Waterside - A Holistic Approach to Munition Clearance in North and Baltic Sea

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***Abstract*—During and after the First and Second World War substantial quantities of munition were shot, lost, and offloaded into the North and Baltic Sea. This unexploded ordnance (UXO) poses a significant hazard to the marine environment and, subsequently, to humans. Hence, the removal of UXOs is of great importance. Currently, the munition is only removed locally and on a small scale. However, to dispose of the estimated amount of over 1.6 million tons of UXOs a holistic and scalable approach is needed. The Waterside project aims to achieve exactly that. The method developed within this project looks at the entire process chain from detection and classification to the removal of the munitions. It provides optimized algorithms for the detection and classification. Furthermore it implements novel sensing capabilities onboard autonomous underwater vehicles (AUV) as well as the implementation of a teleoperation for an underwater manipulator. Those efforts are being supported by the creation of a situational awareness system.**

***Index Terms*—unexploded ordnance, Autonomous Underwater Vehicles (AUV), robotics, S-100, Quantum Sensing and Magnetometry, Underwater Telemanipulation, Maritime Situational Awareness**

I. Introduction

Today, it is estimated that over 1.6 million tons of munitions from the two World Wars remain in the North and the Baltic Sea [1]. These contaminated sites not only pose a considerable safety risk for vessels and persons due to unexploded ordnance (UXO), but are also an immense challenge from an environmental point of view. Investigations have shown that the linings of the munition remnants increasingly disintegrate, releasing harmful substances such as TNT into the sea [2]. These pollutants have a direct impact on the marine ecosystem and are absorbed by marine life. For instance, it has been found that these toxins accumulate in shellfish or flatfish, which are in turn consumed by humans [2], [3]. As a result, munition contamination not only poses a threat to the environment, but also a direct health risk to marine life and humans. In this context, the DLR is participating in the development of technologies to support a holistic approach that will encompass finding, classifying and recovering contaminated sites in the North Sea and Baltic Sea [4]. To be able to cope with these large volumes of munitions, a more structured approach than those currently used is needed.

In this paper we first analyze the state of the art for UXO removal process, as well as outline current challenges and research gaps (II). Thereafter a big picture overview of the approaches chosen to address these challenges is given, followed by a more in depth look at the different parts of this holistic approach to munition clearance (III).

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II. State of the Art

The accumulated explosive ordnance in the North and Baltic Sea poses a considerable danger for shipping, the environment and human health. In recent years the technology for recording, identifying and removing these contaminated sites has developed considerably. This section provides a brief overview of the current state of the art and the challenges that still exist in the field.

In Table I, an overview of other projects regarding the detection, identification and removal of UXOs and other objects underwater can be seen.

A. Search and Identification of Unexploded Ordnance

Before UXOs can be salvaged and disposed, they first must be detected and identified. For this purpose remotely operated underwater vehicles (ROVs) or autonomous underwater vehicles (AUV) equipped with sensors such as side-scan sonars, multibeam echosounders, or magnetometers are often employed to search the potentially contaminated sites [5]. Following their detection, UXOs are classified, and their condition is assessed to minimize risks during salvage operations. Current sensor systems used for the automated differentiation between civilian scrap and actual ammunition quickly reach their technical limits [6].

The classification usually poses different challenges depending on the environment. These range from very low visibility, contaminated sites buried under the sediment and the need to determine whether identified items are in a condition suitable for clearance [7]. For the reliable classification of UXOs, multi-sensor approaches are used, as no single sensor on its own is sufficient to detect all types of UXOs and

