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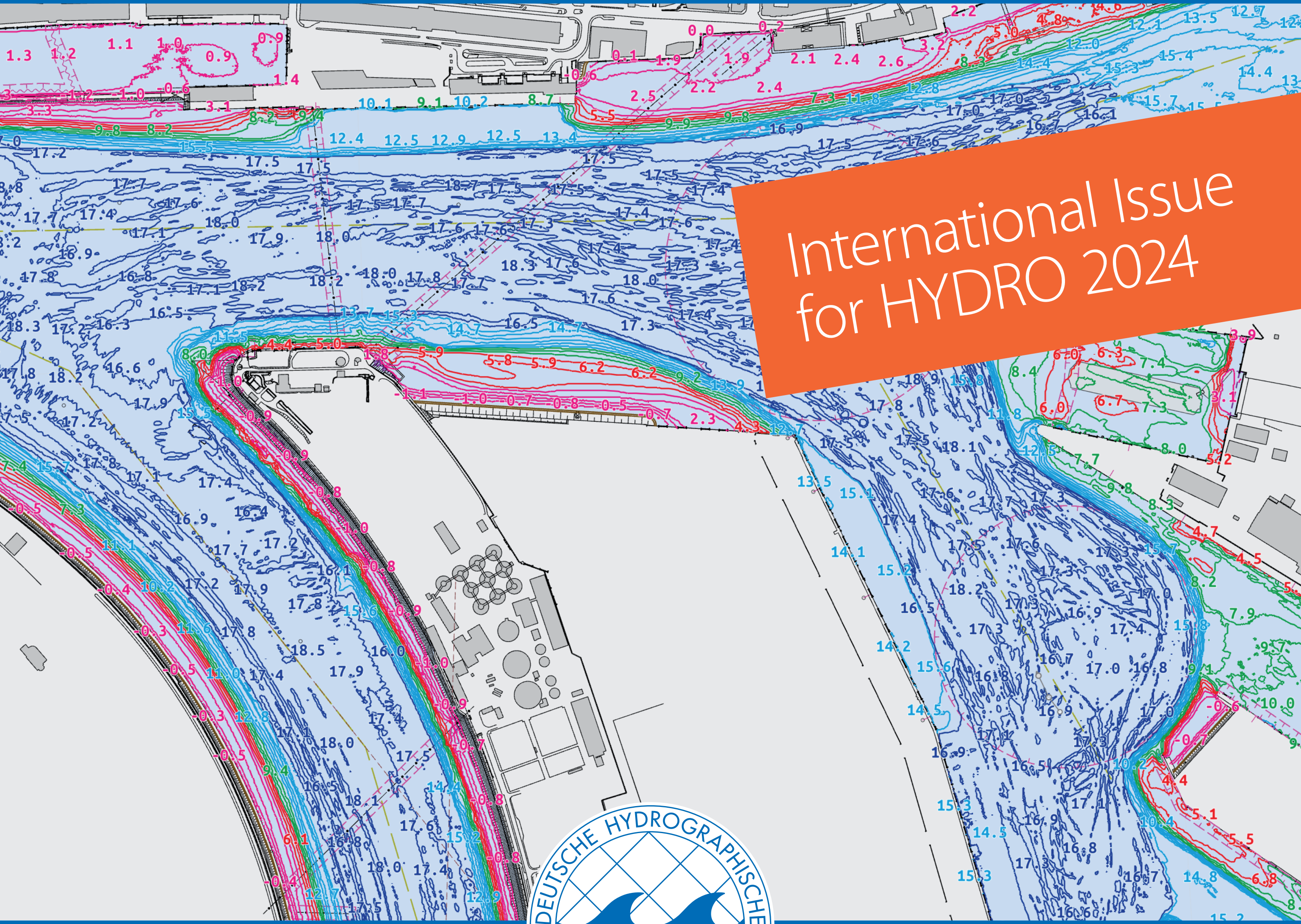

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Transfer of autonomous mapping concepts to a small uncrewed surface vehicle

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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.

