processing pipelines, combining sonar data with photogrammetry techniques to generate detailed, high-resolution models of underwater and surface structures. This will enhance the vessel's ability to map complex environments accurately and provide a richer dataset for scientific analysis, more efficient mission planning as well as for water authorities. Additionally, efforts will be directed towards improving the real-time detection and recognition of surrounding objects and structures. This will involve refining algorithms for obstacle mapping and integrating sensor data to produce real-time visualisations, enabling ASVs to dynamically update mission plans and adapt to changing conditions. Real-time display of bathymetric data from a continuously updated buffer will further enhance situational awareness, allowing for more precise navigation and high-level decision-making for remote operators. Together, these advancements will significantly improve the autonomy, safety and operational efficiency of ASVs in diverse and challenging marine environments

We would like to express our gratitude to everyone who contributed to the development of this paper. We acknowledge the State Office for Culture and Monument Preservation of Mecklenburg Western Pomerania, the Mecklenburg Western Pomerania waterway police and the »Rostocker Fracht- und Fischereihafen« for providing assistance, resources and infrastructure necessary for this work. Special thanks are extended to our colleagues from the Autonomous Robotic Systems (ARS) research group and the Smart Ocean Technology (SOT) research group for their invaluable insights, technical support and constructive feedback throughout the research process. //

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Bathymetry estimation using airborne remote sensing RGB image data of the tidal flats of the North Sea

An article by KILIAN MARTLAGE, ANN-CHRISTIN HACKSTEIN, TOBIAS SCHMID, MARTIN KUMM and JENS WELLHAUSEN

Reliable bathymetric data are essential for safe navigation, as inaccuracies can pose risks for vessels dependent on precise depth information. This study investigates whether a combined approach using colour-based remote sensing systems and wave kinematic methods can improve the temporal resolution of bathymetric information in the Wadden Sea of the North Sea and provide a cost-efficient method for targeting regions with highly variable bathymetry for acoustic measurement techniques.

optical hydrography | remote sensing | optical bathymetry estimation | image-based water wave detection
optische Hydrographie | Fernerkundung | optische Bathymetrieabschätzung | bildbasierte Wasserwellenerkennung

Verlässliche bathymetrische Daten sind für eine sichere Schifffahrt unerlässlich, da Ungenauigkeiten für Schiffe, die auf genaue Tiefeninformationen angewiesen sind, ein Risiko darstellen können. In dieser Studie wird untersucht, ob ein kombinierter Ansatz aus farbbasierten Fernerkundungssystemen und wellenkinematischen Methoden die zeitliche Auflösung bathymetrischer Informationen im Wattenmeer der Nordsee verbessern und eine kosteneffiziente Methode bieten kann, um Regionen mit stark veränderlicher Bathymetrie für akustische Messverfahren zu erschließen.

Authors

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Introduction

The mapping of bathymetric changes is a critical component in a variety of applications, including navigation, research and monitoring (Caballero and Stumpf 2021). In highly variable natural environments such as the German Wadden Sea, the detection of bathymetric changes with a high temporal resolution is particularly important. Reliable bathymetric data are essential for safe navigation, as inaccuracies can pose risks for vessels dependent on precise depth information. Additionally, bathymetric data are indispensable for models that estimate sea level rise (Wachler et al. 2020).

This study investigates whether a combined approach using colour-based remote sensing systems and wave kinematic methods can improve the temporal resolution of bathymetric information in the Wadden Sea of the North Sea and provide a cost-efficient method for targeting regions with highly variable bathymetry for acoustic measurement techniques.

State of the art

Traditionally, monitoring water depths has been primarily achieved using acoustic multibeam echo sounder systems. These systems provide accurate measurements of water depth along transects by emitting sound waves and measuring the time taken for the echo to return from the seabed to the sensor (Gao 2009). However, these systems come with certain disadvantages, including high costs and limited accessibility in coastal and intertidal waters, which are often characterised by obstacles such as sandbanks or shoals (Tronvig 2005). As a result, the sampling rate in these areas is often once in 20 years or more (Grabbert 2022).

Remote sensing has the potential to improve the spatial coverage and temporal resolution of bathymetric data in shallow waters. Airborne remote sensing offers the advantage of more flexible spatial and temporal deployment, allowing data collection to be adapted to weather and tidal conditions. Additionally, airborne remote sensing can achieve a higher ground sample distance (Klemas 2013).

One method for determining water depth through airborne remote sensing is the use of LiDAR (Light Detection and Ranging) systems. These systems use green lasers with a wavelength of 532 nm to achieve sufficient penetration into the water column. A laser with a wavelength of 1064 nm is also used, which reflects off the water surface. The difference between the distance measurements of both wavelengths is used to determine the water depth. With this system, water depths can be measured up to three times the Secchi depth (Szafarczyk and Toś 2022). However, the use of LiDAR systems is limited in optically complex coastal waters (Case 2 waters), such as those found in the Wadden Sea of the North Sea (Holland 2001).

Satellite-derived bathymetry (SDB) is another method for optically determining bathymetry. The quality of the data obtained using this method is highly dependent on water turbidity, seabed reflectance and the wave-dominated structure of the water surface. Colour-based remote sensing systems are capable of detecting small-scale bathymetric features (Al Najar et al. 2022). However, with this method, water depths can only be measured up to the Secchi depth (Véronique Jégat et al. 2016).

Another method for estimating bathymetry is based on wave kinematics. This approach is more suitable for deeper waters than optical methods but relies on surface waves and has a greater margin of error when applied globally (Al Najar et al. 2022). This method is based on the influence of water depth on the structure of shallow water waves. The dispersion relationship describes the connection between wavelength and frequency. Additionally, »wave shoaling« describes the change in wave shape with water depth, while refraction is another effect related to water depth (Bryan et al. 2020).

Technical background

To extract information on bathymetry from the properties of shallow water waves, the relationships between various wave parameters and water depth are considered. The dispersion relationship for shallow water waves approximates the phase velocity as a function of the gravitational constant and the water depth. A wave with a defined period has a single wavelength for the depth (Holland 2001). In addition to wavelength, wave shape is also influenced by water depth, and the change in wave shape in shallow water is described as the shoaling effect. Another parameter that changes with decreasing water depth is the orientation of the wave fronts, which is described by refraction. This phenomenon aligns the wave crest with the bathymetric contours due to the dependency of propagation speed on water depth. Different sections of a wave are in different water depths, causing those in deeper water to move faster than those in shallower depths (Bryan et al. 2020).

In addition to wave characteristics, the colour values from the aerial image data provide additional information about the seabed, as long as it is visible due to the diffuse attenuation of the water body. When the seabed is not visible, the colour information mainly indicates sediment transport due to strong tidal currents. The relationship between tidal currents and bathymetry (Guerra et al. 2021) can also provide insights into the bathymetric profile.

Data collection

To address the research question, aerial imagery was collected from areas in the East Frisian Wadden Sea, near the island of Spiekeroog, using the research aircraft »Jade One« from Jade University. The data was acquired using the MARS (multispectral aerial remote sensor) system of Jade University, mounted in an external pod beneath a wing of »Jade One«. This system is equipped with RGB, NIR, SWIR and IR cameras. For this project, the RGB camera with a resolution of 9504 × 6336 pixels and a field of view of 54° × 37° is used. The image data is triggered by the position together with a high-resolution inertial measurement unit (IMU), controlled by the Pixhawk autopilot system. The research aircraft »Jade One« from Jade University – a Touring Motor Glider of type Diamond Aircraft HK36-TTC-ECO, that can be equipped for remote sensing tasks in an extremely flexible way – is shown in Fig. 1.

The RGB image data represent the reflectance of the water surface across three wavelengths. The light field produced by reflection from the water surface is related to the gradient of the sea surface elevation (Bondur and Murynin 2021). Capturing the reflected light field with an area sensor produces an image showing the sea surface gradients as intensity, depending on the light field incident on the water surface.

Method

To extract information on the structure and changes in surface waves, analysing spatial and temporal frequencies is a suitable method (Collard et al. 2008). Spectral analysis of aerial imagery is

Fig. 1: The Jade University research aircraft »Jade One« with two external sensor containers

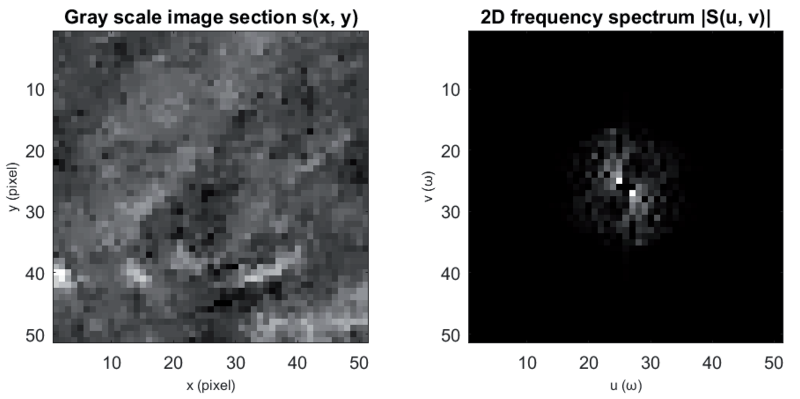

Fig. 2: Section of an aerial image showing the North Sea surface (left) and its frequency spectrum in spatial representation (right)

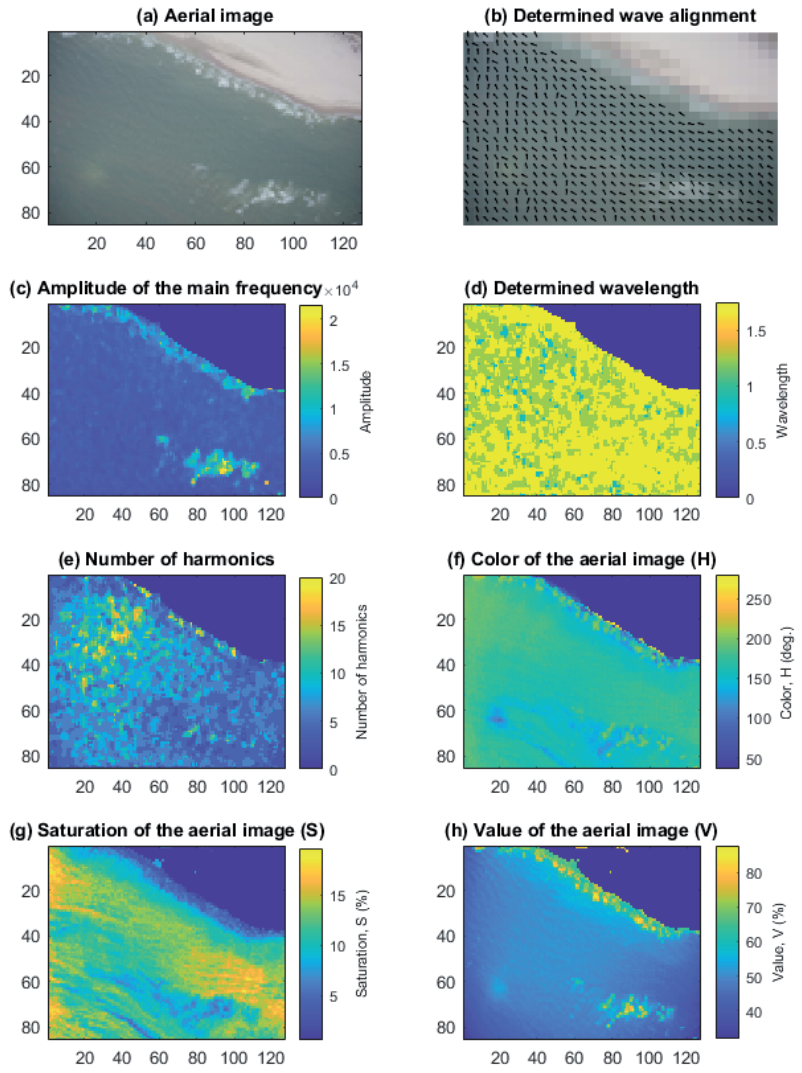

Fig. 3: (a) Partial section of an aerial image of the northern coast of the barrier island of Spiekeroog, (b) alignment of the waves determined from the frequency spectrum, (c) amplitude of the main frequencies, (d) wavelengths determined from the frequency spectrum, (e) number of harmonics, (f) colour from the HSV space of the aerial image, (g) saturation from the HSV space of the aerial image, (h) value from the HSV space of the aerial image

an appropriate technique for analysing these frequencies. Bondur and Murynin (2021) developed a method for obtaining spatial wave spectra based on the brightness field of the water surface using aerial image data. The collected images were divided into segments of 50 × 50 pixels for data analysis. These segments were transformed into the frequency domain F(u,v) using the 2D Fourier Transform.

$$F(u,v) = \sum_{x=0}^{X-1}\sum_{y=0}^{Y-1} f(x,y)e^{-j2\pi(\frac{ux}{X}+\frac{vy}{Y})}$$

Subsequently, key parameters such as the primary frequency, wave propagation direction, and the number of harmonics were derived from the resulting 2D amplitude spectrum. Fig. 2 shows an example of an image segment along with its corresponding frequency spectrum.

