

# Conceptual Framework for Teleoperated Robotic Recovery of Large Subsea UXOs

Annika Schmidt<sup>1,2</sup>, Dennis Höhn<sup>1</sup>, Harsimran Singh<sup>1,3</sup>, Michael Walter<sup>1</sup>, Maximilian Mühlbauer<sup>2,1</sup>, Eyk-Uwe Pap<sup>4</sup>, Michael Panzirsch<sup>1</sup>, Bregje Lodewikus<sup>5</sup>, Hubert van Strien<sup>5</sup>, Siwei Zhang<sup>1</sup>, Armin Dammann<sup>1</sup>, Fabio Broghammer<sup>1</sup>, Axel Hahn<sup>1</sup>, Thoralf Noack<sup>1</sup>, Neal Y. Lii<sup>1</sup>, Alin Albu-Schäffer<sup>1,2</sup>, Thomas Hulin<sup>1,3</sup>

**Abstract**—Decades after the World Wars, vast quantities of discarded munitions and unexploded ordnance (UXO) remain submerged in coastal waters worldwide, posing severe risks to marine ecosystems, public health, and maritime operations. While autonomous and remotely operated underwater vehicles provide promising solutions for the UXO detection and recovery of small-scale objects, they fall short when large munitions exceeding 200 kg need to be handled. This paper presents a concept to address this open challenge in the current quest for effective mine countermeasures (MCM). As part of the *Waterside* project of the German Aerospace Center (DLR), we envision a teleoperation-based concept using a crawler platform equipped with a force-feedback robotic arm and gripper, where the navigation is enabled through a locally set up swarm navigation system. The individual components required for the realization of this concept are presented, each leveraging previous research achievements developed by DLR for space applications. Combining the different fields of expertise in cooperation with industry partners and governmental authorities, the proposed concept promises to enable safe and efficient recovery of large-scale UXOs in shallow waters. A proof-of-concept demonstration is planned to take place in the near future, bringing the technology from the lab to the water. The approach is set up to be extended in the future to increase autonomy features, such that eventually the reliance on large vessels and extensive human presence can be reduced.

## I. INTRODUCTION

As remains of past wars and years of military training and demilitarization measures, discarded munitions and unexploded ordnances (UXO) can be found in the waters of Europe, Asia, and the United States [1]. In German waters alone, an estimated 1.6 million tons of conventional munitions and 5,000 tons of chemical munitions remain scattered across 71 identified contaminated sites [2]. Especially UXOs that failed to detonate as intended and remain intact pose a high risk, as any disturbance could trigger an explosion.

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<sup>1</sup>German Aerospace Center (DLR), Cologne, Germany. annika.schmidt@dlr.de

<sup>2</sup>Technical University of Munich, TUM School of Computation, Information and Technology, Garching, Germany

<sup>3</sup>Centre for Tactile Internet with Human-in-the-Loop (CeTI), Germany.

<sup>4</sup>Baltic Taucherei- und Bergungsbetrieb Rostock GmbH, Germany.

<sup>5</sup>Royal IHC, IHC Defence B.V., The Netherlands

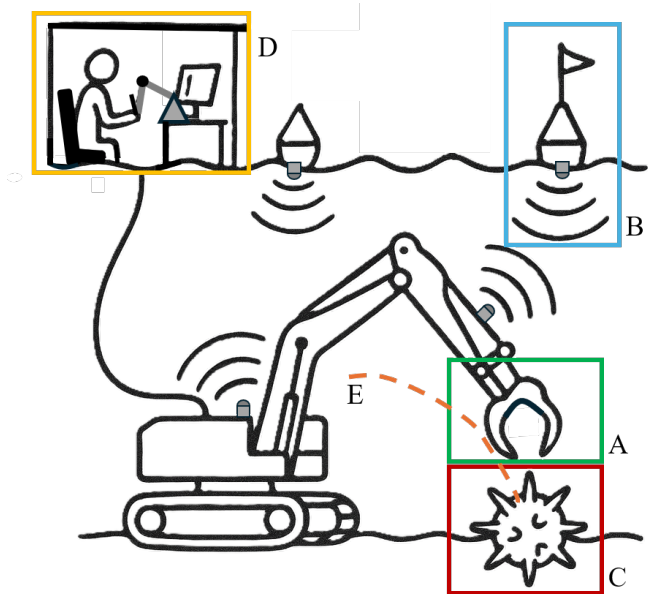


Fig. 1. Overview of the conceptual framework envisioned in DLR's *Waterside* project to recover large-scale UXOs based on a teleoperated robotic underwater system, in which different existing technology components will be unified. Each individual component is marked with the letters referring to the respective subsections of III: (A) gripper claw, (B) navigation and mapping, (C) robotic control and force rendering, (D) operator station (E) Virtual Fixtures.