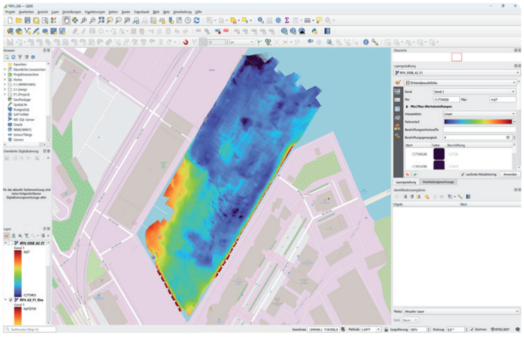

Fig. 4: Visualisation of the bathymetry data recorded at the »Rostocker Fracht- und Fischereihafen« in QGIS using the Maritime Robotics control software

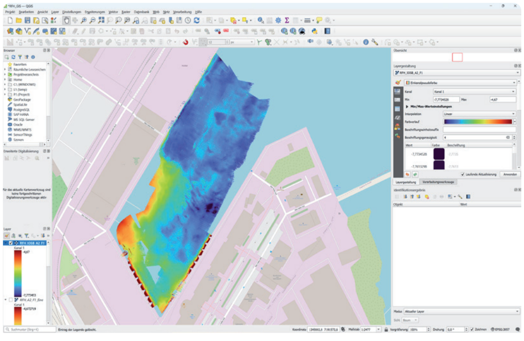

Fig. 5: Visualisation of the bathymetry data recorded at the »Rostocker Fracht- und Fischereihafen« in QGIS using the Autonomy Toolbox of the Fraunhofer IOSB

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

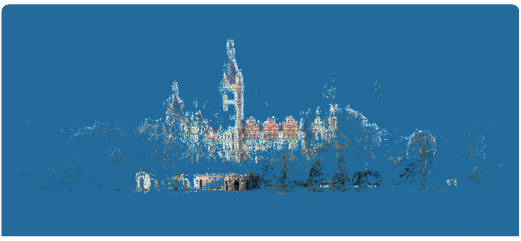

Fig. 8: Photogrammetric reconstruction of Schwerin Castle from Otter's camera data

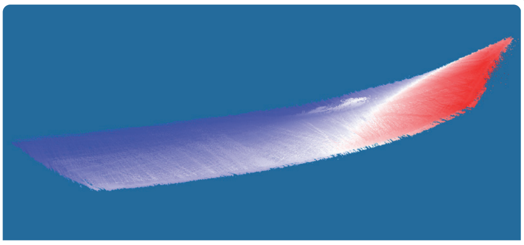

Fig. 9: Lateral view of part of the bathymetry of the Schwerin Inner Lake with the protruding bow of a brick barge

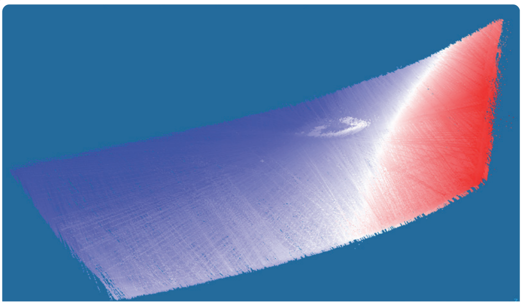

Fig. 10: Oblique top view of part of the bathymetry of the Schwerin Inner Lake with the protruding bow of a brick barge.

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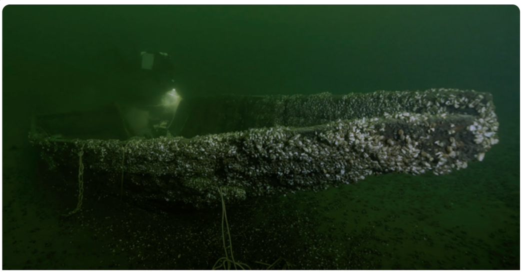

Fig. 11: Underwater camera shot of the sunken brick barge

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-

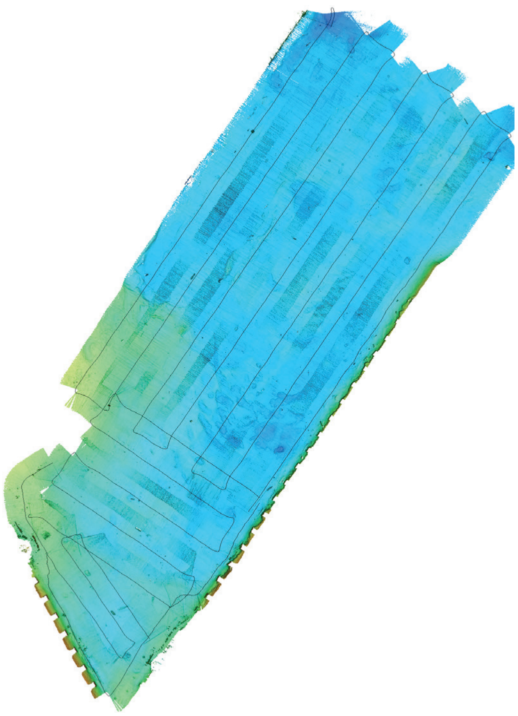

Fig. 12: Visualisation of the bathymetry data recorded at the »Rostocker Fracht- und Fischereihafen« in MB-System using the Maritime Robotics control software