In the frequency spectrum, the main frequency is clearly identifiable, along with several secondary maxima that describe the non-sinusoidal components of the wave. The primary frequency of the image segment reflects the spatial variation of the light field reflected from the water surface, which is related to the gradients of the sea surface (see section »Data collection«). Therefore, the primary frequency of the image represents the spatial frequency of the sea surface's vertical displacement and, consequently, that of the waves. The dispersion relationship provides a connection between the primary frequency of the wave image and the water depth. However, this relationship only holds for shallow water waves.

It is also known that waves begin to build up and break as water depth decreases (see section »Technical background«). This aspect can be used to identify shallow areas. The wave shape can also be determined from the 2D frequency spectrum of the water surface by extracting the number of harmonics with an amplitude of 0.3 times the primary frequency. This value is useful for distinguishing signal noise.

Another feature considered is the orientation of the wave fronts. Due to refraction, the alignment of the wave crests conforms to the bathymetric contours (see section »Technical background«). This can also be derived from the frequency spectrum of the image data.

In addition to the features obtained from surface waves, features based on the water body's colour impression are also used. For this, the RGB data are transformed into the HSV (hue-saturation-value) colour space. In the HSV space, the image data are represented by hue as an angle, saturation and an intensity value.

Fig. 3 (a) shows an aerial image of the northern coast of Spiekeroog, along with the described features from the frequency spectra of the image segments. Fig. 3 (b) illustrates the alignment of the main frequencies and wave crests derived from the frequency spectrum. A clear alignment of the waves is observed in the surf zone. In the lower right area of the image, the wave alignment in the surf zone also indicates a possible change in bathymetry.

The other image data obtained from the frequency spectrum were spatially resolved using pixel coordinates and filtered with a 2D median filter over 3 × 3 pixels. The amplitude (c) of the reflectance shows a significant local increase at the breaking zones, at the water's edge, and at the lower left side of the image. This observation can be explained by »wave shoaling« (the build-up of a wave) in shallower areas. The wavelength (d) derived from the main frequency shows only minor differences across the examined water surfaces. The comparison between the wavelength and the number of harmonics (e) reveals slight local minima of the wavelength in areas with a high number of harmonics.

The hue (f) remains relatively constant across the water surface, with small deviations caused by foam crests at the breaking zones. The saturation (g) shows local differences of about 10 % to 15 %. It is lower in areas along the surf zone at the beach and in the offshore breaking zone compared to other water surfaces, suggesting shallower zones. The value component of the HSV space (h) exhibits a characteristic increase due to the high reflectance of foam crests at the breaking zones.

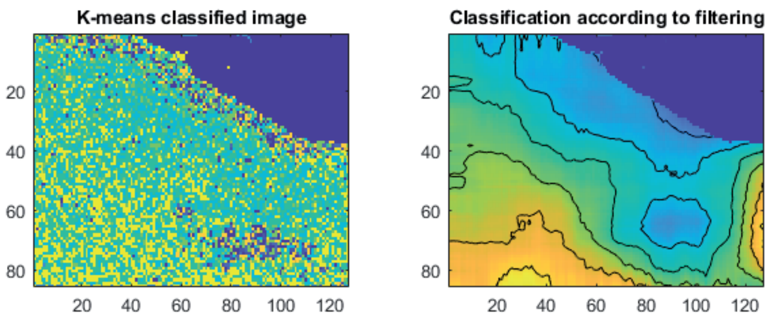

Fig. 4: Spatial distribution of classes from k-means classification based on wave parameters: amplitude, primary frequency, number of harmonics and wave crest orientation (left image), and filtered spatial distribution of the classes (right image)

Results

A k-means classification was performed for each pixel based on the features described above. Pixels were classified into ten categories, with areas of the same class having similar properties influenced by water depth. It is assumed that areas of the same class have approximately the same water depth. The spatial distribution of the classes is shown in Fig. 4 (left image). The data shows a high degree of scatter due to the influence of waves from additional non-linear forces, different wave-driving forces or irregularities in the light field. However, spatial clustering of certain classes is evident. By applying a mean filter, the matrix is smoothed, and gradients are generated, as shown in Fig. 4 (right image). The figure shows a shallower area on the right side of the image, which coincides with a surf zone in the original image. The decreasing bathymetry from the coastline to the sea also represents a plausible bathymetric profile.

Validation using BSH reference data

To validate the data, reference data from the Federal Maritime and Hydrographic Agency (BSH) of the »Exclusive Economic Zone of Germany« were used (BSH 2018). The aerial image data were collected in 2022. For comparison with the BSH dataset, the processed data were geo-referenced. The gradient profile was scaled to the maximum depth from the reference data. Subsequently, a difference matrix was calculated from the reference data and the estimated bathymetric profile. Fig. 5 shows the geo-referenced estimated bathymetric profile, the BSH reference data and their difference map. The image data are oriented to the north. Both the estimated bathymetric profile and the BSH reference data show a slope to the north, with a local maximum depth at the northern boundary. However, unlike the estimated bathymetric profile, the reference data reveal a depression in the centre of the image. The difference map indicates that the greatest deviation occurs on the western side, where the estimated bathymetry drops significantly more. The tidal currents present in the Wadden Sea influence the wave field in this region, causing waves to become increasingly non-linear due to countercurrents (Dodet et al. 2013). Additionally, the lower resolution of the reference data and the different survey periods of the two datasets are further reasons for discrepancies in the data.

Conclusion and outlook

This study has demonstrated that RGB aerial imagery can efficiently provide defined wave parameters over large water surfaces. It was also shown

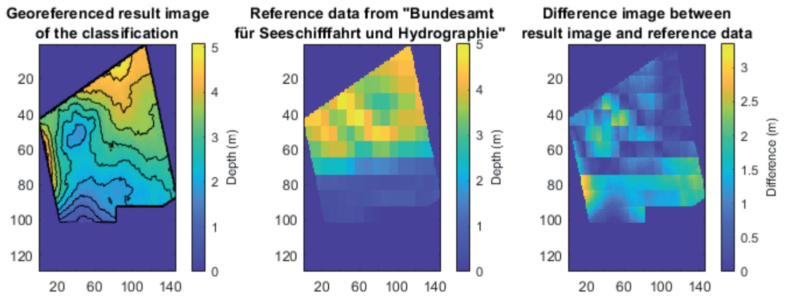

Fig. 5: Geo-referenced results matrix for bathymetry estimation (left image), BSH reference data (middle image) and difference matrix between the results matrix and the reference data

that it is possible to estimate bathymetric conditions based on wave properties, although this method does not provide absolute depth measurements but rather describes the bathymetric profile. In the Wadden Sea areas of the North Sea, tidal currents significantly affect surface wave properties in addition to bathymetry. To improve methods for determining bathymetric conditions, it is essential to separate these signals. The next step should involve estimating the influence of tidal currents on the wave fields. Another potential approach to mitigate this issue is to conduct measurements during slack water.

In conclusion, the examined method offers the capability to detect bathymetric changes but does not provide quantitative information on water depths. Remote sensing can be used to identify potential shallow areas and regions with interesting bathymetric developments over large areas. This allows subsequent collection of bathymetric data using conventional methods to be spatially focused on areas of interest. //

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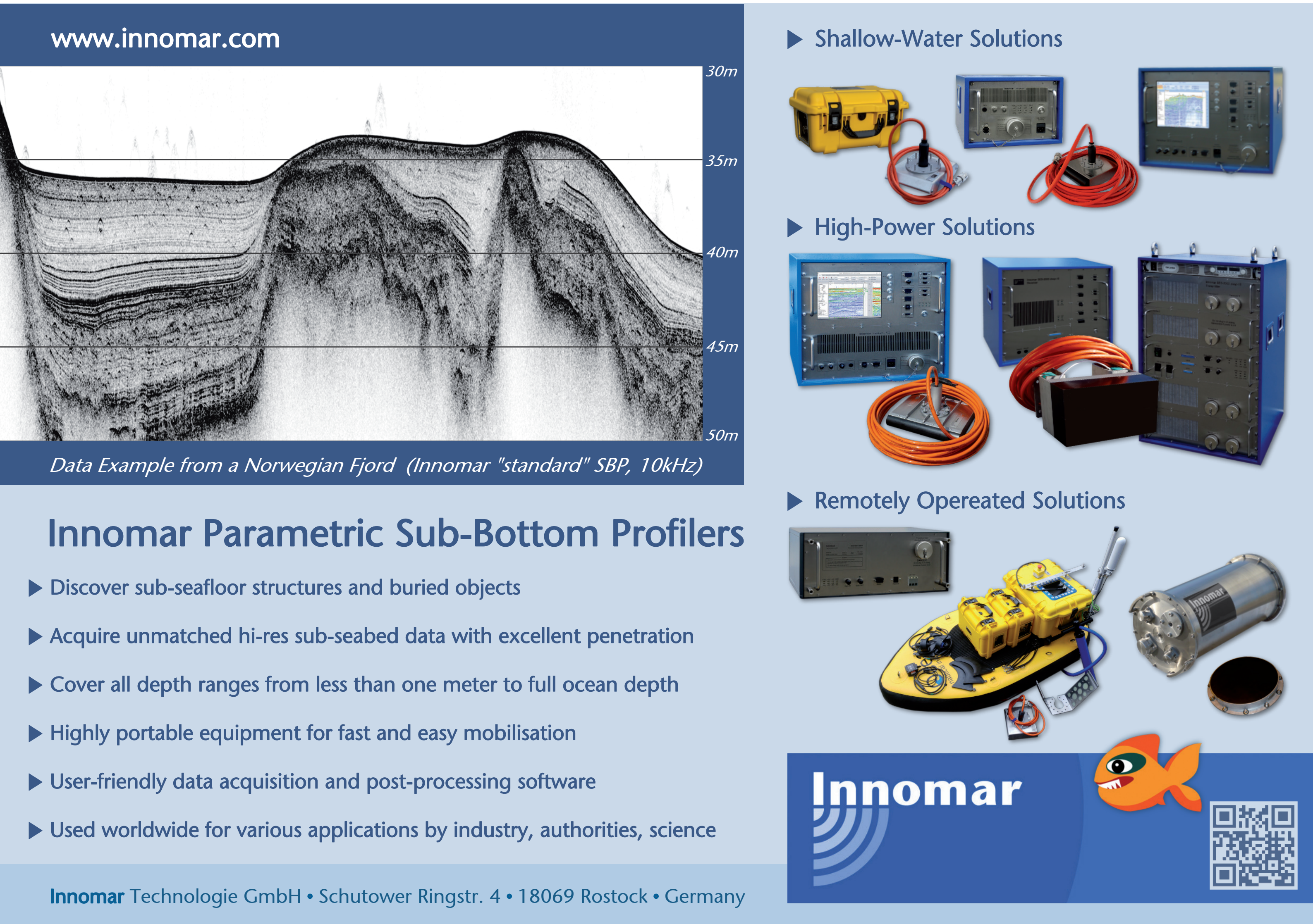

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Combined technologies for 3D cable tracking

Integrated data acquisition of a 3D sub-bottom profiler and an array of magnetometers

An article by JENS WUNDERLICH, JAN-ERIK RYGH, MICHAEL ENDLER, JENS LOWAG and STEIN-ARILD NORDRUM

With an increasing number of offshore cables being installed, depth of burial (DOB) surveys are an important and regular task. DOB surveys determine the exact position and burial depth of the cable immediately after dredging and later at regular intervals throughout its lifetime. Innomar and Aquadyne have combined forces and technologies to use the positioning and real-time guidance information provided by Aquadyne's MagTrack magnetic cable tracking system to efficiently acquire acoustic data using Innomar's sixpack sub-bottom profiler (SBP) to produce a three-dimensional visualisation of the subsea environment around a cable in a single pass along the target. This paper summarises user requirements for DOB surveys, discusses the technologies used and presents encouraging field data from initial trials. The application of the methods presented is not limited to cable DOB surveys, they can also be used for pipeline surveys or other activities during construction and maintenance of offshore structures.

cable tracking | 3D sub-bottom visualisation | parametric acoustics | magnetometer | buried object localisation
Kabelverfolgung | 3D-Visualisierung des Meeresbodens | parametrische Akustik | Magnetometer | Lokalisierung vergrabener Objekte

Da immer mehr Offshore-Kabel verlegt werden, sind Vermessungen der Verlegetiefe (DOB) eine wichtige und regelmäßige Aufgabe. DOB-Vermessungen bestimmen die genaue Position und die Vergrabungstiefe des Kabels unmittelbar nach der Ausbaggerung und später in regelmäßigen Abständen während seiner gesamten Lebensdauer. Innomar und Aquadyne haben Kräfte und Technologien gebündelt, um die Positionierungs- und Echtzeit-Führungsinformationen des magnetischen Kabelverfolgungssystems MagTrack von Aquadyne zur effizienten Erfassung akustischer Daten mit dem Sub-Bottom-Profiler (SBP) sixpack von Innomar zu nutzen und eine dreidimensionale Visualisierung der Unterwasserumgebung um ein Kabel in einem einzigen Durchgang entlang des Ziels zu erstellen. Dieser Beitrag fasst die Anforderungen der Nutzer an DOB-Vermessungen zusammen, erörtert die eingesetzten Technologien und präsentiert ermutigende Felddaten aus ersten Versuchen. Die Anwendung der vorgestellten Methoden ist nicht auf Kabel-DOB-Vermessungen beschränkt, sondern kann auch für Pipeline-Vermessungen oder andere Aktivitäten während des Baus und der Wartung von Offshore-Strukturen verwendet werden.