However, dumped munitions that have had their detonators removed before disposal still present significant hazards. Over time, these munitions continue to corrode and degrade, releasing toxic substances into the surrounding environment. The leaching of chemicals and byproducts pollutes the marine ecosystem, impacting biodiversity and food chains. Ultimately, this contamination can enter the human food supply, raising serious public health concerns and threatening the entire fish industry [3], [4].

Consequently, efforts to recover UXOs and other munitions have intensified in recent years, along with growing interest in proactively pursuing and neutralizing these threats, as seen in the joint effort of European industries like in the *E=MCM* project [5]. Traditional mine countermeasure (MCM) operations still rely heavily on human divers to manually assess and neutralize ordnance, as well as to attach lifting equipment - a process that is hazardous for the divers

and involves significant time and financial costs [6]. To reduce the risks and demands associated with human involvement, modern approaches leverage advances in robotics and teleoperation by employing remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) for the detection and recovery of UXOs and other submerged munitions [7]. Despite the challenges that underwater missions pose with low-visibility conditions and continuous disturbances from waves, multiple missions have shown the potential of using AUVs with sophisticated sensors based on LiDAR and sonar technology to map regions and characterize munitions [8], [9], [10].

Nevertheless, beyond the significant progress through advancements in sonar, optical, and magnetometric sensors, the subsequent recovery and disposal of the hazardous munitions remains a substantial challenge. In this area, recent years have seen a number of successful projects demonstrating the use of ROVs for the recovery of smaller UXO items [11]. For the recovery, these ROV systems are often equipped with robotic manipulators that can be controlled remotely to handle objects underwater. Especially in the case of UXOs, where possible detonation poses an additional risk, haptic feedback can be included in the teleoperation control to improve the precision and safety despite the limited visual feedback [12]. In such operations, UXOs up to approximately 50 kg to 100 kg have been safely retrieved using ROVs deployed from surface vessels. Thus, the use of AUVs and ROVs presents a promising direction to tackle underwater recovery tasks of UXOs and other objects [13] in a semi-autonomous or remotely piloted manner. However, ROV and AUV platforms are limited in terms of payload capacity and mechanical strength. As a result, most current recovery solutions focus on small- to medium-sized munitions of up to 100 kg. Yet, a substantial portion of the total ordnance mass dumped in coastal waters, particularly in the Baltic and North Seas, consists of large aerial bombs and naval mines, frequently weighing between 200 kg and 1000 kg [2]. These heavy, voluminous items exceed the capabilities of most free-swimming ROVs and AUVs and cannot be handled with their comparatively small manipulators.

To address this limitation, hybrid solutions have been proposed. For instance, solutions by *Eggers Kampfmittelbergung* [14] and *Hughes Subsea* [15] have explored the use of large-scale grabbing tools mounted to a crane or crane-assisted ROV. In such a system, the ROV acts as a positioning interface, enabling precise placement of lifting gear on heavy UXOs, which are then hoisted using a ship-based crane. While effective for specific tasks, these systems require large support vessels, are costly to deploy, and rely heavily on human operators and surface infrastructure, making them unsustainable for large-scale clearance efforts. Given the estimated millions of tons of munitions still submerged across European coastal waters, scalable and efficient recovery solutions are urgently needed. Long-term solutions must reduce dependence on large vessels and manpower. One promising avenue is the development of crawler systems that can navigate the seafloor semi-autonomously, equipped with

tools to locate and recover large UXOs [16], [17].

However, autonomous systems and supervised control architectures face significant challenges in high-fidelity task execution, particularly in complex and uncertain environments like the one presented underwater for the UXO recovery [18]. Limitations could arise from the low temporal resolution and sensitivity of onboard sensors, the accumulation of drift in inertial systems, and the high computation associated with processing high-volume of data from multi-modal sensor fusion frameworks. These factors, when combined with uncertainties in environmental perception, especially under occlusion, turbidity, or limited visibility, demand large safety margins for autonomous operation. Such conservative operation constraints inherently limit the system's ability to fully leverage its kinematic and dynamic capabilities. Thus, in the initial conceptualization and testing of new methods for effective recovery of UXOs and other munitions in the open water, a trained human-in-the-loop remains indispensable to compensate for these limitations and ensure robust and precise task execution, especially in our safety and precision-critical application [19].