Project	Lead/Funding	Primary aim	Core technologies	Target hazard
WATERSIDE	DLR (national)	Prioritize and enable remediation of dumped ammunition across German waters	underwater sensor R&D; long-range monitoring; teleoperated recovery research	Large seabed munitions and contaminated sites
CAMMera	GEOMAR/EU & national funds (CINEA)	Develop methods and pilots for large scale ammunition clearance with environmental safeguards	AUVs; environmental sampling; clearance protocols; industrial-scale disposal concepts	Mixed dump sites (boxes, mines, bombs)
ExPloTect	GEOMAR / CINEA (EU-funded)	Detect munition related chemicals in seawater to flag contaminated areas and reduce geophysical false positives	In-situ water-chemistry sensors; ex-situ rapid analysis; sampling platforms	Objects leaking explosive compounds; chemical contamination
SeaClear2	Horizon Europe consortium	Scale autonomous robotic detection and collection for seafloor and surface marine litter remediation	Teams of USVs/AUVs; AI perception; collection and valorisation systems	Marine litter (not designed for UXO without adaptation)
E=MCM	European Defense Fund consortium (Naval Group Belgium lead)	Deliver a sovereign European extended mine countermeasures system	Unmanned platforms; autonomous toolboxes; neutralisation tooling	Naval mines and UXO's

TABLE I
PROJECTS ON UXOS DETECTION, IDENTIFICATION AND REMOVAL

reliably identify and assess all types of UXOs under the various environmental conditions. Research is currently being carried out into which sensors combination will prove most effective. Combinations of multibeam echosounders, side-scan sonars and magnetometers have already been tested. Both the choice of sensors and, in particular, the methods for processing sensor data remain subjects of investigation and still have considerable potential for optimization [8]–[11].

B. Salvage and Disposal of Unexploded Ordnance

In Germany it is preferred to salvage the UXO first and then dispose of them in specialized facilities, although in the future a mobile facility might be deployed at sea [12]. Other countries prefer to intentionally detonate the munitions directly in the sea. However, this practice has considerable negative effects on the entire ecosystem and the marine life, such as harbor porpoises [13]. In addition to the resulting pressure wave, which can lead to serious injuries, pollutants are also distributed over a wide area in the sea. Disposal in dedicated facilities is therefore preferable [14].

However, this approach presents several (technical) challenges. For example, after the identification and classification of the contaminated sites, it must be decided whether the UXO is still in a condition that allows safe salvage or not. To reduce the risks to human operators - especially divers - it is desirable to conduct the salvage using unmanned systems [14]. Yet, salvage with underwater robots remains highly challenging: ideally, such systems must be autonomous or supervised. These system especially miss the experience and intuition, that divers have, but also human dexterity is still a challenges for these systems.

C. Digital Platforms

UXOs pose a significant risk to marine traffic [14]. Therefore, notifying all relevant stakeholders about these threats is paramount for safe operation and for reducing incidents. Currently, information about hazards at sea -including UXOs- is provided as navigational warnings, which are part of Maritime Safety Information (MSI). The provision of MSI is done via the Navigational Information over Telex (NAVTEX) System, which is a component of the Global Maritime Distress and Safety System (GMDSS). In the NAVTEX system MSI are broadcast over VHF [15].

However, NAVTEX has several shortcomings. For example, it is not possible to authenticate the origin of broadcasted navigational warnings. Furthermore, the warnings are not provided in a machine-readable format, making integration into increasingly digitalized shipboard systems difficult. To address these challenges, the International Maritime Organization (IMO) developed the e-Navigation strategy. As part of this effort, a service-based architecture, referred to as Maritime Services, and a universal hydrographic data model, S-100, were developed [16]. S-124, and S-100–based data products, together with the MSI Maritime Services, aims to enable the provision of navigational warnings in a more digitalized and interoperable form [17].

III. WATERSIDE

The removal of UXOs can be divided into four different phases, as shown in Figure 2. The process begins with an initial investigation and planning phase to identify potentially contaminated areas (Phase I). This is primarily carried out by analyzing historical documents and more recent studies. After this step, the identified areas are examined, potential UXOs are located, and subsequently first verified and then classified (Phases II and III). In the fourth and final phase, the identified UXOs are salvaged and disposed (Phase IV) [18].