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DOB survey requirements

Cables are often buried in the seabed to avoid damage from ships, waves, anchors or other impacts. The depth of burial depends on the location of the cable and is typically between one and three metres. In areas of heavy fishing or very dynamic seabed morphology, burials of up to ten metres or additional rock placement may be necessary.

The requirements for cable position density along the cable route depend on the type of survey. Immediate post-laying surveys need positions at least every metre, whereas maintenance surveys typically demand positions every 50 to 200 metres. For cable tracking systems, a position density of up to 25 cm may be required. Horizontal (XY) cable position accuracy requirements are mainly based on the accuracy of the positioning system used. Depth of burial (Z) accuracy requirements vary from 5 % of the sensor tilt range to 10 % of the depth of burial with limits of 5 to 10 cm r.m.s. For a sensor two metres above the seabed and a cable buried two metres below the seabed, these requirements give a vertical accuracy of 20 cm (Wunderlich et al. 2016).

Operating costs depend mainly on the cost of the vessel, so the survey time must be as short as possible. If a high position density is required, the cable detection system must run along the cable route and cover a wide swath across the route. It should also guide the vehicle steering along the cable to ensure that the cable does not fall out of the survey corridor. Cable positions are often required immediately after trenching, so good online data visualisation is essential for quality assurance and fast on-board post-processing with full positional accuracy.

Equipment

There are several types of equipment used for DOB surveys, mainly electromagnetic (EM) or acoustic sensors. EM cable locators either detect the magnetic field of an energised cable (passive mode) or emit an EM pulse and detect the presence of metal objects within the field generated (active mode). In either case the cable is located by triangulating two or more EM sensors. This gives the XYZ position of the cable, but the depth of burial also requires the position of the seabed, which is typically determined by multibeam echo sounders (MBES). The accuracy of the cable position depends on the distances between the sensors and to the cable, with typically less accuracy in Z (depth) than in XY. Acoustic sensors emit sound pulses and detect material changes within the sonified volume. They can therefore detect both, the cable and the seabed at the same time and determine the burial depth. Another advantage is that it does not matter whether the cable is energised or not. The resolution and therefore the accuracy of the cable position is limited, but typically better in Z than in XY. It therefore seems to be a good idea to combine the two technologies and obtain a common dataset.

In this study we used an Innomar sixpack SBP, an Aquadyne MagTrack cable tracker, a Kongsberg Seatex MRU-5 motion sensor (providing heave, roll and pitch data) and a Septentrio dual-antenna GNSS positioning and heading sensor. Further details of the acoustic and magnetic sensors are given below, and Table 1 summarises both sensors.

	Innomar sixpack SBP	Aquadyne MagTrack
Sensor type	acoustic projector / hydrophone	3-axis magnetometer, 2-axis inclinometer
Number of sensors	6	2 / 4 / 8
Sensor separation	adjustable, typ. 0.25 … 0.5 m	1 … 10 m
Range below sensor	0.5 … 20 m	0.5 … 20 m (*)
Range resolution	5 cm	4 cm at 4 m range
Frequencies	100 kHz / 4 … 15 kHz	10 … 1,000 Hz
Beam width	circa 5° × 5°	n/a
Depth rating	surface	500 m / 1,500 m / 4,500 m
Sensor bearing angle to cable	n/a	30° … 150°; ideal 90°

Table 1: Acoustic and magnetic sensors utilised in this study
(*) depending on sensor baseline and current in the cable

Sixpack sub-bottom profiler

The sixpack SBP uses a rigid linear array of six transducers (combined projector and hydrophone) with adjustable spacing to optimise the overlapping footprints of the individual sound beams depending on water depth and location. The acoustic data is recorded together with all the auxiliary sensor data (position, heading, motion) in the same data file. To minimise reverberation and ambiguity, short narrow-beam, low-frequency sound pulses are generated using the principle of non-linear (parametric) acoustics (Lurton 2002). The use of multiple narrow-beam projectors and hydrophones aligned across the cable route reduces ambiguity in the dataset (Wunderlich et al. 2016). The sixpack SBP model is mainly used for

- high-resolution 3D visualisation of buried objects in archaeological projects (Missiaen et al. 2018; Pydyn et al. 2021),
- for site surveys and route surveys, searching for boulders and UXO (Barradas et al. 2022; Ouglov 2022)
- and for the mapping of buried pipelines and cables.

The Innomar multi-transducer SBPs have been on the market for a number of years and are constantly being improved. The latest generation with a new multi-channel data acquisition and improved processing algorithms, provides significantly increased data resolution, which also improves cable detection capabilities.

MagTrack cable tracker

The newly developed MagTrack is a passive cable tracker system with four small sensors, each containing a three-axis magnetometer and an inclinometer. It can accurately locate cable positions, typically in front of and behind a ROV or trencher (Fig 1).

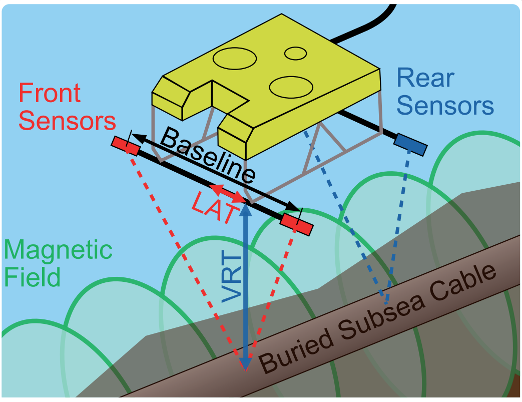

Fig. 1: MagTrack principle mode of operation in a typical four-sensor setup, building two independent cable trackers. Important distances are highlighted: sensor spacing (baseline), lateral cable offset (LAT) and vertical cable offset (VRT)

The system has been used on a variety of cable types including:

- fibre-optic cables, with a tone injected to the fibre protection tube inside the cable, Baltic Offshore used the MagTrack system for positioning;
- high voltage direct current (HVDC) and high voltage alternating current (HVAC) cables with either a separate or integrated return path, Reach Subsea has used several MagTrack systems on various cables for several clients including Nexans and NKT;
- 3-phase cables.

The MagTrack sensors detect a magnetic field generated by an energised cable and measure the XYZ components of the field. These measurements are then converted in the Subsea Electronics Module (SEM) to a direction towards the source of the field, i.e. the cable. The position of the cable is then calculated and displayed on the operator's graphical user interface (GUI) as the depth below the sensors (VRT) and the distance off track (LAT). This allows to steer the vehicle along the cable. Cable position and raw magnetic data can be recorded for quality assurance and post-processing.

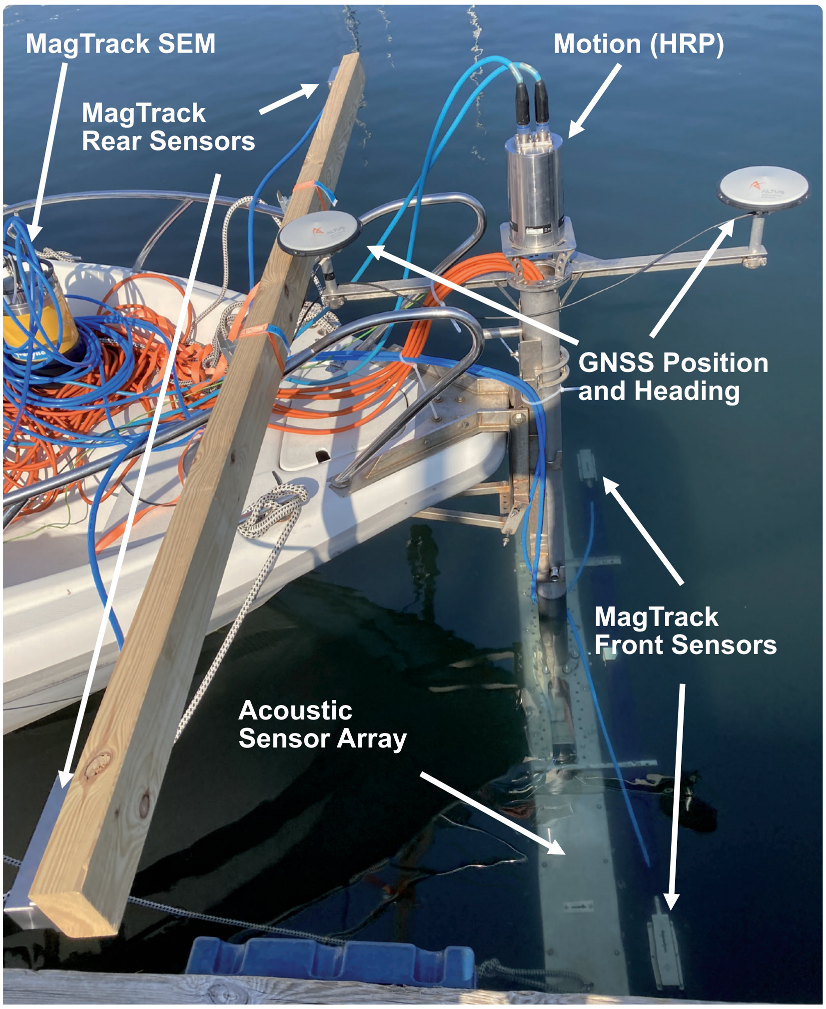

Fig. 2: Experimental sensor setup

The MagTrack system works well with currents of a few amps either from a single phase (one conductor) or from an unbalance between the phases in a three-phase cable. For high-voltage DC cables, the system is set to ignore the DC current and look for ripple frequencies from the rectifiers at 300 Hz. In fibre optic cables, the fibres are often protected by stainless steel tubes, which can be used to inject a low-frequency tone to make the cable detectable. Often this armour has a relatively high impedance, 150 to 250 ohms/km. For long cables it can be a challenge to drive a suitable current of more than 1 amp through this resistance. Tone generators with high voltage output (several thousand volts) may therefore be required for good detection of existing cables. For new cable designs the electrical impedance of the tubes should be minimised. Copper foil or tape wrapped around the fibre protection tube is commonly used for this purpose.

Sea trials

As both systems, the sixpack SBP and the MagTrack, are proven sensors for DOB surveys, the aim of this case study was to evaluate whether both sensors could be used simultaneously on a small surface vehicle. The sea trials for this study took place on three separate days in August 2024 off the coast of Rostock-Markgrafenheide on two near-shore power export cables connecting the Baltic 1 and Baltic 2 wind farms to the grid. The three-phase cables, which are operated by 50Hertz, are 25 cm in diameter (50Hertz 2012).

The sixpack acoustic sensor array and the front pair of the MagTrack sensors were mounted at the bow of a small survey boat. The motion, heading and position sensors were installed on the same pole, aligned with the centre of the acoustic array. The rear pair of the MagTrack sensors was mounted above water level on the deck or on the roof of the boat to reduce the potential noise from the SBP array. The sensor setup is shown in Fig. 2. Both systems were monitored in real-time to ensure quality and efficiency of data acquisition. All data was time-stamped and recorded on the same computer for post-processing.

The probability of cable detection and the accuracy of the MagTrack cable location depend on the signal-to-noise ratio (SNR) of the cable's magnetic field at the sensor positions and the distance between the sensors (baseline) used for triangulation. The SNR depends on the magnetic field strength of the cable (signal) and the strength of other magnetic fields (noise), e.g. from electrical equipment, such as motors and transformers, at the sensor positions. The field strength of the cable at the sensor position decreases with increasing distance and increases with increasing electrical current in the cable.

To ensure optimum boat operation, days with minimal wind have been selected. However, low wind speeds result in less power from the wind farm and therefore less current in the cable, making detection more difficult. In a perfectly balanced three-phase cable the field from each phase is 120° apart from the other two phases, resulting in a magnetic field that cancels each other out. However, the load is rarely 100 % balanced and the cables are not perfectly symmetrical. Therefore, a detectable field will still be present even from three-phase cables, but at a low field strength.

The distance between two grouped MagTrack sensors, the baseline, determines the angle between the sensors and the cable, which is ideally 90°. In the survey area of this case study the water depth ranges from 5 to 6 metres and the cable's burial depth was expected to be around 1 metre. The front MagTrack sensors had a baseline of 1.9 m (angle approximately 20°), while the rear sensors were spaced 2.9 m apart (angle approximately 30°). At the given distance from the cable the baseline should be increased, but with a stable survey platform and a strong magnetic field, even a 20° angle may be sufficient.

Electromagnetic noise can be reduced by avoiding using equipment that operates at the same frequency as the electrical current in the cable. The MagTrack is DC powered and can be battery operated. During the sea trials, the equipment used had to be mains powered and the generator was set to operate slightly below 50 Hz. The generator frequency and another strong component at 16.7 Hz from a railway were removed by notch filters set in the MagTrack GUI.

Data processing and results

Post-processing of the acoustic data includes transducer offset correction, individual trace motion compensation, bandpass filtering and amplitude normalisation to the echo signals. Correction and conversion of the irregularly distributed point cloud to a regular grid with adjustable cell sizes is a prerequisite for the visualisation in 3D software packages. The gridding process can also include multiple survey lines along the cable, which may result in a higher point density and increased coverage across the cable. 3D visualisation within a volume renderer allows for adjustable amplitude and opacity transfer functions to enhance the visibility of specific reflectors and clip planes are used to remove noise and unnecessary parts of the volume. Fig. 3 illustrates the visualisation of the acoustic data in a 3D renderer and how the cable position and the burial depth are determined in the 3D volume. Fig 4 compares the traditional cable position picking from 2D seismic sections with the cable position extraction from the 3D volume.