Inspired by technologies developed for robotic teleoperation in space, such as those implemented by the German Aerospace Center (DLR) for controlling robots from the International Space Station in the Surface Avatar mission [20], [21], this paper proposes a concept for remotely teleoperated large-scale UXO recovery. By combining robotic crawler platforms equipped with a gripping end effector, real-time haptic teleoperation, and scalable control and communication interfaces, this approach could offer a viable path toward safer and more efficient handling of large-scale UXOs in shallow maritime environments. This paper outlines the conceptual framework for this solution that will be developed as part of DLR's *Waterside* project and identifies the key technical and operational components that must be addressed to realize the envisioned underwater UXO recovery using teleoperated robotic systems (Fig. 1).

## II. OVERALL CONCEPT

In the *Waterside* project, DLR is collaborating with industry partners and governmental authorities to address current challenges of clearing UXOs, particularly those of large size and heavy weight. The challenges can be divided into three main topics, with this paper focusing on the third:

**1) Search, positioning, and identification of UXOs:** Precise classification is crucial in order to avoid unnecessary recovery operations, reduce costs, and minimize risks. The challenges vary depending on the area of application and range from poor visibility and sediment coverage to assessing the condition of UXOs. To enable reliable detection and evaluation, *Waterside* relies on multisensory approaches, as no single sensor can provide reliable identification under all environmental conditions [22]. Among others, gravity sensors, magnetometers, and sonar technologies are used, which are further developed and combined.

## 2) Data management and provision of Maritime Safety

**Information (MSI):** Efficient and secure data management is crucial to ensure that different parties involved in UXO detection and recovery have access to the relevant information throughout the entire process. Waterside is therefore working on an infrastructure that enables the secure and cooperative exchange of sensitive data without restricting the data sovereignty of the individual partners.

**3) Recovery of UXOs:** Finally, the identified UXOs must be safely recovered using the previously acquired sensor data. This task is particularly challenging due to harsh underwater conditions, which in some aspects resemble those encountered in space teleoperation scenarios, such as communication delays and limited visual feedback (Fig. 1). Consequently, the *Waterside* project aims to leverage teleoperation algorithms developed and tested in space applications [21], [23] and terrestrial disaster control [24].

The central element of the concept for the recovery of large-scale UXOs is a track-based underwater crawler, e.g., like the *IHC* seabed crawler (Fig. 2a) [5], which should be equipped with a robotic arm for grasping controlled by a remote operator with force feedback. A crawler platform is deemed favorable for this task compared to the more commonly used AUVs and ROVs, which are limited in size and lifting capabilities. In contrast, a heavy crawler platform with stable ground support is more resilient against disturbances through waves and provides enough lifting capabilities to lift large-scale UXOs of up to a few tons.

The robotic arm attached to the crawler should be equipped with sensors that provide sufficient sensor information to determine the shape and position of the UXO and gripper, and ideally provide force information when attempting to grasp the UXO (Fig. 1A). To track the position of the moving robotic arm on the end effector and its position compared to the standing crawler platform and the UXO, a navigation network should be set up underwater, most likely realized through data transfer of sonar signals (Fig. 1B). In order to safely grasp the UXO without the risk of exerting too much force to damage the object and potentially cause an explosion, haptic rendering methods developed for applications with high time delays can be employed (Fig. 1C). In this way, the remote operator can control how much force will be exerted on the object through a haptic force feedback device, while using safety features to compensate for occurring time delays due to the needed processing of sensor information (Fig. 1D). The commanded motions of the operator could additionally be supported by Virtual Fixtures, which aid in suggesting the most suitable path when approaching the UXO and orienting the gripper claw, while still keeping the operator in control (Fig. 1E). The underlying technology and algorithm groundwork needed for each of the mentioned components (Fig. 1A-E) will be detailed in the following sections. Within the *Waterside* project, these technologies will be combined, aiming to improve and extend current MCMs, leading to a new application field that is especially promising when scaled up with increasing autonomy features in future developments of this concept.

## III. COMPONENTS

In order to realize the proposed concept for large-scale UXO recovery, different existing technologies and approaches need to be unified and adapted. The following sections describe the state of the art of each technology and possible adaptations for the unified approach.