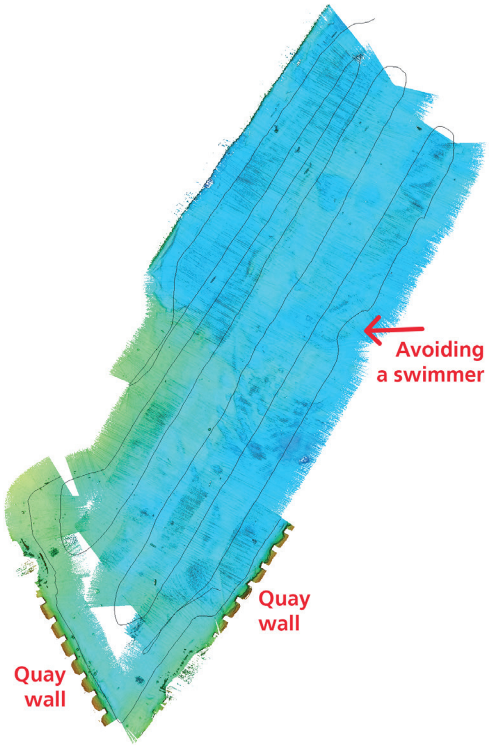

Fig. 13: Visualisation of the bathymetry data recorded at the »Rostocker Fracht- und Fischereihafen« in MB-System using the Autonomy Toolbox of the Fraunhofer IOSB

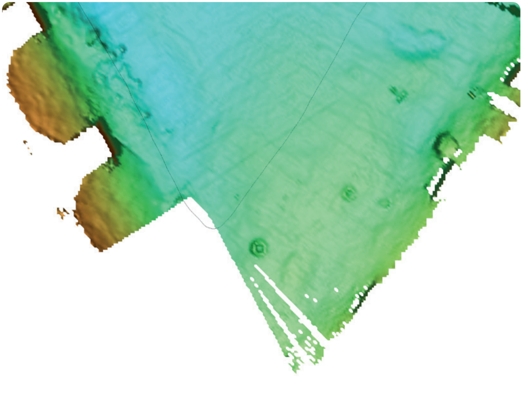

Fig. 14: Visualisation of a tyre on the seabed near the quay edge of the »Rostocker Fracht- und Fischereihafen« in an MB-System generated grid

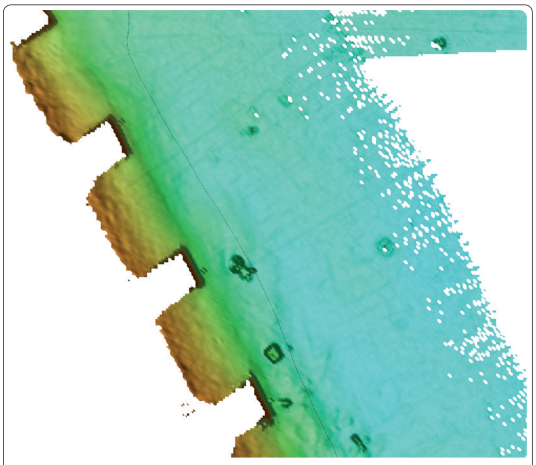

Fig. 16: Visualisation of undefined objects on the seabed near the quay edge of the »Rostocker Fracht- und Fischereihafen« in an MB-System generated grid

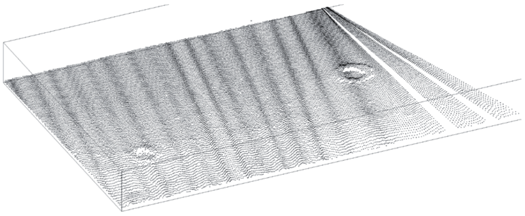

Fig. 15: Visualisation of a tyre on the seabed near the quay edge of the »Rostocker Fracht- und Fischereihafen« in an MB-System generated point cloud

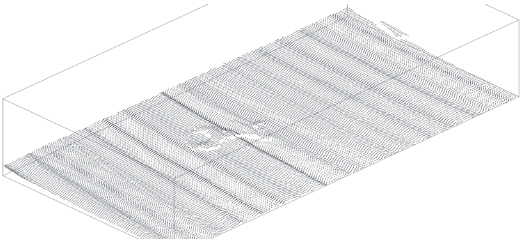

Fig. 17: Visualisation of undefined objects on the seabed near the quay edge of the »Rostocker Fracht- und Fischereihafen« in an MB-System generated point cloud

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

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