The Waterside project aims to identify, test and develop key technologies, sensors and software to support a holistic, technical approach to UXO removal (Figure 1). It focuses on Phases II to IV while supporting the overall process through a digital platform to enhance the situational overview. The project thus seeks to develop solutions to the problems and

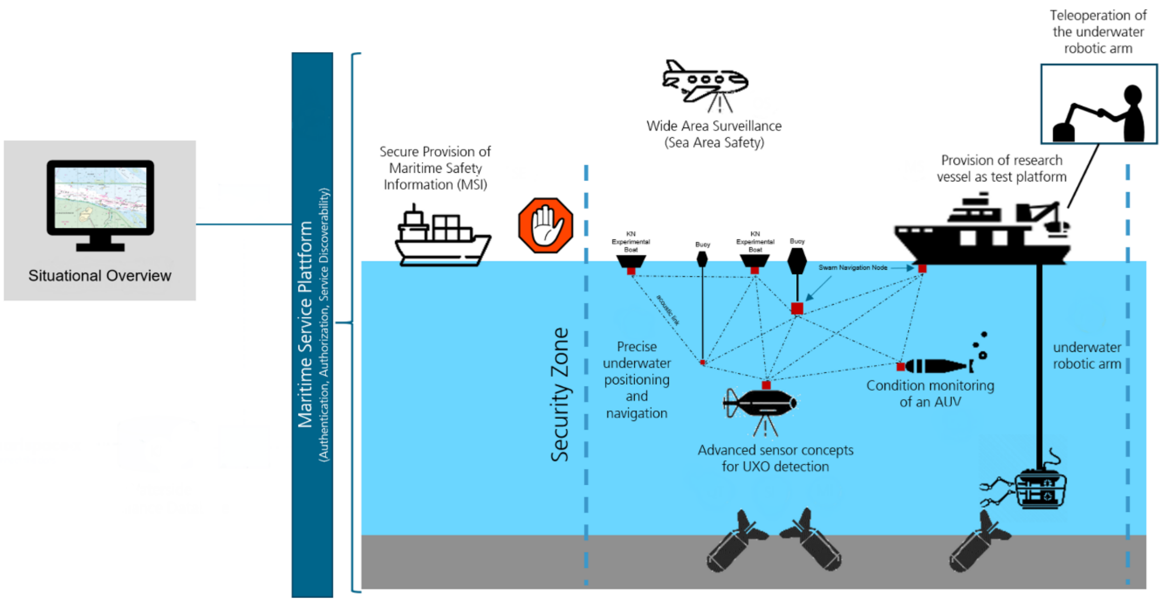

Fig. 1. Waterside: The whole picture

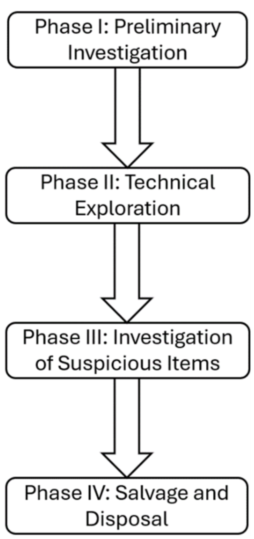

Fig. 2. Phases of UXO removal (based on [18])

research gaps outlined in II. However, the disposal of UXOs remains out of scope of the project.

To address the phases II and III, new algorithms for UXO detection are being developed and deployed on an AUV for onboard data processing (III-B). In addition, quantum magnetometers and gravimetric quantum sensors are being tested for integration into the AUV to enhance detection capabilities (III-A). For the salvage of UXOs (Phase IV), a teleoperation for a crawler is being developed, supported by a swarm-navigation system for precise underwater positioning, as well as an automated condition-monitoring system to detect potential damage of the hardware for recovery (III-B). Especially larger UXO, are a focus of Waterside, for recovery, since this is still a challenging task and require the involvement of divers. Lastly, to support these efforts, a digital platform is being developed to provide a situational overview and issue navigational warnings regarding UXOs (III-C & III-D).