### A. Robotic Arm and Gripper

Underwater crawler systems, such as those developed by Royal IHC [5], offer a promising solution for recovering UXOs (Fig. 2a). The overall design of such an arm with gripper appears trivial, taking inspiration from various existing systems, e.g., the Octopustool I500 from *Eggers* [25]. The greater challenge for MCMs is the identification of the necessary sensors to incorporate in the arm and gripper (Fig. 1A). For instance, the UXO's shape and position need to be determined to compute a path to approach it and reliably and carefully grasp the UXO. However, since the visibility in waters like the Baltic Sea is generally limited, relying on camera images alone is not viable. Instead, sensors such as sonar or LiDAR will likely be used to identify the surroundings and generate a 3D point cloud of the object. This allows for appropriate localization and subsequently planning a path to approach and grasp the UXO. To further reduce the risk of accidentally damaging the UXO, potentially causing a detonation, due to position inaccuracies, interaction forces should be recorded such that they can be reflected to a human operator to manually correct and adjust the positioning during the grasp procedure. Although this feedback can be generated from a collision detection or a haptic rendering method based on the object point cloud [26], force measurements allow for precise control of the forces applied by the robotic manipulator because such precise control is essential to prevent unintended contact or damage. For this, force sensors on the gripper or force-torque sensors in the robotic joints [13] could be included or derived from hydraulic measurements [27]. Within the *Waterside* project, the minimum required sensor information that needs to be provided through the robotic arm and gripper for safe handling of UXOs should be determined.

### B. Underwater Navigation and Mapping

In order to approach the UXO safely, it is crucial to track and update the positioning of the gripper claw in relation to the crawler, on which it is mounted, and the UXO itself. To enable such realtime tracking in a visually limited environment, a new communication and navigation concept for underwater applications is envisioned (Fig. 1B). The system topology will be based on the concepts of previously developed radio-based swarm navigation [28]. In particular, self-organization and decentralized algorithms for communication and navigation are important basic characteristics for such a relative positioning system based on measuring the signal propagation time between the swarm elements. However, in the underwater scenario, acoustic waves will be used as the carrier instead of radio waves, since the propagation characteristics of water only support acoustic

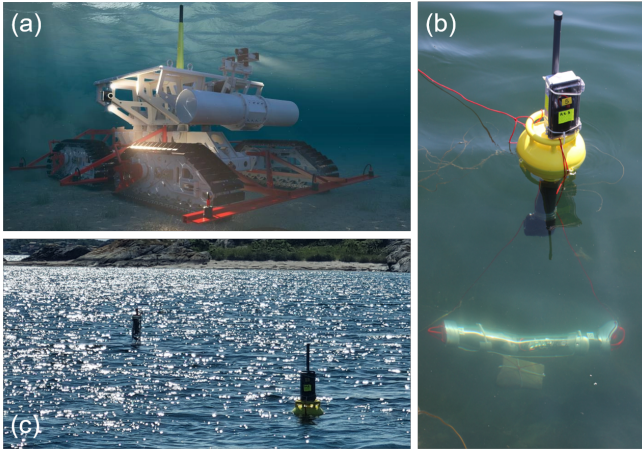


Fig. 2. (a) Underwater systems like the IHC crawler [5] provide a promising stable platform to mount a robotic arm and gripper to recover large-scale UXOs. Credit: Royal IHC. (b, c) To enable navigation underwater, the DLR is designing new signal processing hardware based on acoustic waves, which have recently been tested at Kristineberg, Sweden, in 2025.

waves for longer-distance communication. While relatively high bandwidths are possible with radio-based swarm navigation, we are limited to a frequency spectrum of up to approximately 100 kHz for acoustic communication underwater. Nevertheless, the estimation theory for sound-based distance determination promises similar accuracy compared to radio-based navigation systems previously developed by DLR [29]. Consequently, communication and navigation signals must be redesigned for the new underwater positioning concept, considering the significantly different frequencies, bandwidths, and propagation characteristics compared to the radio-based swarm navigation system. This entails a new development and fabrication of the signal processing hardware to be pressure resistant according to the requirements. First prototypes of such hardware are currently being tested in real environment conditions (Fig. 2b,c). Adapting the previous radio technology for underwater navigation with acoustic waves promises precise positioning in underwater environments, such that the gripper claw position can be mapped underwater even when visual navigation fails.

### C. Robotic Force Feedback Control

Although it is envisioned to eventually carry out the UXO recovery autonomously or with supervised control to effectively reduce the large amount of UXOs and other munitions, these approaches currently face significant challenges for high-fidelity tasks in complex and uncertain environments encountered in the UXO handling underwater. Thus, our concept for large-scale UXO recovery envisions initially including a human operator who can intuitively adapt grasping and manipulation strategies when presented with multi-modal sensory feedback, visual, and force cues (Fig. 1C). However, extracting suitable sensor information and rendering meaningful haptic feedback remains a non-trivial challenge, as mentioned in Section III-A. Additionally, stabilizing bilateral teleoperation systems under communica-

tion delay, while ensuring safe collision, compliant response to unforeseen contacts, and active environment interaction, can be challenging.