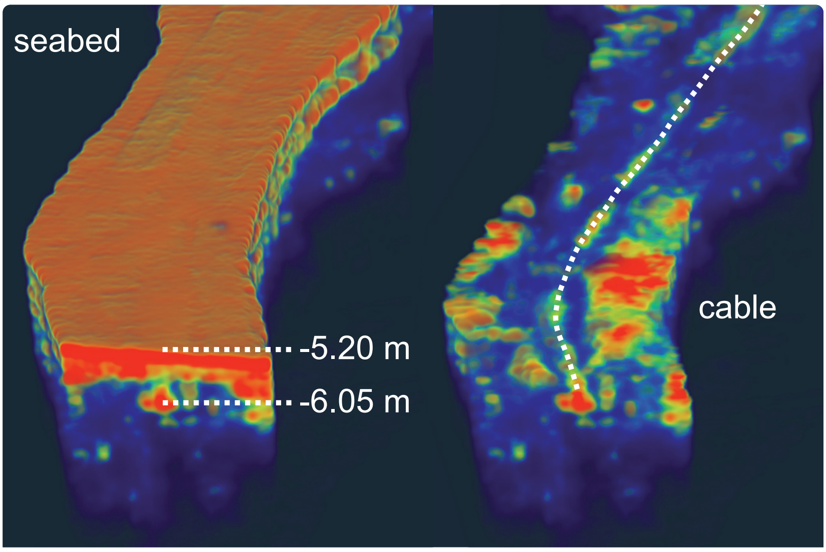

Fig. 3: 3D volume rendered from the acoustic data showing the cable buried approximately 0.85 m below seafloor

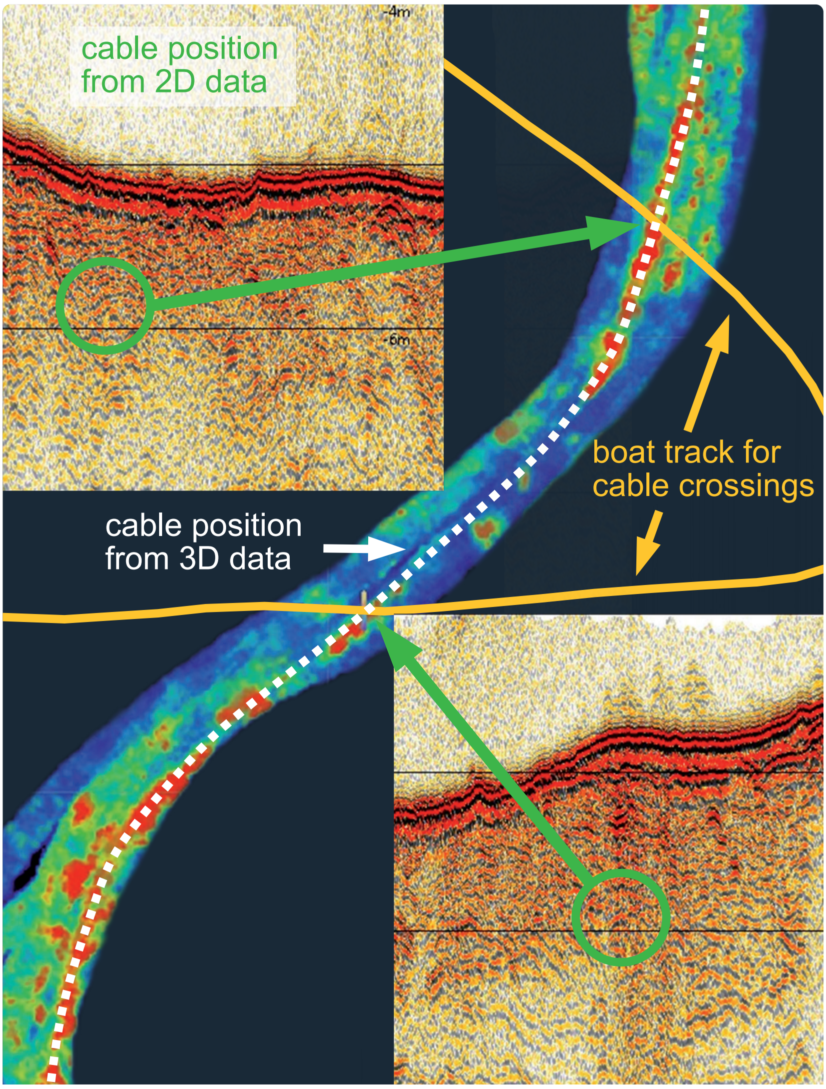

Fig. 4: Top view of the 3D volume rendered from the acoustic data and cable detection in the 3D volume vs. in the 2D sections of cable crossings

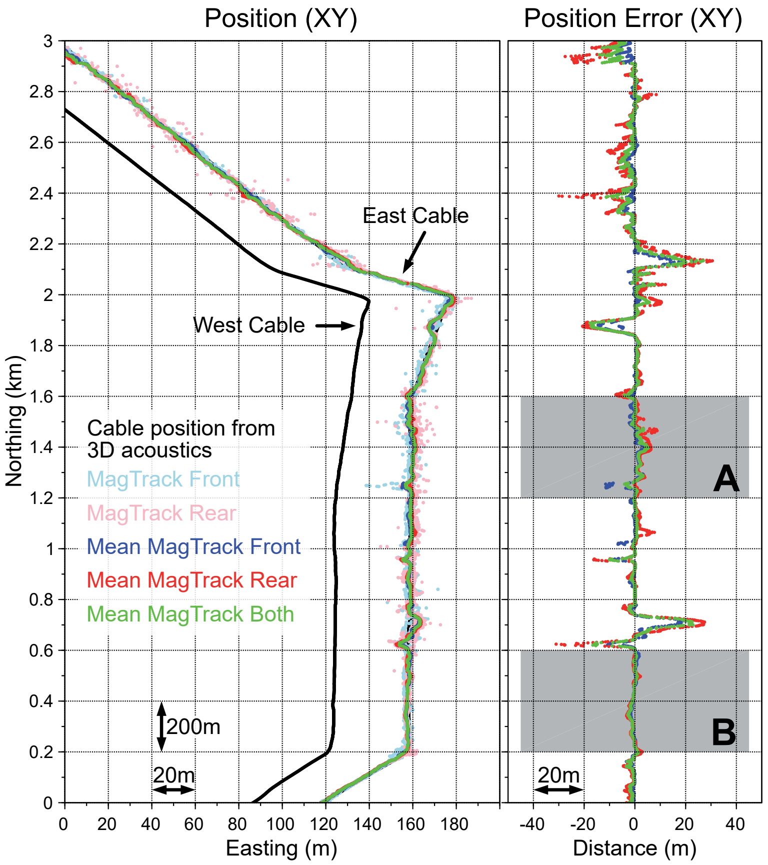

Fig. 5: Cable positions from the acoustic data (black; both cables) and from the MagTrack (three runs, front blue, rear red; east cable only) and difference between the acoustic and averaged MagTrack XY cable position; two sections A and B are highlighted, see text

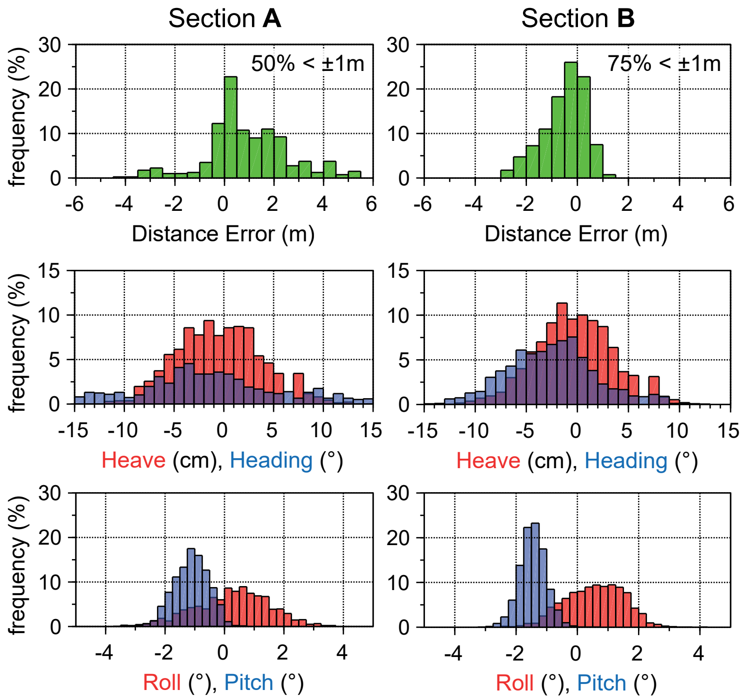

Fig. 6: Histogram plots of the position difference and motion data of the two sections higlighted in the position plots in Fig. 5

The latter gives a much higher position density along the cable without any additional effort and the cable is much easier to locate than in the 2D sections.

Post-processing of the MagTrack data includes position correction, motion compensation and outlier removal based on the Modified Z-Score method. The XY position of the cable shows significant variance, but improves when averaging three runs along the cable (see Fig. 5). This variance is probably due to the relatively large distance between the sensors and the cable, the low magnetic field strength of the three-phase cable and the short sensor baseline. However, there are sections with less variation, particularly in the south. The position obtained from the front pair of sensors, mounted directly on the acoustic array, mostly just follows the boat track rather than the cable. This can be attributed to the lower SNR due to the large amount of metal, the electromagnetic fields from the acoustic array and the associated cables, and the shorter baseline. Despite being even further away from the cable, the rear pair of sensors performed better, especially for the cable depth. This is probably due to the longer baseline and the greater distance from the acoustic array.

Further analysis of two sections of the cable route, each 400 metres long, showed differences in the XY position error and the heading variations (see Fig. 6). The other motion data (heave, roll, pitch) show almost the same distribution and with their small range of values they cannot cause larger position errors. Also, the water depth was almost the same in both areas, so the larger position errors seen in section A compared to section B are probably related to the larger heading variance. However, to guide the vehicle to ensure that the acoustic data will cover the cable, an XY positional accuracy of the MagTrack of ±1 m is sufficient. This was the case for more than 50 % of the averaged values in both sections.

Conclusions

Both sensor systems proved to provide good data for DOB surveys. The positional accuracy of the MagTrack was not as good as hoped, suffering from the much too short sensor baseline for the given cable distance and the unstable survey platform, especially the rapid changes in heading. However, the averaged cable position was good enough to ensure that the acoustic array was positioned over the cable. The on-line data output and visualisation of the MagTrack will need to be improved to guide the vehicle steering in these conditions.

The 3D volume rendered from the acoustic data proved to be a good tool for extracting the XYZ positions of the cable with high positional accuracy and density. However, this requires some post-processing and is not yet possible in real-time. The workflow needs to be improved.

The combination of both sensors improves survey speed and data quality. This in turn reduces the cost of data acquisition and post-processing. //

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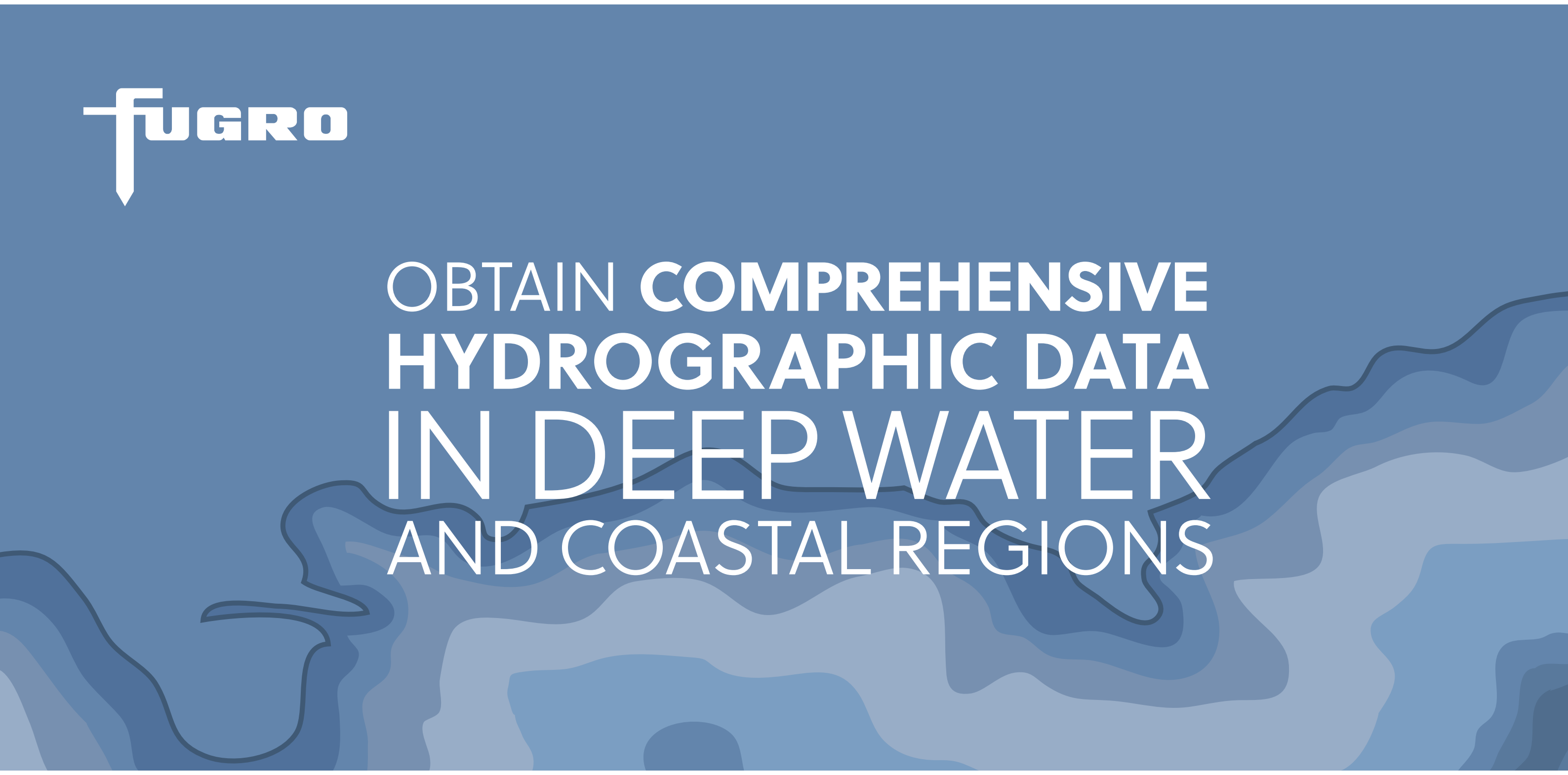

