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Review

A Review of Touching-Based Underwater Robotic Perception and Manipulation

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Abstract: This review focuses on touching-based underwater robotic perception and manipulation, and provides a comprehensive overview of the current research landscape. We begin by examining underwater tactile sensors, discussing their basic types and recent advancements that have facilitated their integration into underwater robotic manipulation. Additionally, we explore the development of force control algorithms for underwater manipulators and grippers, emphasizing their critical role in underwater environments. Furthermore, we analyze the application of force control algorithms in underwater robotic manipulation, considering different autonomy levels, basic manipulation tasks, and specific operational scenarios. Through this investigation, we identify existing limitations and propose future research directions aimed at enhancing the operational capabilities of underwater vehicle manipulator systems (UVMS) and expanding their application range. Finally, this review highlights key challenges and outlines pathways for advancing the field.

Keywords: tactile sensor; force control; underwater robotics manipulation

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1. Introduction

The exploration and exploitation of ocean resources have become critical in addressing global challenges related to energy, food security, and environmental sustainability. Oceans are rich in minerals, oil, gas, and biological resources, making them vital for various industries. Accessing and extracting these resources often requires operations in deep and harsh underwater environments, posing significant challenges. Underwater robots, such as the one shown in Figure 1, have emerged as essential tools for performing tasks such as inspection, maintenance, and resource extraction, reducing the risk to human divers and increasing efficiency. Despite their advantages, underwater robotic operations are fraught with difficulties, particularly in the manipulation and handling of objects in unpredictable and complex underwater conditions.

Underwater environments are inherently challenging, due to factors such as high pressure, low visibility, strong currents, and complex terrains. These conditions complicate the precise control and manipulation of objects by underwater robots. Traditional methods relying solely on visual feedback are often inadequate, due to poor visibility and the dynamic nature of the underwater setting. Consequently, the development of effective underwater manipulation strategies requires advanced sensing capabilities. Tactile and force sensing technologies have been identified as crucial for overcoming these challenges, enabling robots to perceive and interact with their surroundings more effectively.

Tactile and force sensing provide underwater robots with the ability to detect and measure physical interactions with objects and the environment. These sensors allow robots to perceive attributes such as texture, shape, stiffness, and temperature, which are essential for delicate and precise manipulation tasks. The integration of tactile and force feedback enhances a robot's capability to perform complex tasks such as gripping, cutting, and assembling with greater accuracy and reliability. Moreover, these sensors enable adaptive control strategies that can respond to the dynamic and unpredictable nature of underwater environments, improving the overall robustness and performance of underwater robotic systems.

Recent research in underwater robotic manipulation has focused on developing and integrating tactile and force sensing technologies. Advances in sensor design, materials, and data processing algorithms have led to more sensitive, accurate, and robust sensing solutions. Innovative approaches to sensor integration, such as embedding sensors in robotic grippers and arms, have improved robots' ability to perform intricate tasks. Additionally, sophisticated control algorithms that leverage tactile and force feedback are being developed to enhance the dexterity and adaptability of underwater robots. These advancements are paving the way for more efficient and effective underwater operations.