Numerous research studies at DLR have been conducted to address these concerns. Mobile robotic platforms equipped with onboard sensors, stereo cameras, and LiDAR have demonstrated reliable navigation and environment reconstruction in unstructured terrains and will be extended for the underwater scenario with the methods described in Section III-B. With sufficient sensor data, locally generated point cloud data can be abstracted into a 2.5D VE for remote teleoperation and augmented visualization [30], [24]. Such VEs facilitate realtime manipulation via VR interfaces and enable haptic interaction through control overlays [31].

Additionally, maintaining system stability and transparency is critical in delayed teleoperation scenarios. For position–position architectures, robust synchronization under arbitrary delay can be achieved by introducing a local proxy reference on the haptic device side and only closing the feedback loop when it can preserve stability [32]. This eliminates position drift and minimizes conservatism, without requiring prior knowledge of system dynamics or communication delay. In the case of position–force architecture, the Time-Domain Passivity Approach–Energy Reflection (TDPA-ER) [33] reduces conservatism by considering the energy reflection from an energy storage element in the network, which is part of the IEEE standardization activity P1918.1.1 [34]. For high-impact tasks, where collision forces can pose a risk both to the robot and the human operator, Time-Domain Passivity Approach–High Delay (TDPA-HD) [35] proposes a delay-invariant approach that uses measured force feedback to exploit the artifact of position drift in TDPA. This ensures safe environmental interactions and accurate force reflection, regardless of latency.

Another core challenge in dynamic interactions is achieving compliant yet responsive robot behavior during active environment interaction. The robot must be compliant to safely manage collisions while retaining sufficient stiffness for high-precision object manipulation. To this end, Elasto-Plastic Robot Compliance (EPRC) [23] demonstrates an enhancement of active robot compliance by introducing a virtual plastic first-order impedance component. The approach can detect active environments via energy observation and enable adaptive plastic compliance, allowing evasive maneuvers. This would ensure that no force is exerted on a UXO due to delayed control feedback, such that an explosion is not risked. Both TDPA-HD and EPRC have been experimentally verified in space missions [20], [21].

The different methods mentioned lay the groundwork to provide powerful tools that also enable human-in-the-loop teleoperation underwater. However, selecting the appropriate controller or architecture for the UXO application requires detailed task-specific consideration, which will be determined within the *Waterside* project.

#### D. Operator Station

To ensure precise and reliable teleoperation of the crawler platform and its gripper, it is important that the human operator be situated in a stationary, land-based control station rather than aboard a sea vessel. Maritime environments inherently involve continuous motion due to the waves, which can compromise the operator's situational awareness and degrade fine manipulation capabilities. Therefore, the human operator will operate from an offshore control center (Fig. 1D).

We envision adapting the existing remote operator station design developed for remote operation in disaster control [24] and merging it with current crawler remote stations [17]. The physical mirroring of the crawler control interface would maximize intuitiveness and performance. By maintaining familiarity, skilled crawler operators can leverage their existing skill sets without the need for retraining. To this end, we envision a control station outfitted with two custom-designed, multi-DoF haptic-enabled joysticks incorporating thumb controls and buttons. In addition, traditional excavator-style input modalities, including mechanical hand levers and foot pedals, will be integrated for motion control. The operator interface will also include an array of switches and buttons dedicated to critical functions such as system ignition, emergency shutdown, and lighting. A comprehensive visual display panel will support operator awareness. This will include high-resolution displays showing multi-camera feeds from the remote site, a 3D reconstructed environment, 2.5D VE for visual augmentation, and an overlay of telemetry data such as engine load, hydraulic pressure, system health metrics, and current operational modes. This approach takes inspiration from the AHEAD project for disaster response [24], where an immersive control station was shown to significantly enhance operator effectiveness by replicating the spatial and functional configuration of the remote platform (Fig. 3).