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Lab experiment for photo bathymetry

Simultaneous reconstruction of water surface and bottom with a synchronised camera rig

An article by LAURE-ANNE GUEGUEN and GOTTFRIED MANDLBURGER

In photo bathymetry, the refraction of the optical rays at the air-water interface, according to Snell's law, causes image blurring and topographic reconstruction errors. Modelling the dynamic, wave-induced water surface can correct this refraction, enhancing bathymetric accuracy. This study presents a technical approach for simultaneously capturing and reconstructing both the water surface and bottom using a synchronised camera rig. Various acquisition configurations were tested to assess the possibility to extract water surface information. The design, acquisition plan, insights and initial results of this feasibility study are discussed, along with suggestions for future improvements and outlooks.

photo bathymetry | water surface | synchronised camera rig | refraction | structure-from-motion
Fotobathymetrie | Wasseroberfläche | synchronisiertes Kamera-Rig | Refraktion | Struktur-aus-Bewegung

Bei der Fotobathymetrie führt die Brechung der optischen Strahlen an der Luft-Wasser-Grenzfläche nach dem Snelliusschen Gesetz zu Bildunschärfen und Fehlern bei der topografischen Rekonstruktion. Die Modellierung der dynamischen, welleninduzierten Wasseroberfläche kann diese Brechung korrigieren und die bathymetrische Genauigkeit verbessern. In dieser Studie wird ein technischer Ansatz zur gleichzeitigen Erfassung und Rekonstruktion der Wasseroberfläche und des Bodens mit Hilfe eines synchronisierten Kamera-Rigs vorgestellt. Es wurden verschiedene Aufnahmekonfigurationen getestet, um die Möglichkeiten zur Gewinnung von Informationen über die Wasseroberfläche zu bewerten. Das Design, der Erfassungsplan, die Erkenntnisse und die ersten Ergebnisse dieser Machbarkeitsstudie werden zusammen mit Vorschlägen für zukünftige Verbesserungen und Ausblicke diskutiert.

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1 Introduction

Photo bathymetry is the use of photogrammetry for underwater topography reconstruction. It provides an alternative to traditional acoustic systems which can be more practical and affordable, particularly for water bodies with limited depth and low turbidity like inland rivers or coastal areas. In aerial photo bathymetry, where the imaging systems are above the water, the optical rays must pass through air and water. This is then a case of two-media photogrammetry, requiring the application of Snell's law to correct the refraction of the rays at the interface. As of today, this issue is the main obstacle to achieving high accuracy photo bathymetry.

A 3D model of the water surface is therefore a prerequisite to correct the ray paths, but many current methods simplify the problem by approximating the surface as a static plane, ignoring its dynamic, wave-induced nature. Okamoto (1982) has highlighted that waves introduce substantial errors in underwater topography reconstruction. Existing methods for reconstructing wave patterns are diverse, including the use of surface markers (Chandler et al. 2008) or using the optical properties like specular reflection (Rupnik et al. 2015) or refraction (Murase 1992; Morris and Kutulakos 2011). However, these methods often rely on restrictive assumptions, like previous knowledge of the mean water height or the topography, and are not ideal for reconstructing both the water surface and underwater topography in natural environments.

Our work aims to address these limitations by developing a method for the simultaneous reconstruction of the water surface and bottom, which would then contribute to the development of a solution that would be deployable over inland rivers and coastal areas.

The following sections discuss our methodology, results and future research directions.

2 Methodology

2.1 Goal and design of the experiment

We designed and implemented a lab experiment allowing different data acquisition set-ups for simultaneous capture of the water surface and the

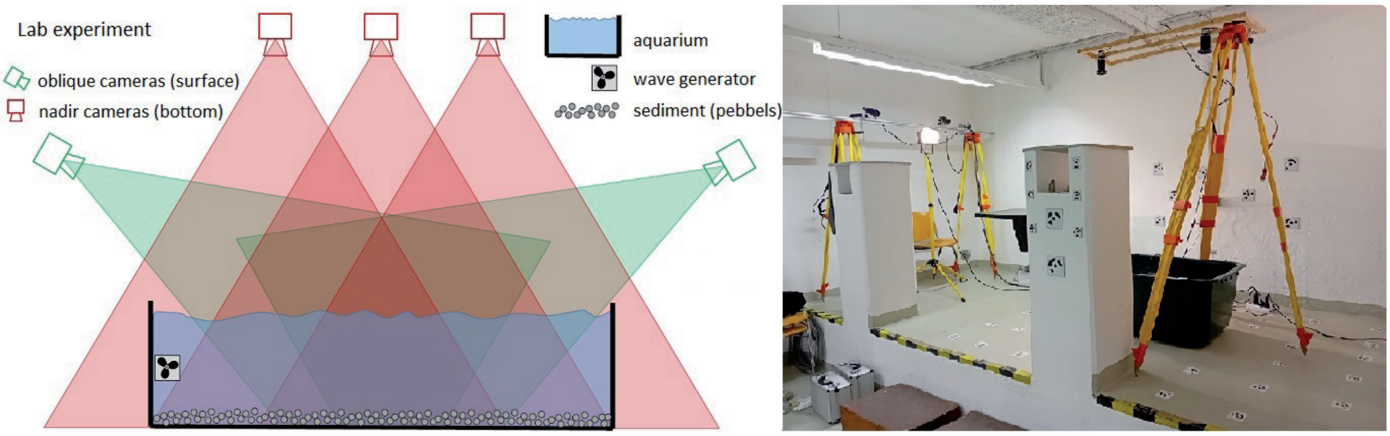

Fig. 1: Left: Data acquisition set-up with multiple static cameras over a water tank. The nadir cameras deliver the bottom via multimedia photogrammetry whereas the oblique cameras are only used for water surface reconstruction. Right: Implementation of the experiment in the measurement lab at TU Wien

water bottom, as illustrated in Fig. 1. The focus of the experiment is to assess the feasibility of (i) capturing and (ii) reconstructing the water surface, which are two distinct issues. Capturing the water surface involves identifying the optimal configuration in terms of equipment, imaging parameters, lighting, positioning, etc. On the other hand, reconstructing the water surface relates to what extent the water surface can be modelled, specifically which parameters can be extracted, which area can be covered, etc. Additionally, this setup is intended as a preliminary step towards a more ambitious experiment, namely surveying inland waters using cameras mounted on a squad of unmanned aerial vehicles (UAVs).

To implement this experiment in the measurement lab of TU Wien, we used a complete camera rig provided by IfP Stuttgart. The setup includes four cameras with lenses, an Arduino Leonardo and the associated cabling. The Arduino functions as a controller, synchronising the cameras by sending an electrical trigger signal at user-defined intervals via a USB connection. Due to technical limitations, the maximum achievable frame rate is 1 Hz, which is the rate used for all results presented in this paper. Two cameras are positioned obliquely from the side to capture the water surface, while the other two are positioned directly above to capture the water bottom. We filled an aquarium with water and added a layer of stones and photogrammetric targets (fixed in a concrete frame) to create a textured topography and to provide checkpoints for later assessment. In addition, we used an indoor fountain pump to generate a dynamic water surface with a regular wave pattern. Setup and equipment are depicted in Fig. 1.

2.2 Preliminary steps

Calibration and geo-referencing

Before conducting the lab experiment, attention was given to calibration and geo-referencing. We use Agisoft Metashape (Over et al. 2021) to estimate the radial distortion, as well as the interior and exterior orientations of the cameras via bundle-block adjustment.

For geo-referencing in the laboratory local coordinate system, we use ground control points (GCP). Approximately 80 coded markers were installed around the scene and surveyed with submillimetre precision using a total station (Leica TS16). These markers were selected to allow automatic detection in Metashape and were strategically placed around the aquarium to function as GCPs and checkpoints. Their placement was carefully considered to align with the cameras' field of view, aiming for an even distribution along the three axes despite the restrictive environment. The markers were measured using angle and distance measurements from six different positions but only angle measurements were used during processing. The coordinates of the points within the laboratory local coordinate system were thus estimated via forward intersection, resulting in a maximum standard deviation of 0.2 mm for any point coordinate.

Reference model

Before filling the aquarium with water and acquiring the data, several images of the aquarium were captured still in dry state using a 28 mm focal length Nikon camera. These images were used to create a reference model of the topography. The final model was generated by applying dense image matching in Metashape and serves as validation. It is presented in Fig. 2.

Acquisition plan

In order to gather a comprehensive dataset and analyse the impact of various parameters, an extensive acquisition plan was implemented in several stages, with each stage building on and improving the previous one based on the insights gained.

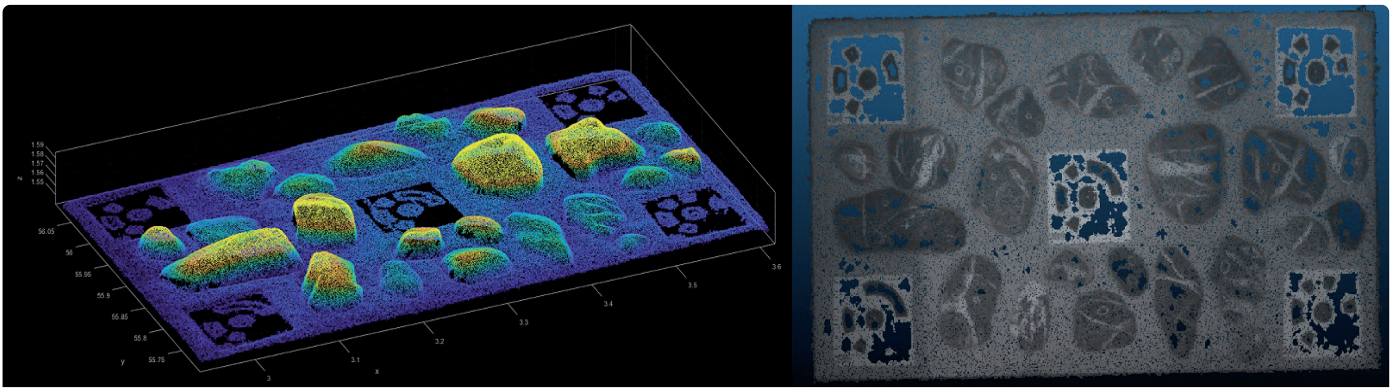

Fig. 2: Reference model of the topography

Two obliquely looking cameras are positioned on the side and two nadir looking cameras above the water tank. The oblique cameras were mounted on a horizontal bar supported by two tripods. The goal of this configuration was to identify tie points on the water surface using a standard Structure-from-Motion approach (Schönberger et al. 2016). Another approach could involve using the specular reflections to derive the surface normal vectors.

For this standard setup, different scenarios were carried out to define the setup that would optimise the number of tie points found on the water surface. In individual scenarios, we tested different heights for the oblique cameras, different levels of turbidity in the water, different lighting setups (position, intensity and subsequent specular reflection) and different camera parameters such as exposure time (3 to 9 ms, depending on the lighting), gamma value (1 or 1.6), gain (0 to 10 %) and aperture (F/1.8 or F/2).

For all scenarios, datasets of 60 frames (equivalent to 1 minute) were collected with a dynamic water surface generated by the pump, and datasets of 20 frames were collected with a flat water surface.

3 Results

3.1 Processing workflow

Our work was primarily focused on the oblique pairs to gain information of the water surface. All acquired data were put through the same processing workflow in Metashape composed of the following steps: feature detection on each image and then matching across the pair, alignment of cameras, geo-referencing with GCPs and dense matching.