A. Detection of Unexploded Ordnance

For the salvage of UXOs under water, knowledge about their precise localization is necessary (see Phase II and III in Figure 2). Due to the physical properties of the underwater domain, especially the attenuation and turbidity, the use of conventional camera systems is limited. The aim is therefore to explore the reliable detection of UXOs using various alternative sensor technologies. As mentioned before the use of multiple sensors is essential. The main sensor platform used in the Waterside project is a Seacat[1] AUV which will be equipped with a side-scan sonar as well as quantum-based magnetometers. This allows for a high-sensitive and drift-free measurement of the magnetic field gradient in three dimensions. Furthermore, the feasibility of using quantum-based gravimeter for UXO detection under water on a stationary as well as on a moving platform is investigated.

Although a stationary gravimetric approach has been demonstrated in the monitoring of gas reservoirs for water influx and the movement of injected CO2, a dynamic approach using a gravimeter on an AUV for the identification of new sites has not been demonstrated yet [19]. While the stationary approach would be useful for determining the mass of UXOs

[1] https://www.dlr.de/en/research-and-transfer/research-infrastructure/large-scale-research-facilities/autonomous-underwater-vehicle-auv (accessed: 29.01.2026)

at an already identified site, a dynamic approach would offer a greater flexibility especially for a first technical investigation of a possible UXO infested site (see Phase II Figure 2). Both the quantum-based magnetometer as well as the quantum-based gravimeter are able to detect buried UXOs which are not visible on the sidescan sonar images. Importantly the gravimeter can help determining the amount of munition lying under the seafloor. Since different sensors have different requirements on the survey path, e.g., a larger distance to the ground increases the area coverage rate of the sidescan sonar but reduces the sensitivity of the magnetometer and gravimeter, a simulation environment is setup to determine optimal survey routes for the technical exploration.

For analyzing the captured sonar data, the use of deep learning methods onboard the AUV is explored. To achieve this, the AUV will be equipped with a newly constructed head designed to house additional computing hardware alongside the sensors. This modification enables the provision of near-real-time information to higher-level systems, such as positioning systems or the surveillance database. Once a potential UXO has been identified, its location, alongside with additional information, such as a sonar image snapshot of the object and data on the surrounding seafloor, will be stored in a database to support its subsequent identification and selvage.

B. Condition Monitoring for Reliable AUVs

A large part of the work in the Waterside project involves the acquisition of situational imagery and identification of munitions, which in future will be carried out by AUVs (see III-A). Due to the extensive pollution of the North and Baltic Sea, the availability and operational readiness of the vehicles is of particular importance. Furthermore, the AUVs must fulfill their tasks independently and reliably to achieve the required scalability.

This requirement also implies that deployed vehicles lack a physical connection to a mothership, as is common practice in many current missions. Due to the lack of this coupling, failures or loss of these vehicles must be minimized. Even if the AUVs are passively buoyant, localization and recovery after a failure cannot always be guaranteed due to the harsh environmental conditions at sea. Furthermore the vehicles are equipped with sophisticated technology and high-quality sensors, which results in a high replacement cost. In addition, such vehicles are not manufactured in large enough quantities to be rapidly available for replacement. Therefore, a continuous condition monitoring and predictive maintenance is needed to assure the operational readiness of the AUVs and to avoid the loss of those vehicles.

In the waterside project the AUV SeaCat will serve as the reference platform for condition monitoring. The initial focus of the analysis is on wear-prone and critical components. These include, in particular, the propulsion system from the battery to the propulsor and control elements. Batteries lose capacity over their lifespan and the potential to deliver high outputs, while in the propulsor and control elements, blockages and failures are more relevant. In order to develop methods for condition monitoring, the first step is to examine critical system components using an example-set of 24 missions of the SeaCat.

C. Robotics for UXO Salvage

Although much work has been done in the underwater localization with robotic aids as well as the retrieval of small-scale ammunition (Phase IV, see III), especially the recovery of larger explosive objects still poses a challenge (see II-B). To autonomously recover large explosives underwater, the robotic systems do not only need to be equipped with diverse sensors, but also need to embed an inherent stability against disturbances from waves and have a large enough load capacity for heavy lifting. Small-scale AUVs are generally insufficient for this task [20]. Hence, the Waterside project specifically investigates the possibilities to recover large-scale ammunition's safely [21]. Ideally, the final tests will be carried out in open water using a grounded mobile platform, like an underwater crawler system.