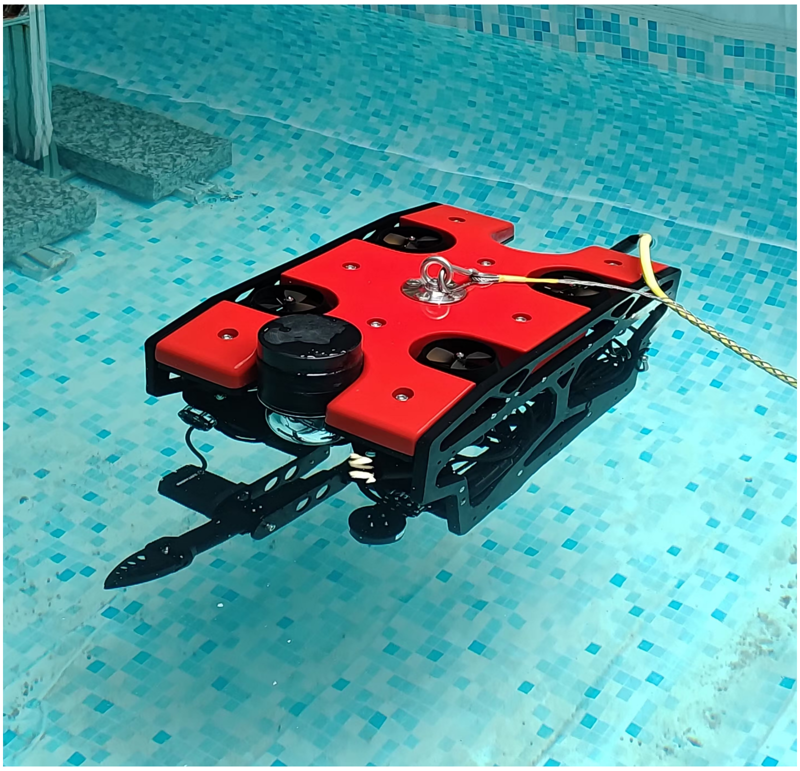

Figure 1. A UVMS in a test pool. With dexterous manipulability, it can perform complex intervention tasks.

It is important to examine previous research on underwater robotic manipulation to understand the foundation for current advancements. The first survey of this field [1] listed all projects of autonomous underwater intervention systems and gave a timeline of these systems. Aldhaheri et al. [2] gave a newer list of funded European projects on underwater manipulation and provided a discussion on these projects and the limiting factors for underwater manipulation. Kumar et al. [3] delved into the advancements, challenges, and prospects of control systems for underwater manipulation and focused on the aspect of modeling the systems. Simetti [4] focused on autonomous underwater intervention, providing insights into the latest developments in autonomous systems designed to perform complex underwater tasks without human intervention. Youakim and Ridao [5] conducted a survey on motion planning for autonomous mobile manipulators, with a case study on underwater manipulators. Their research highlighted the importance of efficient motion planning algorithms in enhancing the autonomy and effectiveness of underwater robots. Wang and Cui [6] provided an outlook on soft underwater manipulators, discussing their potential for safe and compliant interactions with delicate marine environments. Their review underscored the growing interest in soft robotics as a means to improve the adaptability and safety of underwater manipulations. Morgan et al. [7] provided a comprehensive review of the current methodologies in underwater manipulation, covering dynamics, control, planning, and perception. They highlighted recent advancements and experimental validations, and identified critical challenges for achieving fully autonomous underwater systems. Sivčev et al. [8] provided an extensive review of underwater manipulators and offered a detailed comparison of electrically and hydraulically actuated manipulators, and covered various control algorithms, including low-level motion control, high-level kinematic control, and motion planning schemes, underscoring the evolution of manipulator technologies and the challenges posed by the harsh underwater environment. Mazzeo et al. [9] systematically reviewed the current state of underwater gripping technologies used for deep-sea specimen collection. They highlighted the limitations of industrial grippers, originally designed for heavy manipulation tasks, in handling delicate biological samples. The review categorized existing grippers and tools, analyzed research trends, and discussed the evolving focus from demonstrating specific technologies to addressing specific needs in underwater manipulation. Their paper concluded by identifying the environmental and operational requirements essential for designing effective underwater grippers.

These studies collectively provide a robust foundation for the ongoing development of underwater robotic manipulation technologies. They highlight the critical advancements made in sensor integration, control algorithms, and mechanical design, while also identifying persistent challenges such as sensor durability, environmental adaptability, and the complexity of autonomous operations.

Despite significant progress, there are still notable gaps and challenges in the field. Current sensors often face limitations related to durability, sensitivity, and integration complexity. Furthermore, the harsh underwater environment can affect sensor performance and longevity. There is also a need for more comprehensive studies that integrate tactile and force sensing with advanced control strategies, to fully exploit their potential. This review aims to address these gaps by providing a detailed overview of the latest advancements, identifying key challenges, and proposing future research directions. Our contribution lies in synthesizing current knowledge and highlighting the potential of tactile and force sensing technologies to transform underwater robotic manipulation.