#### E. Virtual Fixtures

Although the human-in-the-loop approach is deemed favorable to initially test the recovery procedures for large-scale UXOs and other munitions underwater, teleoperation in such environments remains challenging due to the limitations mentioned in Section III-C. To further support the remote op-

erator in controlling the robotic arm underwater, where visual feedback is limited and force feedback may be rudimentary, Virtual Fixtures (VF) should be employed [36] to safely approach UXOs or other munitions (Fig. 1E). These VFs allow for augmenting real force feedback with virtual haptic cues to guide a human operator along a preferred trajectory. For example, VFs can define “forbidden” regions which the operator should avoid or attractor points the human will be guided towards [37]. In this way, the robotic arm attached to the crawler underwater could guide the remote operator along a theoretically suitable path to approach a UXO, but still leaves the operator in control in this very unpredictable environment, where manual adjustments are likely needed. Recent methods developed at DLR have expanded the capabilities of VFs to deal with uncertainty in measurements and trajectories and extended the type of available fixtures [38], [39]. These methods will be especially important to enable the UXO recovery in muddy waters, as they allow defining fixtures based on uncertain measurements caused by view obstructions to provide the best available guidance to the operator. Depending on the current manipulation phase, *coarse* feedback can be given to reduce the time needed for recovery from desired velocities, e.g., to reach a desired approaching configuration. When close to the object to be manipulated, *precise* feedback can be given from trajectory fixtures guiding the operator along a desired manipulation path. In the context of the *Waterside* project, suitable combinations of different VF types as well as approaches for their user-friendly definition and modification will be investigated.

#### IV. CONCLUSION AND OUTLOOK

This paper presents a concept to enable the recovery of large-scale UXOs to extend current MCM to reduce the munition remnants, especially targeting shallow water areas in the Baltic and North Sea. We envision an underwater crawler platform with a robotic arm and gripper claw that will be teleoperated by a remote operator and use a newly developed navigation setup based on acoustic waves. To realize this concept, DLR will cooperate within the *Waterside* project with industry partners and governmental authorities to provide a proof-of-concept demonstration of the envisioned technology within the next years by adapting and combining previous research achievements, merging the expertise of different fields.

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Eyk-Uwe Pap made fundamental contributions to the development of the operational concept and the system requirements, which were further refined with Royal IHC to support the definition for current and future technology requirements, that will eventually result in simulation and prototyping of solutions to be tested as part of the EDF program for European Extended Mine Countermeasures (E=MCM). Further, we thank Laurenz Thomsen, Vikram Unnithan, and the iFOODis Summer School 2025 for their support on our Kristineberg measurement campaign.



Fig. 3. Control station used for teleoperating a remote mobile robot. Credit: DLR (CC BY-NC-ND 3.0)