Instead of interacting fully autonomously, a human will be kept in the loop to enable the careful grasping of the potentially explosive ammunition and thus ensure safety. This is crucial in underwater scenarios with limited visibility, where a forceful collision of a gripper with a UXO could lead to fatal outcomes [22]. Thus, methods for telemanipulation, originally developed for space robotics, will be employed. These methods guarantee stability even with communication latencies of several 100 milliseconds [23], which will be equally important for untethered underwater interactions. In addition to pure telerobotic remote control, functions of shared and monitored autonomy will be investigated in order to significantly improve efficiency and safety in the demanding environments [24]. One important aspect will be the implementation of Virtual Fixtures (VF), i.e. artificially generated force fields, so that the operator receives haptic support via force feedback devices. This approach enables more precise control, increased safety, faster task execution and a reduced workload [25]. The VFs rely on precise detection and localization of the old loads, leveraging the aimed improvements of Phase II and III. In addition, the limitations (e.g. workspace boundaries or dynamic limits) of the teleoperated underwater manipulator should also be conveyed haptically in order to minimize the risk of damage.

D. Underwater Mapping and Navigation

Both, localization and grasping with robotic systems (see III-C) require underwater mapping and navigation. Thus, in the Waterside project, new communication and navigation technologies for underwater applications will be developed. The system topology is based on the approaches of radio-based swarm navigation system [26].

The navigation system utilizes self-organization and decentralized communication and navigation, which are important properties for the development of a scalable and resilient approach to support the large-scale robotic selvage of UXOs. However, since the system will be deployed for the navigation of submerged vehicles, radio-based communication cannot be used, due to the limited available frequency of approximately 100 kHz underwater. Therefore, sound-based distance determination will be employed, which introduce challenging limits in the usable bandwidth. Nevertheless, the estimation theory for sound-based distance determination promises similar or even better accuracy compared to a radio-based system. However, unlike radio propagation in air, acoustic propagation in the ocean is strongly affected by spatial variations in temperature, salinity, and pressure, which induce sound-speed variability and lead to the bending of acoustic rays.

This swarm navigation approach enables combined networks of ASVs and AUVs to collectively sense and monitor large-scale physical processes through coordinated operation. Achieving these capabilities relies on continuous cooperative navigation. This requires vehicles to estimate their positions. While ASVs can, for the most part, rely on Global Navigation Satellite System (GNSS) services, submerged AUVs are unable to do so. Those vehicles must estimate their position relative to one another. Furthermore, a simultaneous adjustment of the position is required, to form optimized spatial configurations that enhance sensing performance.

E. Maritime Surveillance

An operation to recover and/or dispose of UXO's naturally poses a considerable potential danger to uninvolved maritime traffic in the surrounding area. In addition, unauthorized forces must be prevented from acting with malicious intent in the area of operation. It's therefore essential that the operational command has access to an up-to-date and as complete as possible situational picture of all objects on water in the immediate vicinity. A continuous surveillance of affected areas during the Phases II to IV (see III) increases the overall safety of the operation as well as the maritime traffic. Such a surveillance should include data on all watercraft of any size. The established approaches that are usually used for tracking maritime traffic (e.g. AIS) are not always sufficient. Small seagoing vessels (such as fishing and recreational boats) and water sports equipment (such as RIB's, SUP's, kites etc.) are neither subject to transponder [27] nor can they be detected using satellite-based methods. Even larger vessels can evade the usual detection, e.g. by means of AIS, by omission or active measures. Alternative airborne procedures for maritime surveillance should therefore be tested and evaluated. The main aim is to address the weaknesses of existing monitoring techniques. Specifically, operational improvements are to be achieved in the following areas:

- Increasing the temporal resolution of monitoring
- Detection of previously poorly recognized or unrecognizable maritime traffic participants and objects
- Detection of uncooperative maritime traffic participants

Commercial off-the-shelf drones have become widely available for end users in recent years. The majority of these drones have operate in the visible spectrum, while some are equipped with more advanced ISR (Intelligence, Surveillance, and Reconnaissance) payloads usually have EO/IR (Electro-Optical/Infra-Red) sensors, that are suited for maritime surveillance (see Figure 3).