The relationships between tactile sensors, control algorithms, and manipulation capabilities are characterized by bidirectional influences across three key pairs, as shown in Figure 2. Tactile sensors provide critical feedback on contact forces and environmental interactions, informing control algorithms to dynamically adjust the manipulator's movements for optimized grip and precision. Conversely, effective control strategies enhance tactile sensor performance by ensuring optimal operational parameters, reducing noise, and improving accuracy. Control algorithms dictate how manipulators execute tasks, thereby enhancing their speed, accuracy, and responsiveness. Meanwhile, the specific demands of manipulation tasks can lead to refinements in these algorithms. Additionally, the effectiveness of the manipulator directly influences the utility of tactile sensors, and precise movements enhance the quality of tactile feedback, which in turn improves manipulation outcomes by providing essential data for task adjustments. This interconnectedness ensures that UVMSs can operate effectively and autonomously in dynamic underwater environments.

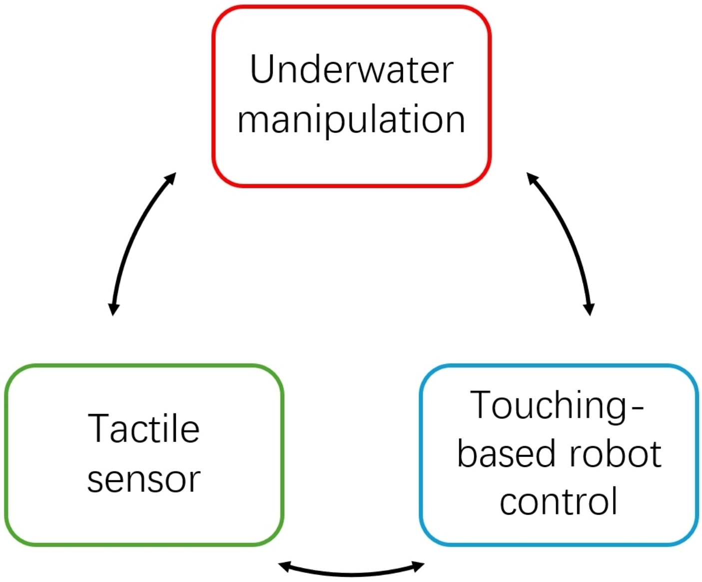

Figure 2. The interactive influences across sensor, control, and manipulation.

This review begins by briefly introducing previous research on underwater tactile sensors in robotics in Section 2. It first outlines the basic types of tactile sensors, followed by a discussion of the advancements in underwater tactile sensing technology that have paved the way for the use of force-related sensors, such as tactile sensors, in underwater UVMS manipulation. Section 3 explores the development of force control algorithms for underwater manipulators and grippers, as these algorithms are crucial for achieving precise force control in underwater environments. Section 4 analyzes the role of force control algorithms in UVMS manipulation, considering autonomy levels, fundamental manipulation tasks, and specific operational applications. Section 5 highlights the current limitations in research and discusses perspectives on future directions, drawing from the insights of the previous sections. Finally, Section 6 provides a summary and conclusion of the review.

2. Tactile Sensors

This section delves into tactile sensors, which are critical for enhancing the interaction capabilities of underwater robotic systems. Tactile sensors provide valuable feedback that informs manipulation strategies, enabling more precise and adaptive control in dynamic underwater environments. To systematically explore this topic, we start with an introduction of the types of tactile sensors, then explain capacitive-based sensors, piezoelectric-based sensors, piezoresistive-based sensors, visual-tactile-based sensors, force sensors, and finally discuss the available tactile sensors in underwater environments. Each subsection addresses the unique mechanisms, advantages, and limitations of the different sensor types, culminating in an examination of their specific applications and challenges in underwater settings.