The initial results of the processing pipeline applied to all pairs of oblique images showed first and foremost that the perfect transparency of water was a problem because this leads to the tie points being on the topography instead of the water surface. We also observed that most of the tie points on the water surface were located on the specular reflection, meaning that higher specular reflection significantly increases the number of surface tie points. During the iteration of acquisition configurations, we have then decided to add turbidity in the water to get rid of the transparency. And, even though we are aware that an error is induced when a tie point is found on both images where there is specular reflection (due to lighting direction, camera exterior orientations and the

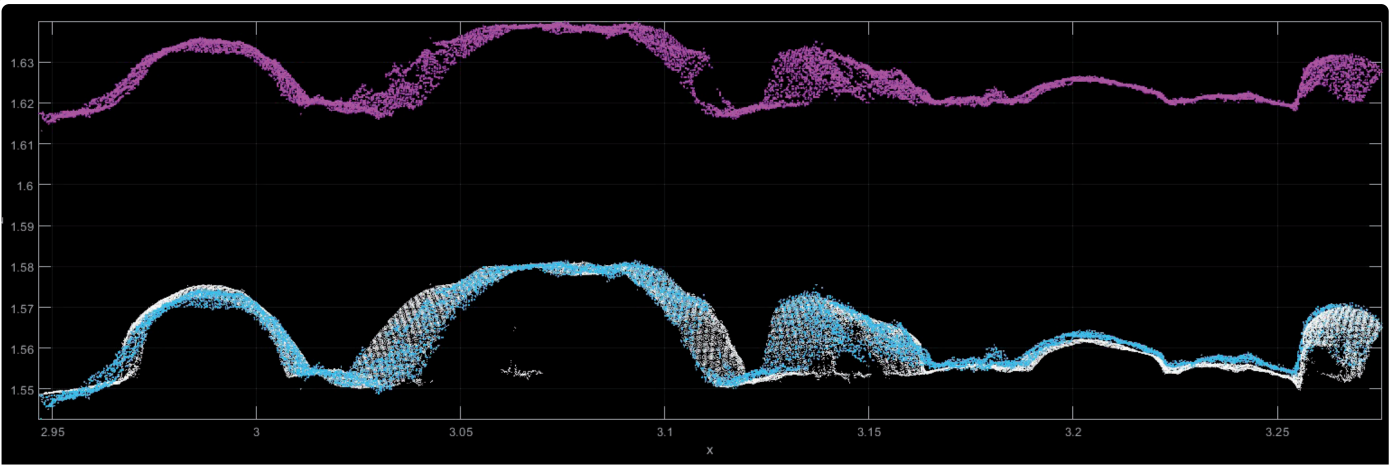

Fig. 3: Profile in XZ plane of the ground truth (white), the model resulting from the four nadir images (magenta) and the model after refraction correction (light blue)

shape of the water surface), we have also decided to maximise the specular reflection to try to obtain more tie points on the water surface.

With enough turbidity to create full opacity in the water column and specular reflection on the surface, the number of tie points on the water surface jumped on average from around two to 50 tie points for a similar pair of images.

3.2 Estimation of mean water height

Using a configuration providing a significant amount of tie points on the water surface, we are able to retrieve the Z coordinate of these tie points, and the average value is therefore an estimation of the mean water height.

To assess this value, we use a model of the topography resulting from four nadir images taken through a flat water surface and we use the Snellius module of the OPALS software (Orientation and Processing of Airborne Laser Scanning data) developed at TU Wien (Mandlburger 2016). The Snellius module allows correcting the refraction effect if the refractive index of water and a 3D model of the water surface are given as input parameters. In our case, we use 1.33575 for the refractive index and the surface is approximated as a flat water surface of height 1.8075 m as this is the parameter to be assessed. The choice of this specific value for the refractive index is detailed in section 3.3.

Fig. 3 shows a profile in the XZ plane of the ground truth and the models of the topography before and after refraction correction. To compare the models with the ground truth, we generate the subsequent digital elevation models (DEM) and compute the histograms of the differences with the DEM of the ground truth.

The results in Table 1 highlight that we are now able to reconstruct the bottom topography with sub-millimetre accuracy compared to the reference model (dry state). This shows that the used technique provides a decent estimation of the mean water height, despite the dynamic nature of the water surface.

3.3 Refractive index of water

During the processing workflow presented in section 3.2, the refraction correction step has been carried out with various values for the refractive index as we had no direct measurement in the context of our lab experiment. We have tested the following values: 1.33, 1.335 and 1.34, but also different mean water heights around the average value of the tie points. The results are presented in Table 2.

	Before refraction correction	**After refraction correction**
Mean	65.7 mm	0.7 mm
Median	66.1 mm	0.9 mm

Table 1: Differences with the ground truth of the topography before and after refraction correction by the estimated mean water height

The results highlight the significant impact of the refractive index in comparison with the mean water height. The third line corresponds to our water height estimation and we can see that there is approximately a 1-mm difference with the ground truth for a change of 0.005 of the refractive index. On the other hand, these results also show that a 1-mm change of the mean water height (out of 25 cm depth) only affects the results by 2 or 3 mm, which is quite satisfying since the average value is calculated over a dispersed set of values as the water surface is dynamic.

More importantly, this study accentuates the necessity of having a better estimation of the refractive index. Maas (2015) provides the model below for the refractive index:

$$n_W = 1.338 + 4 \times 10^{-5} (486 - \lambda + 0.003d + 50S - T)$$

with n_W the refractive index of water, λ the wavelength in nm, d the depth in m, S the salinity in % and T the temperature in °C.

Using the following values: λ = 520 nm (average according to our panchromatic sensor sensitivity), d = 0.15 m (around half of maximum depth), S = 0 % (measured) and T = 22.2 °C (measured), our estimation of the refractive index in the lab is $n_W = 1.33575$.

4 Conclusion

Our lab experiment provides an opportunity to study the feasibility of capturing and reconstructing the water surface by images only. Several acquisition scenarios have been implemented to provide an extensive collection of data and give us the possibility to study the impact of various parameters to understand the optimal setup for our final goal of using the technique for surveying rivers later on. While we neither obtained a full nor an accurate water surface reconstruction so

	Index = 1.33	**Index = 1.335**	**Index = 1.34**
Height = 1.806 m	Mean = 2.3 mm Median = 2.5 mm	Mean = 1.4 mm Median = 1.5 mm	Mean = 0.4 mm Median = 0.6 mm
Height = 1.807 m	Mean = 2.0 mm Median = 2.1 mm	Mean = 1.0 mm Median = 1.2 mm	Mean = 0 mm Median = 0.2 mm
Height = 1.8075 m	**Mean = 1.8 mm** **Median = 2.0 mm**	**Mean = 0.8 mm** **Median = 1.0 mm**	**Mean = −0.1 mm** **Median = 0.0 mm**
Height = 1.808 m	Mean = 1.6 mm Median = 1.8 mm	Mean = 0.6 mm Median = 0.8 mm	Mean = −0.3 mm Median = −0.1 mm
Height = 1.809 m	Mean = 1.3 mm Median = 1.4 mm	Mean = 0.3 mm Median = 0.5 mm	Mean = −0.7 mm Median = −0.5 mm

Table 2: Assessment of the refraction correction (mean and median of differences with ground truth) with different refractive index and mean water height values

far, preliminary results have shown that it is possible to gain some information on the water surface from oblique images, starting with the mean water height. We have also gained knowledge on the strong impact of the refractive index and the importance of having a proper estimation.

The main focus of our work has been on optimising the data acquisition setup to maximise the number of tie points that can be found on the water surface. However, the accuracy of these tie points is not optimal and further work is currently underway to assess the error due to specular reflection as well as to obtain more accurate tie points. Furthermore, we are also researching whether deep learning solutions for feature description and matching on images could be suitable in our case of water surface reconstruction, as such approaches have proven to provide many more tie points of high accuracy for dry and diffusely reflecting surfaces. Thus, we focus more on the post-processing side of the problem now.

Eventually, the goal is to obtain enough surface points or surface parameters, like the mean water height, wavelengths, elevation of peaks, etc., which could be used to formulate a mathematical model of the water surface. //

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Innovative quay wall surveys – leveraging unmanned surface vehicles

An article by JANNE SILDEN, EZEKIEL DAVID and JORGE IBACETA

Regular surveys of quay walls ensure they remain structurally sound and operational, but traditional inspection methods can be labour-intensive and limited by access constraints. However, new approaches that leverage autonomous technologies are advancing the field in terms of operational efficiency on the water, data quality and the extent to which 3D models can be created and applied for engineering and maintenance purposes. Subsea Europe Services GmbH has been working on a solution based on the integration of a tilted multibeam echo sounder (MBES) mounted on an unmanned surface vehicle (USV). It was put to the test this summer in the »Alter Hafen Süd« port in Rostock, Germany, during a successful quay wall survey that demonstrated how the combination of cutting-edge acoustic and autonomous systems can significantly enhance surveying and analysis in complex harbour environments.

quay wall survey | 3D model | USV
Kaimauervermessung | 3D-Modell | USV

Regelmäßige Inspektionen von Kaimauern stellen sicher, dass sie strukturell solide und funktionsfähig bleiben, aber traditionelle Inspektionsmethoden können arbeitsintensiv und durch Zugangsbeschränkungen begrenzt sein. Neue Ansätze, bei denen autonome Technologien zum Einsatz kommen, bringen Fortschritte in Bezug auf die Betriebseffizienz auf dem Wasser, die Datenqualität und das Ausmaß, in dem 3D-Modelle erstellt und für technische und Wartungszwecke verwendet werden können. Die Subsea Europe Services GmbH hat an einer Lösung gearbeitet, die auf der Integration eines geneigten Fächerecholots (MBES) auf einem unbemannten Überwasserfahrzeug (USV) basiert. Sie wurde in diesem Sommer im Alten Hafen Süd in Rostock bei einer erfolgreichen Kaimauervermessung erprobt, die zeigte, wie die Kombination von modernsten akustischen und autonomen Systemen die Vermessung und Analyse in komplexen Hafenumgebungen erheblich verbessern kann.

Tightly integrated quay wall survey

At the heart of the survey was the R2Sonic 2026 V+, an MBES well known for its high-resolution capabilities and versatility. By tilting the sonar horizontally using a mount customised at Subsea Europe Services' R&D centre, it was a straightforward process to optimise beam alignment with vertical structures like quay walls, enabling more accurate and detailed data acquisition. The system operates across a frequency range of 170 kHz to 450 kHz, with up to 1024 soundings per ping, providing exceptional detail of underwater structures. This, combined with its roll- and pitch-stabilised beams, ensure robust performance even in dynamic conditions.

The MBES was mounted on the »Autonomous Surveyor«, a 3.6-metre USV manufactured by Martac Systems and owned by Subsea Europe Services. The USV's compact size and electric twin-screw propulsion system made it ideal for navigating the tight, shallow areas under and around quay walls. With survey speeds ranging from 2 to 12 knots, the USV is agile enough to access confined spaces while still collecting high-quality data. The vehicle's autonomous and semi-autonomous capabilities allow for flexible operations with minimal human intervention, improving both safety and efficiency.

The survey aimed to capture detailed images of the vertical structures along a section of the quay wall in »Alter Hafen Süd«. Traditional horizontal sonar beams can struggle with accuracy when surveying vertical or near-vertical structures. To address this, the R2Sonic 2026 V+ MBES was deployed using a 25-degree tilt angle; a configuration to ensure the beams struck the wall perpendicularly, reducing distortions and improving data fidelity (Fig. 1).

The USV was equipped with the SBG Pulsar 40, an inertial navigation system that provided high-precision positioning and motion compensation. Dual antennas were mounted on the USV to en-

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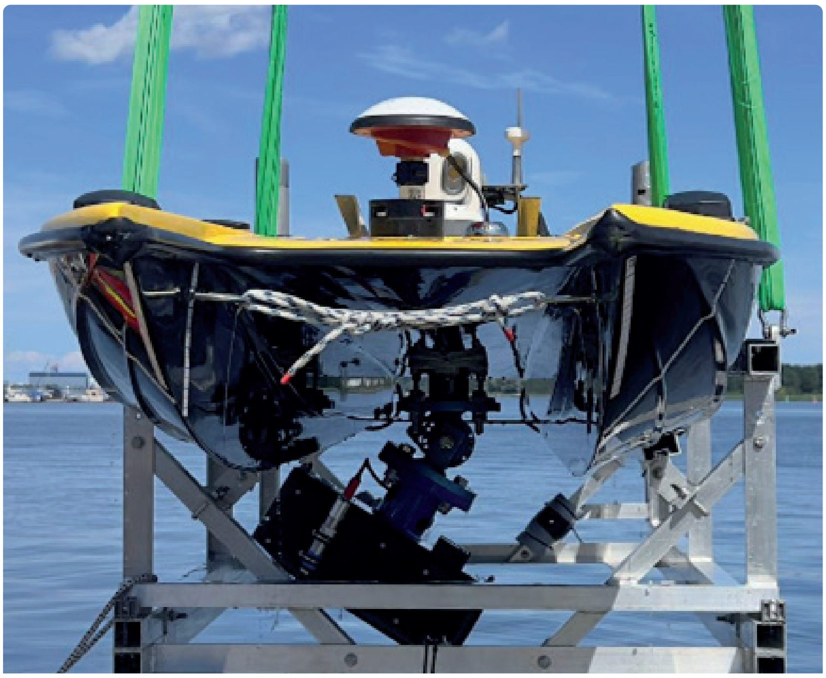

Fig. 1: The multibeam echo sounder was mounted on a tilted flange

hance heading accuracy, which is critical for maintaining alignment with the quay wall. A comprehensive sound velocity profile of the water column was obtained, followed by a patch test to calibrate the MBES system.