## REFERENCES

- [1] E. Gasperikova, U. Conti, and H. F. Morrison, "Underwater unexploded ordnance discrimination based on intrinsic target polarizabilities—a case study," *Geophysical Prospecting*, vol. 73, no. 1, pp. 315–329, 2025.
- [2] C. Böttcher, T. Knobloch, N.-P. Rühl, J. Sternheim, U. Wichert, and J. Wöhler, *Munitionsbelastung der deutschen Meeresgewässer: Bestandsaufnahme und Empfehlungen*. Bundesamt für Seeschifffahrt und Hydrographie (BSH), Sekretariat Bund/Länder ..., 2011.
- [3] E. Maser and J. S. Strehse, "'don't blast': blast-in-place (bip) operations of dumped world war munitions in the oceans significantly increase hazards to the environment and the human seafood consumer," *Archives of toxicology*, vol. 94, pp. 1941–1953, 2020.
- [4] C. Price, "Unexplored opportunities: Multi-sector strategies for collaboration in underwater unexploded ordnance remediation," *The Journal of Conventional Weapons Destruction*, vol. 25, no. 2, p. 12, 2021.
- [5] Royal IHC, "Smarter mine countermeasures with new seabed crawler." <https://www.royalihc.com/defence/innovations/smarter-mine-countermeasures-new-seabed-crawler>, 2025-06-18.
- [6] G. Schultz, "Demonstration of roV-based underwater electromagnetic array technology," 2016.
- [7] M. D. Richardson and M. T. Tuley, "SERDP/ESTCP munitions response program: A summary of progress and a way forward for underwater remediation of unexploded ordnance (uxo)," in *OCEANS 2022, Hampton Roads*, pp. 1–6, IEEE, 2022.
- [8] M. Kampmeier, E. van der Lee, U. Wichert, and J. Greinert, "Exploration of the munition dumpsite kolberger heide in kiel bay, germany: Example for a standardised hydroacoustic and optic monitoring approach," *Continental Shelf Research*, vol. 198, p. 104108, 2020.
- [9] M. Kampmeier, P. Michaelis, D. Wehner, T. Frey, M. Seidel, J. Wendt, and J. Greinert, "Workflow towards autonomous and semi-automized uxo survey and detection," in *Proceedings of Meetings on Acoustics*, vol. 44, AIP Publishing, 2021.
- [10] N. Dahn, M. B. Firvida, P. Sharma, L. Christensen, O. Geisle, J. Mohrmann, T. Frey, P. K. Sanghamreddy, and F. Kirchner, "An acoustic and optical dataset for the perception of underwater unexploded ordnance (UXO)," in *OCEANS 2024*, pp. 1–6, IEEE, 2024.
- [11] L. Rowiński, T. H. Truong, and P. Q. P. Nguyen, "Toward safe and efficient recovery of gas munitions dumped at sea," *Polish Maritime Research*, vol. 30, no. 3, pp. 181–190, 2023.
- [12] P. Xia, K. McSweeney, F. Wen, Z. Song, M. Krieg, S. Li, X. Yu, K. Crippen, J. Adams, and E. J. Du, "Virtual telepresence for the future of roV teleoperations: Opportunities and challenges," in *SNAME Offshore Symposium*, p. D011S001R001, SNAME, 2022.
- [13] A. Đuraš, B. J. Wolf, A. Ilioudi, I. Palunko, and B. De Schutter, "A dataset for detection and segmentation of underwater marine debris in shallow waters," *Scientific data*, vol. 11, no. 1, p. 921, 2024.
- [14] O. Geisler, "Innovative Techniken zur wasserseitigen Kampfmittelbergung in Hafengebieten." Kongressbeitrag, HTG Kongress, Bremen, Germany, 2023-11-01/2023-11-03.
- [15] Hughes Subsea, "Subsea Multi-Tool (SMT) ROV." <https://www.hughes-subsea.com/services/boulder-relocation-debris-removal/>, 2025-06-18.
- [16] T. Ducoineau, B. Jardí García, J. Lidman, and B. Moczowski, "Development of an underwater crawler: A remote platform exploring unexploded ordnance in the baltic sea," B.S. thesis, Universitat Politècnica de Catalunya, 2024.
- [17] M. Buitendijk, "Royal ihc presents next phase in autonomous dredging," *Autonomous operation, Digitalisation, Dredging, News, SWZIMaritime*, Feb 2024.
- [18] S. Aldhaheri, G. De Masi, È. Pairet, and P. Ardón, "Underwater robot manipulation: Advances, challenges and prospective ventures," in *IEEE Oceans 2022*, (Chennai, India), pp. 1–7, IEEE, Feb 2022.
- [19] R. S. Ferreira, J. Guérin, K. Delmas, J. Guiochet, and H. Waeselynyck, "Safety monitoring of machine learning perception functions: A survey," *Computational Intelligence*, vol. 41, no. 2, p. e70032, 2025.
- [20] N. Y.-S. Lii, P. Schmaus, D. Leidner, T. Krueger, J. Grenouilleau, A. Pereira, A. Giuliano, A. S. Bauer, A. Köpken, F. S. Lay, *et al.*, "Introduction to surface avatar: the first heterogeneous robotic team to be commanded with scalable autonomy from the ISS," in *Proc. Int. Astronautical Congress (IAC IAF)*, 2022.
- [21] N. Y.-S. Lii, T. Krueger, P. Schmaus, D. Leidner, S. Paternostro, A. S. Bauer, N. Batti, A. Köpken, F. S. Lay, A. N. Manaparampil, *et al.*, "Everything is awesome if you are part of a (robotic) team: Preliminary insights from the first iss-to-surface multi-robot collaboration with scalable autonomy teleoperation," in *75th Int. Astronautical Congress, IAC 2024, IAF*, 2024.