The active monitoring of larger areas in the North and Baltic Sea with remotely piloted drones is likely not feasible due to limited human resources in the future. Therefore, procedures need to be developed to automatically analyze aerial image information. The main focus in the Waterside project is on the detection of objects on water and their temporal and spatial localization. Therefore, an analysis and evaluation of suitable optical sensor configurations and operation modes of passive imaging camera systems in the visible, near-infrared and thermal spectral range will be carried out. State-Of-The-Art (SOTA) payloads and ISR gimbals are taken into consideration as well. Suitable workflows will be developed to evaluate technologies under real operating conditions on a drone and/or manned aircraft. This will be done by using DLR's Modular Aerial Camera System (MACS) [5]. The modular concept allows the simple integration of different optical sensor technologies and data processing toolchains into an overall real-time capable airborne camera system. Suitable image analysis algorithms will be developed and assessed for detecting objects on water automatically. The main focus here is on AI-based SOTA frameworks (e.g. YOLO and RT-DETR). This allows the provision of additional information such as date, time, class, confidence score, position, size and course for each detected object, a functionality which is often not available in established vessel tracker systems.

The real-time mapping capabilities by MACS [6] can be used to send the imagery data to a server continuously via radio link (i.e. 4G/5G, SatCom, Starlink, mobile networks, etc.). By employing the Open Geospatial Consortium (OGC) Web Map Service Interface Standard [28] and the OGC Web Feature Service Interface Standard (WFS) [29] identified Objects with their accompanying information can directly be distributed to any geoinformation service (see Figure 4). For this rapid provision of real-time information new components and workflows for information processing and real-time communication will be developed and evaluated.

Demonstrations will be carried out over the Baltic Sea and/or North Sea to monitor a spatially limited area by means of small drones and optical sensors, to automatically localize all maritime traffic participants over water up to the size of small pleasure craft and to integrate this information into a central situational awareness system.

F. Digital Platforms

The aim is to develop a digital service and data platform that provides functions to support the safe execution of the munition's recovery mission (Phases II to IV; see III). To address the challenges of current systems, as described in II-C, the platform will enable all involved actors, such as the parties carrying out the munitions recovery as well as external stakeholders, including shipping companies and harbor authorities, to securely authenticate every received warning and the issuing authority. To achieve this, the platform will be based on the IEC 63173-2 (SECOM) standard [30] and will incorporate the

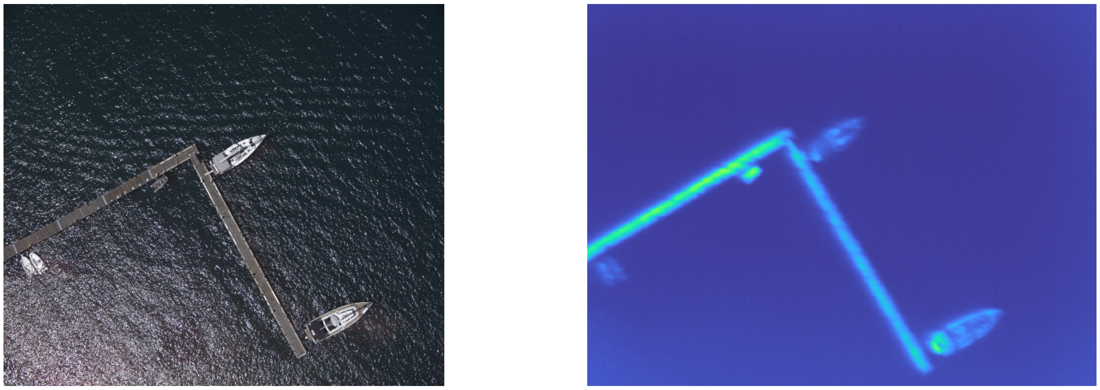

Fig. 3. Aerial image example of small ships in the visual (left) and thermal infrared spectrum (right)