During the survey, the USV navigated multiple passes along the quay wall to capture overlapping datasets. The tight manoeuvring allowed it to access areas that would be challenging for manned vessels. Data was continuously transmitted to a remote monitoring station set up near the survey site, ensuring real-time observation and control in accordance with maritime safety regulations.

The use of a tilted MBES offers several key advantages over traditional beam-steering methods. One of the most significant is the optimised beam alignment, which allows the sonar to strike the quay wall most effectively. This minimises distortions commonly caused by the incidence angle on vertical surfaces, resulting in more accurate data. The tilted configuration also captures enhanced detail, detecting small cracks, signs of erosion and structural anomalies that could be missed with standard setups.

Additionally, the simplicity of the tilted MBES reduces the need for complex beam-steering algorithms, making it easier to operate in confined harbour spaces without sacrificing data quality. The system offers considerable cost and time efficiency too.

Data processing, analysis and modelling

The MBES data was processed using BeamworX AutoClean software, streamlining the removal of noise and artefacts, and producing a clean dataset ready for analysis. A grid with 15 cm resolution was applied to create a detailed 3D model of the quay wall and surrounding seabed (Fig. 2). The model revealed critical details such as structural deformations and underwater obstructions, aiding in maintenance planning.

The tilted configuration of the MBES proved especially beneficial in the creation of the 3D model. With the sonar beams directed towards the quay wall at an optimal angle, the system captured surface features more accurately than traditional methods. The survey extended 0.9 metres below the water surface, providing a comprehensive view of the wall's condition (Fig. 3). This high-resolution dataset was instrumental in identifying potential weak points that could compromise the wall's structural integrity if left unaddressed.

While the summer survey focused on the application of a tilted MBES and USV to acquire quay wall data, future developments could further enhance the 3D modelling capabilities by incorporating above-water sensors like LiDAR to create a unified model that spans from the seabed to the structures above the waterline. LiDAR, captures precise 3D data of objects and surfaces in real-time, enabling comprehensive surveys of port infrastructure, including vertical walls and surrounding features that rise above the water.

The »Autonomous Surveyor« USV is particularly well-suited for this integration due to its stable, flat design, allowing for the simultaneous mounting of both sonar and LiDAR systems. The fusion of these two data streams – MBES for underwater features and LiDAR for above-water structures – provides a seamless, full-profile model of the quay wall. This can improve both maintenance planning and structural integrity assessments, covering potential areas of concern from the bottom of the quay wall up to overhead components like cranes or fenders.

LiDAR's independence from light conditions ensures reliable operation in low-visibility environments or challenging weather, which is often critical in port surveys. The ability to match LiDAR data with underwater sonar data in real time – using integrated software systems like those in development at Subsea Europe Services – further enhances the accuracy of the survey and provides a holistic view of the area being inspected

Sensor and autonomous platform integration

The combination of the R2Sonic 2026 V+ multibeam echo sounder and the Martac USV presents a unique solution that significantly enhances the efficiency, flexibility and quality of marine surveying. The primary benefit of using a tilted MBES on a USV was the ability to perform high-precision surveys in difficult-to-reach areas without compromising data quality, however, one of its most notable advantages is the system’s ability to be rapidly deployed to any port or harbour across Europe.

Unlike traditional survey vessels that require extensive planning, crew and logistical support, this system can be transported by a van and trailer, allowing for swift setup on-site. This capability is particularly beneficial for time-sensitive operations, such as urgent inspections or when quick data collection is essential. It eliminates the delays associated with larger, more cumbersome survey vessels.

Another standout feature is the Martac USV’s durability and performance in rougher weather conditions. Designed for harsh offshore environments, the USV continues to operate efficiently even when weather conditions become challenging, a limitation that often hampers the performance of other USVs or manned survey vessels. This robustness ensures that survey operations can proceed without interruption, regardless of external conditions. Whether it’s calm waters or more turbulent offshore environments, the system maintains a consistent level of precision and efficiency.

Selecting the R2Sonic 2026 V+ offers the highest resolution in shallow water MBES systems currently available. The level of detail it captures makes it ideal for surveys that demand exceptional accuracy. Whether assessing the condition of port infrastructure or mapping vertical structures, the system excels in detecting even the smallest anomalies, such as cracks, erosion or deformations that might otherwise go unnoticed. This combination of high data density and quality ensures that the survey results are both precise and reliable, enabling better decision-making for maintenance and infrastructure planning.

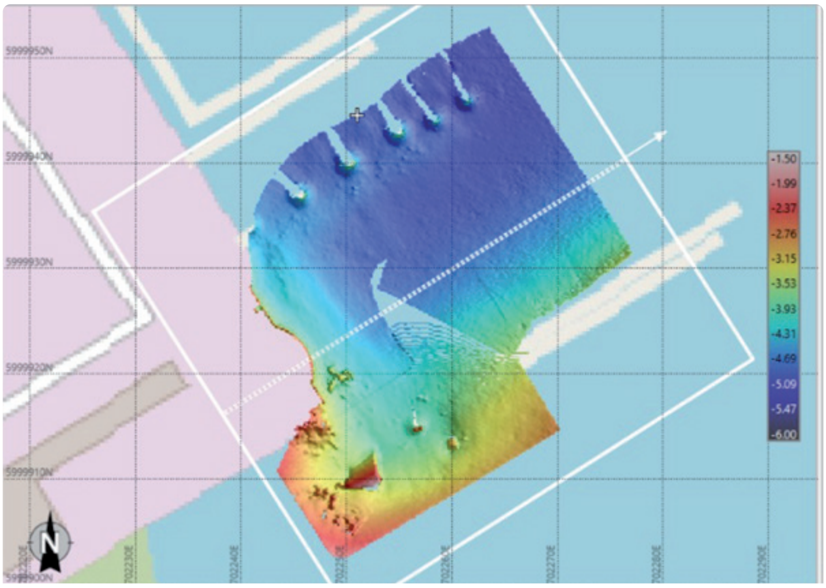

Fig. 2: A 3D model of the whole area showing the wall, pillars and other objects on the seabed was created

The integration of the chosen MBES and an advanced USV enables high-precision surveys in hard-to-reach areas without sacrificing data quality, while offering significant cost savings compared to a fully crewed approach on a standard survey vessel achievable. Further, the potential for a seamless integration of additional sensors, such as LIDAR, creates a comprehensive framework for geophysical surveys above and below the water surface. With easy deployment and exceptional data resolution, the system offers a complete solution that outperforms traditional methods.

Ultimately, for ports, harbours and coastal infrastructure projects that require accurate, reliable data in challenging environments, it reduces costs, minimises risk and extends operational weather windows. //

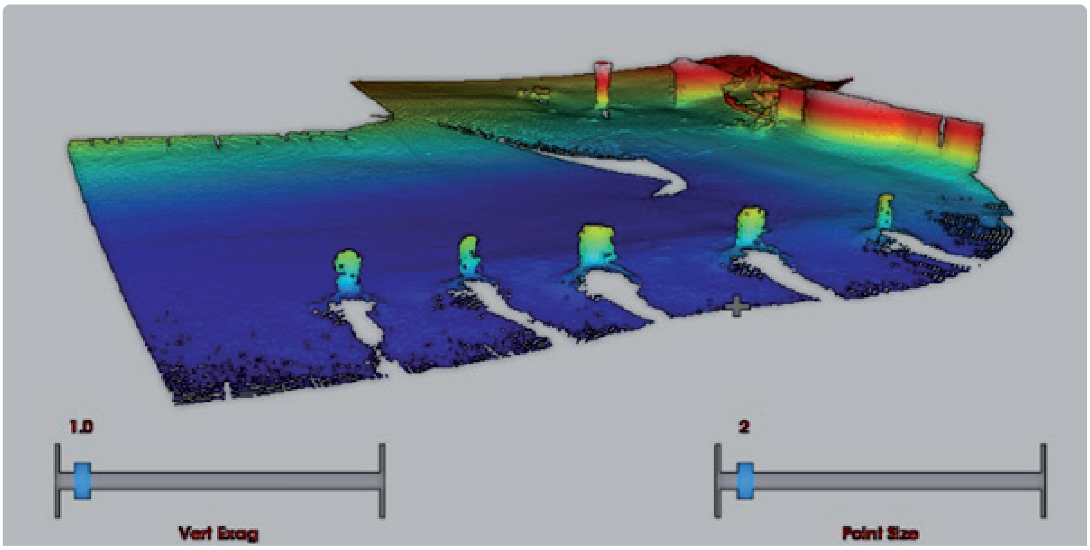

Fig. 3: The multibeam depth was 0.6 m below the water surface, and with the 25° tilt, the quay wall up to 0.9 m below the water surface was reached

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»We are proud to state that the Innomar SBPs are ›Made in Germany‹«

An interview with SABINE MÜLLER

Sabine Müller says of herself that she finds it difficult to say »no«. This probably explains why we don't just talk about one topic in our interview with her, but three. Firstly, there is her job as Managing Director of Innomar Technologie GmbH in Rostock. Secondly, there is her commitment to the DHyG, whose office she has headed for many years. And there is - most recently - the fact that she is the main organiser of HYDRO 2024 in Rostock. Sabine may not be able to say »no«, but she can give clear answers.

HYDRO 2024 | Innomar | parametric sub-bottom profiler | DHyG
HYDRO 2024 | Innomar | parametrisches Sedimentecholot | DHyG

Sabine Müller sagt von sich selbst, dass sie nur schwer »Nein« sagen kann. Das erklärt vermutlich, warum wir im interview mit ihr nicht nur über ein Thema reden, sondern gleich über drei Themengebiete. Da ist zum einen ihr Beruf als Geschäftsführerin der Innomar Technologie GmbH in Rostock. Da ist zum anderen ihr Engagement für die DHyG, deren Geschäftsstelle sie seit vielen Jahren leitet. Und da ist – ganz aktuell – die Tatsache, dass sie als Hauptverantwortliche die HYDRO 2024 in Rostock organisiert. Mag sein, dass Sabine nicht »Nein« sagen kann, aber klare Antworten geben kann sie.

Interviewer
Lars Schiller conducted the interview with Sabine Müller by e-mail in October.

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You know what it means to organise a HYDRO conference, because this is the third time you've done it. I'm only marginally involved in the organisation, but I have the impression that the effort increases from time to time. You would think that you would benefit from previous experience. What do you say?

This is the third HYDRO conference in Germany in 14 years. As in all other areas of life and business, conditions changed significantly, especially after Covid. It is very helpful, that the same venue site was chosen and most importantly, that almost the same people are supporting the organisation of the HYDRO 2024 as before in 2016 and 2010. It was a short moment of relief when we recognised, that almost all the »old« partners would be part of the game again. This shows that the companies and people involved do not have too bad memories of the organisation of our HYDRO events. There are some changes with reference to the marketing activities for the HYDRO event. Previously, the focus was on advertising in magazines like *Hydro International,* but this time we have a team to promote the event on LinkedIn and this works quite well.

When does the planning phase for such an event actually begin? And when does it enter the hot phase? Does the tension build up until the day of the opening?

We started more than two years ago to secure the venue. With the organisation we started few months later than for the two previous events. This experience made it easier to define the requirements for the venue hotel (Yachthafenresidenz Hohe Düne) We knew, which partners we needed, we could evaluate the costs of the event and we had a functional team in place from the beginning.

Several people are involved in the organisation – first and foremost you, your colleague Caren Korte, Christian Maushake and Thomas Dehling. How are the tasks distributed?

Although Thomas and I are responsible for the organisation of the HYDRO 2024, we are lucky to have very committed and reliable people in the core team. For the organisation I can name Caren Korte and Christian Maushake. I am sure, that all participants know their names by now. Both take care on almost all communication regarding registration, exhibition and all related issues. Patrick Westfeld and Jens Schneider von Deimling and other colleagues in the background have been working hard to put together an interesting lecture programme. A few people are working on social media marketing. There are also issues such as special requests for the exhibition, transport and customs, transfers from the airports, organising the cultural programme and the dinner, where our team is supported by local companies.

Which tasks are particularly time-consuming?

Communicating with all the participants and exhibitors and all their wishes is the most time consuming part of the job. Caren does most of the work. In general, 90 per cent of the communication is very easy to handle. The work is caused by the remaining 10 per cent.

How difficult is it to find sponsors for such an event these days?

The initial phase of finding sponsors and selling exhibition stands was somewhat slow. Nobody wanted to be the first. But once the first exhibitors and sponsors were on board, things went surprisingly smoothly and now almost all the sponsoring packages and the exhibition were fully booked by early summer. We are very happy about this, because the exhibitors and sponsors are essential for the success of the event.

In 2010, when the first edition of HYDRO was held in Rostock, there were 53 presentations; in 2016 there were also 53 presentations. This year, 59 presentations are on the programme. That is an increase of 10 per cent. And there were a few more applications that could not be considered. There was also an increase in prices. Prices for venue hire have risen sharply. Of course, this also leads to higher admission prices. Please give us a little insight into the finances of HYDRO 2024.