- [22] Deutsche Allianz Meeresforschung, "Munition im Meer - Sachstand und Perspektiven," Oktober 2022.
- [23] M. Panzirsch, H. Singh, X. Wu, M. Iskandar, A. Köpken, R. Luz, N. Batti, F. S. Lay, A. N. Manaparampil, L. Mayershofer, X. Luo, R. Burger, S. B. Gomez, J. Butterfass, E. den Exter, W. Friedl, T. Gumpert, P. H. Pavelski, G. Quere, ..., and N. Y.-S. Lii, "Virtual elasto-plastic robot compliance to active environments," *Science Robotics*, vol. 10, no. 99, p. eadq1703, 2025.
- [24] H. Singh, M. Panzirsch, M. Vayugundla, Y. Scheeler, M. J. Schuster, R. Giubilato, R. Balachandran, J. Langwald, H. Wagner, T. Hulin, and A. Wedler, "Skid-steering telenavigation with extended predictive polygon method," in *2025 IEEE Aerospace Conference*, IEEE, 2025.
- [25] Eggers Kampfmittelbeseitigung, "Eggers Octopustool i500." [https://kampfmittelbergung.eggers-gruppe.de/verfahren/bergung-und-vernichtung\\_w](https://kampfmittelbergung.eggers-gruppe.de/verfahren/bergung-und-vernichtung_w), 2025-06-18.
- [26] M. Sagardia, T. Stouraitis, and J. Lopes e Silva, "A new fast and robust collision detection and force computation algorithm applied to the physics engine bullet: Method, integration, and evaluation," in *Conference and Exhibition of the European Association of Virtual and Augmented Reality*, 2014.
- [27] F. Morosi, M. Rossoni, and G. Caruso, "Coordinated control paradigm for hydraulic excavator with haptic device," *Automation in Construction*, vol. 105, p. 102848, 2019.
- [28] S. Zhang, R. Pöhlmann, T. Wiedemann, A. Dammann, H. Wymeersch, and P. A. Hoehner, "Self-aware swarm navigation in autonomous exploration missions," *Proceedings of the IEEE*, vol. 108, no. 7, pp. 1168–1195, 2020.
- [29] S. Zhang, F. Broghammer, E. Staudinger, R. Pöhlmann, C. Gentner, M. Schmidhammer, and A. Dammann, "Swarm navigation in lunar caves: The first proof-of-concept mission on lanzarote," in *2025 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, pp. 1500–1506, 2025.
- [30] M. Panzirsch, H. Singh, M. Stelzer, M. J. Schuster, C. Ott, and M. Ferre, "Extended predictive model-mediated teleoperation of mobile robots through multilateral control," in *2018 IEEE Intelligent Vehicles Symposium (IV)*, pp. 1723–1730, IEEE, 2018.
- [31] J. Lee, R. Balachandran, K. Kondak, A. Coelho, M. D. Stefano, M. Humt, J. Feng, T. Asfour, and R. Triebel, "Virtual reality via object pose estimation and active learning: Realizing telepresence robots with aerial manipulation capabilities," *Int. Journal on Field Robotics*, 2023.
- [32] H. Singh, M. Panzirsch, A. Coelho, and C. Ott, "Proxy-based approach for position synchronization of delayed robot coupling without sacrificing performance," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 6599–6606, 2020.
- [33] M. Panzirsch, J.-H. Ryu, and M. Ferre, "Reducing the conservatism of the time domain passivity approach through consideration of energy reflection in delayed coupled network systems," *Mechatronics*, vol. 58, pp. 58–69, 2019.
- [34] E. Steinbach, M. Strese, M. Eid, X. Liu, A. Bhardwaj, Q. Liu, M. Al-Ja'afreh, T. Mahmoodi, R. Hassen, A. El Saddik, *et al.*, "Haptic codecs for the tactile internet," *Proceedings of the IEEE*, vol. 107, no. 2, pp. 447–470, 2018.
- [35] M. Panzirsch, A. Pereira, H. Singh, B. Weber, E. Ferreira, A. Gherghescu, L. Hann, E. den Exter, F. P. J. van der Hulst, L. Gerdes, L. Cencetti, K. Wormnes, J. Grenouilleau, W. Carey, R. Balachandran, T. Hulin, C. Ott, D. Leidner, A. O. Albu-Schäffer, N. Y. Lii, and T. Krüger, "Exploring planet geology through force-feedback telemanipulation from orbit," *Science Robotics*, vol. 7, pp. 1–11, Apr 2022.
- [36] L. Rosenberg, "Virtual fixtures: Perceptual tools for telerobotic manipulation," in *Proceedings of IEEE Virtual Reality Annual Int. Symposium*, pp. 76–82, 1993.
- [37] S. A. Bowyer, B. L. Davies, and F. R. y Baena, "Active constraints/virtual fixtures: A survey," *IEEE Transactions on Robotics*, vol. 30, pp. 138–157, Feb 2014.
- [38] M. Mühlbauer, T. Hulin, B. Weber, S. Calinon, F. Stulp, A. Albu-Schäffer, and J. Silvério, "A probabilistic approach to multi-modal adaptive virtual fixtures," *IEEE Robotics and Automation Letters*, vol. 9, no. 6, pp. 5298–5305, 2024.
- [39] M. Mühlbauer, F. Stulp, S. Calinon, A. Albu-Schäffer, and J. Silvério, "A unified framework for probabilistic dynamic-, trajectory- and vision-based virtual fixtures."