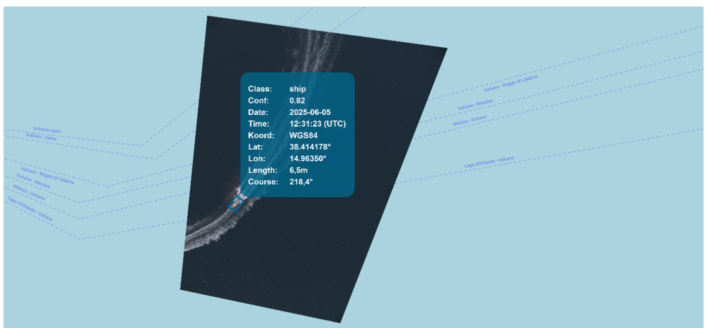

Fig. 4. Example of a detected object on water with derived meta data

Maritime Connectivity Platform (MCP), which incorporates guidelines for a decentralized maritime identity provider.

For the warning of vessels, a service for the digital provision of MSI, in accordance with IMO MS5 [17], will be implemented. Standards for the MCP, as well as the implementation of technical maritime services, are defined by the International Association for Marine Aids to Navigation (IALA), ensuring global interoperability of the service. The MSI service will be able to provide safety-critical information, such as no-go areas, the position of contaminated sites or ongoing salvage operations, enabling stakeholders to incorporate these warnings directly into their voyage planning and operational decision-making processes. Using the IHO's S-100 data schema, specifically the S-124 Navigational Warnings data product, these warnings will follow a consistent, machine-readable format, allowing them to be automatically interpreted by navigational systems, electronic chart display and information systems (ECDIS), and shore-based traffic coordination tools without requiring manual data conversion.

The MSI service will be demonstrated by integrating it into a prototype ECDIS (EPD)[2] and an operable Vessel Traffic Service (VTS) system, and by taking the provided warnings into account when coordinating traffic. Through this demonstration, ship and shore interaction with the navigational warnings will be shown. This integration ensures that VTS operators can view recovery-related restrictions alongside conventional traffic information, enabling them to manage ship movements in a way that minimizes the risk of interference with the ongoing munition recovery activities. Moreover, by embedding S-124 warnings directly into the VTS workflow, the demonstration will show how navigational warnings related to hazardous underwater operations can be treated with the same operational relevance and priority as other real-time navigational data routinely used in maritime traffic management.

[2]https://github.com/DLR-SE/epd (accessed: 29.01.2026)

IV. Conclusion

The estimated 1.6 million tons of unexploded ordnance remaining in the North and Baltic Sea pose an escalating threat to the marine environment and human health, as deteriorating munition casings release toxic substances that accumulate in marine organisms and enter the food chain. Addressing this at scale requires a structured, holistic approach. This paper presents Waterside, a DLR-led project covering the full remediation chain from detection and classification to salvage across Phases II to IV of the UXO removal process. For detection, quantum-based magnetometers and gravimeters are integrated into a SeaCat AUV alongside a side-scan sonar, enabling the identification of both surface and buried munitions, while onboard deep learning provides near-real-time classification. AUV availability is safeguarded through a predictive condition monitoring system covering critical propulsion and control components. Salvage of large ordnance is addressed with an underwater platform equipped with a force-sensing arm and human-in-the-loop telemanipulation, supported by virtual fixtures and haptic feedback to ensure precision under limited visibility. Precise underwater positioning is provided by an acoustic swarm navigation system for coordinated AUV and surface vehicle operation. Operational safety is completed by drone-based maritime surveillance using AI-driven object detection, and a digital platform that distributes authenticated, machine-readable navigational warnings via the S-124 standard directly into ECDIS and VTS systems. Together, these innovations lay the technical foundation for tackling UXO remediation at the scale the situation demands, with field validation of the integrated system as the next step.

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