Not only did the number of papers increase, but the focus shifted to autonomous surveys and optical hydrography. There was an overwhelming interest in presenting papers, but due to limited time slots the paper committee could not accept all submissions. Delegates can look forward to presentations on a wide range of topics, an exhibition featuring more than 50 companies, live equipment demonstrations in the local marina and workshops.

Prices at the venue hotel have almost doubled compared to 2016. So we had to increase the registration fees significantly. Not all costs are allocated to the conference fees and are cross-funded by the main sponsors. The total budget of the HYDRO conference is about 400,000 euros in income and expenses, which is about a factor of ten compared to a usual DHyG financial year.

What about the number of participants registered so far? Has there been a development here too?

We are now just two weeks away from the conference. We are looking forward to welcoming about 400 delegates, exhibitors and visitors, probably more than in 2016. Within the last four weeks more than 100 people registered for the event. Today we are almost fully booked.

I myself cannot attend the conference this year. If there was a hybrid format, I would certainly watch some of the presentations online. Is this being discussed at the IFHS? Or is it a conscious decision in favour of the face-to-face event, which I assume is also in the interests of the exhibitors?

We decided against a hybrid format due to additional organisational effort involved. Presentations will be available for download after the confer-

Sabine Müller with the venue hotel of HYDRO 2024 in the background ence, if the authors agree. This conference should remain a face-to-face event for the community. This is also in the interest of the sponsors and exhibitors, who set up the stands, organise equipment demonstrations and making an important contribution to the funding of the event.

You are an electrical engineer. How did you get into hydroacoustics?

When I was studying electrical engineering, there was the option of specialising in marine electronics and hydroacoustics, which I chose. Hydroacoustics had a long tradition at the University of Rostock and the development of echo sounders had already been forced in the early 1970s with the goal to find suitable gravel in the Baltic Sea for the construction of the highway from Berlin to Rostock. Due to the embargo policy, it was not possible to buy the equipment, so when I joined the research group in the 1990s, there was a lot of experience in the group.

> *»The HYDRO conferences should remain a face-to-face event for the community«*
>
> Sabine Müller

How did you come to set up your own company in 1997?

The success in developing the parametric technology and the first results obtained with our research partner in underwater archaeology in Schleswig (Haithabu) made it very clear that there was great potential for other, more commercial applications. The economic conditions were right at the time and with a mix of venture capital and public funding we were able to take the risk and start a small company to exploit this technology and convert it into a real product.

What did Professor Gert Wendt have to do with the founding of Innomar?

As the scientific brain behind the research, his knowledge of acoustics and electronics was invaluable to future development and he was persuaded to come on board as a co-founder and shareholder. Prof. Wendt held a chair at the University of Rostock, but played an active role in refining the technology for the various products Innomar developed over the years. His advice and support did not stop until his death this year.

You are the Managing Director of Innomar. How do you share the role with Jens Lowag, the second Managing Director?

Jens Lowag and I have been sharing the office since the very first days, so that there is always a back-up for running the company, but also a second thought, so that both, day-to-day business and strategic decisions can be made quickly. While I now focus more on the daily business, administration and project management, and the direction of hardware development, Jens is responsible for software development and, with his background in Marine Geophysics, also for scientific survey projects and customer support. Proximity to users and their applications forms the basis for development and marketing strategies. Keeping in mind that there are still countries and regions of the world where women are not fully recognised, it is mandatory to have at least one male manager.

Finally, running the business would not be possible without the right people behind us and we are lucky to have a long established and committed 2nd level management team covering production, R&D, sales and business development.

Your products were always called SES. The three letters probably stand for sediment echo sounder. English experts usually refer to it as a sub-bottom profiler (SBP). Why did Innomar decide in favour of SES?

When we started selling the products we were not fully aware of the common terms used in the industry and, as native German speakers, we chose Sediment Echo Sounder (SES), which was widely used in the national scientific environment at that time. A few years ago we removed the letters SES from our product names and replaced them by Innomar. It is the brand we want to sell and the users now simply ask for Innomar SBPs.

How many Innomar systems are in use worldwide? Where everywhere?

To date we have sold almost 1,000 systems in more than 70 countries. We have contact with users of more than 90 per cent of the systems and are always keen to hear what they are doing with the equipment, which helps us to focus our R&D activities. There are systems still in use that are over 20 years old. Our main markets are Europe, Asia and North America, but our users operate in many exotic and remote locations, such as Antarctica, the Tibetan Plateau or around the Caribbean Islands. Due to their portability, our sub-bottom profilers can be used not only offshore, but also in lakes, rivers and artificial ponds. If they find water on an exoplanet, we might try to take an Innomar system there too. 😉

Please explain what is special about a parametric sediment echo sounder.

Parametric echo sounders generate the low-frequency sound beam by non-linear interaction of two high-intensity sound beams at higher frequencies in the water column below the transducer. Compared to conventional (linear) sound generation this gives a number of significant advantages, such as narrow sound beams at low frequencies with small and portable transducers, no appearance of distinct side lobes for the low-frequency sound beam during transmission and a high relative bandwidth, resulting in very short sound pulses without ringing effects and hence very high resolution in the detection of sediment layers and embedded objects as well as lower reverberation levels and increased penetration. Let me give you an example: To achieve the same horizontal resolution with a linear system at 10 kHz, the transducer would need an active area 100 times larger than the parametric system (2 m × 2 m instead of 0.2 m × 0.2 m).

How long does it typically take for a sediment echo sounder to be sold? What services are included in the sale?

This mainly depends on the customer's organisation and whether a tender process must be initiated or an immediate industry project is about to start. Sometimes we get a call and have to deliver a system within two weeks, including on-site installation and user training, but there are also sales that take more than two years of planning, equipment demonstration, price negotiation, harbour acceptance and sea acceptance tests, user training and finally regular maintenance checks of hardware and software components. We are always driven by the need for technically profound and responsive after-sales support, because the systems are used on costly vessels at sea, and as a small company we work hard to meet this expectation.

We only ever see such a sediment echo sounder from the outside. Unscrewing is not permitted. What is under the surface of the housing? Is everything actually assembled in Rostock?

There are always two parts, one is the transducer which is a fully moulded device with piezoceramics and electronic components and the transceiver, which contains transmit and receive electronics, power converters and amplifiers, computer devices for system control and real-time data processing and not forgetting lots of connectors and cables. Over the years we have outsourced more and more mechanical and electronical parts, such as circuit boards, which can be produced much faster and cheaper with specialised machines. However, all essential parts – such as the transducers – are manufactured in our workshops in Rostock and the whole assembling is done there as well. There are a lot of companies around us, who deliver parts like the housings, fairings or brackets. We are proud to state that the Innomar SBPs are »Made in Germany«.

A wide variety of qualifications and skills are in demand in your company. What about recruiting new staff?

Many companies are currently in need of skilled personnel, the same applies to us. Due to our long term cooperation with the University of Rostock we could source several engineers through internships and support of student's thesis projects. Recruiting nowadays is getting more and more difficult. We have to look for personnel from other universities, if we want to strengthen our R&D team. To recruite people for the production not only the education counts but especially the work attitude, practical skills and team spirit are very important. People with completely different professions can also be well suited for the tasks.

What challenges did you have to overcome with your company? For example, were there any cutbacks during the coronavirus period?

One of the challenges we experienced in the past are competitors trying to offer solutions with promises they could not keep, for example black box systems with a single button for operation which do not require geophysical expertise. Such activities can distract and confuse clients and actually delay the transfer of new technologies into markets and applications. Macro-economic challenges, such as Covid or periods of inflation and recession, do have an impact on business of course, but we managed to sail around those short-term obstacles on our path so far.

> *»Some competitors try to offer solutions with promises they could not keep, for example black box systems with a single button for operation which do not require geophysical expertise. Such activities can distract and confuse clients and actually delay the transfer of new technologies into markets and applications«*
>
> Sabine Müller

What is the secret of your entrepreneurial success?

Let me highlight a few important factors of our success. First, we always put the focus of our product development onto user and application orientation. We offer products which are able to solve the real-world problems and challenges of our clients with a unique solution. Second, we always provided honest advice to our clients and never tried to sell products just for the sake of a sale. Accompanying our clients from the first contact and providing high-class after-sales service and support will secure a stable long-term business. Third, we were always aware that the basis of success lies in every single person working in the company, whatever role is fulfilled. If you treat people as such, your reward is commitment and identification with the company.

This year it was announced that Innomar would become part of the Norbit family. What does the Norwegian company's entry mean?

This summer, in mid of July, Innomar became a member of the Norbit family. We were warmly welcomed by the board and colleagues there. Also the Innomar team took this as good news. The whole transaction was realised within a very short period. Now in October we feel as it was done a year before. A lot of common activities were started already and we are convinced that Innomar and Norbit get new opportunities and we are keen to »explore more« together now. We believe that a lot of positive synergies, new products and solutions will arise from this opportunity.

You have managed the DHyG office since 2006. You were also active on the Board until 2020. Has there been less work since you ceased to be a member of the Board?

There is no less work so far. The main reason for leaving the board was, that it could be helpful for the DHyG to have an additional committed person in the board to achieve more and to implement more ideas. The DHyG-office is taking care on all communication with the members, on the organisation of the local events »Hydrographentag«, accounting, tax authority, local court, notary.

> *»Due to their portability, our sub-bottom profilers can be used not only offshore, but also in lakes, rivers and artificial ponds. If they find water on an exoplanet, we might try to take an Innomar system there too«*
>
> Sabine Müller

There is a lot of work to do and I have to mention Caren Korte here as well, who is supporting this from her office in Norway, where she lives.

What do you remember as the most outstanding events with the society – whether negative or positive?

Good memories are there of course to the HYDRO events in 2010 and 2016, but also to the »Hydrographentage« in Husum, Lübeck, Bremerhaven or Lindau and the first »big« Hydrographentag in 2008 at the BAW in Karlsruhe, when I was in charge for the organisation for the first time. It was a nice location where the exhibition was setup in the test hall. In Karlsruhe we got a lot of support from the BAW. Further I liked the 25-years DHyG event in the International Maritime Museum Hamburg in 2009.

A bad memory was the Hydrographentag in Bonn in 2011. The organisation was done with the same efforts as before, but there were less than 30 delegates including the speakers. The same small group attended the evening event on board of a passenger vessel for a cruise on the river Rhine. The boat had a capacity of about 300 people. We were really embarrassed there.

Of course there are some negative memories of disputes with the court, notary and the tax authorities, but this is more the daily business.

At some point, the DHyG lost its non-profit status. That had serious consequences for the finances. But not just disadvantages, right?

Yes, this is correct. There are advantages and disadvantages to have a non-profit status or not.

The funny story is, that the reason for the cancellation of the non-profit status was not the financial success of the HYDRO 2010, but the fact that the society purpose is beneficial for people with a certain education only and not for the whole community. Even arguments like the fact that every water sports enthusiast can use the OpenSeaMap charts did not help. From that moment on, we decided to operate as a professional association as from now. A small disadvantage is, that the membership fees, which counted before as donations, now count as advertising expenses. The tax declaration was due every three years formerly, now it is due annually and the VAT declaration quarterly.

On the other hand the society can decide how to spend the money with significant less restrictions. In my opinion this offers the DHyG much better opportunities for their work.

The two HYDRO conferences in Rostock so far have brought in real money. What does our society do with the money?

We were happy, that both HYDRO events ended really successfully. We hope the same for 2024. The society is using the money to support student activities in a first attempt. Students receive reimbursements of travel expenses and grants to enable them to attend conferences and trade shows. Additionally, after the first successful HYDRO in 2010, the DHyG focused on organising the biennial »Hydrographentage« with an accompanying exhibition at a high level to make it attractive for as many participants as possible.

Generally speaking, why should you get involved in a society like the DHyG?

Speaking as a member like Innomar, I think that companies should join a society, which is at least partly concerned with the subject. The society offers opportunities for professional exchange of knowledge and ideas and therefore the possibility to find business or research partners. Further it is a platform for networking and recruiting. On the other hand there is the chance to get an idea of how the work is organised in other comparable companies or completely different organisations, such as much larger or smaller companies, authorities or scientific organisations. It helps to get input about how to solve certain tasks, even if they have nothing to do with the subject of the society.

What would you like to be better at?

I am very bad in saying »no«, which can be very difficult in my position. Even after so many years it is very difficult for me to clearly disagree and I am not very optimistic, that this will change.

Further I did not finish to learn to play an instrument. Maybe this is a plan after retirement. But there are other things on the list as well, e. g. that I am still not able to communicate in Norwegian although my son moved to Norway ten years ago.

What do you know without being able to prove it?

During a job interview I know very fast, without any further evidence, if the candidate would fit into the team. And I am sure that the time will come when the information we now get from the seabed using underwater acoustics will be obtained much better and with unexpected knowledge using other scientific methods. //

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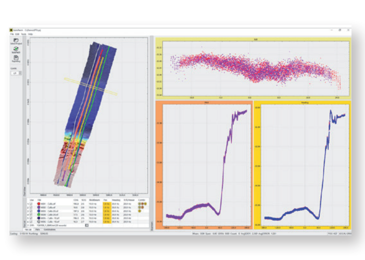

Software

Position and motion sensors

Integration

Denmark | Norway | Sweden | United Kingdom | France | Italy | Netherlands | Germany
USA | Canada | South America | Australia | Singapore | China