2.1. Types of Tactile Sensors

Tactile sensors can be broadly divided into two main categories: extrinsic sensors and intrinsic sensors. **Extrinsic sensors** are external devices designed to detect tactile information from the environment, and they include four main types. **Capacitive tactile sensors** measure changes in capacitance resulting from contact with an object, providing detailed information on surface texture and pressure. **Piezoelectric tactile sensors** generate an electrical charge in response to mechanical stress, enabling the detection of dynamic forces and vibrations. **Piezoresistive tactile sensors** change their electrical resistance when subjected to pressure, allowing for accurate force measurement on their surface. Finally, **visual-tactile sensors** combine visual data with tactile feedback, integrating sight and touch to enhance environmental perception and object recognition. Each type offers unique capabilities, contributing to a comprehensive tactile sensing approach.

Figure 3 provides a schematic illustration of the four typical working principles of flexible tactile sensors, highlighting (i) piezoresistive, (ii) capacitive, (iii) piezoelectric, and (iv) triboelectric mechanisms. These mechanisms represent key technologies used in extrinsic sensors, enabling diverse sensing functionalities to meet the demands of underwater manipulation tasks.

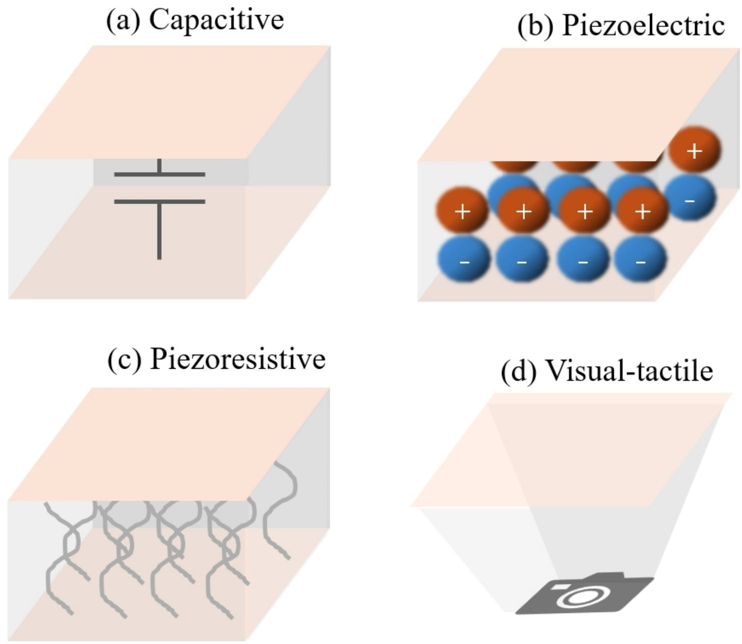

Figure 3. Diagram showcasing four common operating mechanisms of flexible tactile sensors: (**a**) capacitive, (**b**) piezoelectric, (**c**) piezoresistive, and (**d**) visual-tactile sensors.

In contrast, **intrinsic sensors** are embedded within the manipulator itself and primarily measure forces directly at the point of interaction. The most common type in this category are **force sensors**, which assess the magnitude and direction of forces exerted on the manipulator, providing essential data for force control and manipulation tasks. Together, these tactile sensors significantly enhance the ability of underwater robots to interact effectively with their environment, improving their operational capabilities across various applications.

2.2. Capacitive Tactile Sensors

Capacitive tactile sensors operate on the principle of measuring changes in capacitance when an object comes into contact with the sensor surface [10,11]. These sensors consist of conductive plates separated by an insulating material, and when an external force or object is applied, the distance between the plates changes, altering the capacitance. This change is detected and translated into tactile information, allowing for the measurement of pressure, texture, and surface characteristics.

In underwater environments, capacitive sensors offer high sensitivity and can detect fine details, making them suitable for tasks requiring precision, such as delicate object handling. However, their performance can be affected by the presence of water and contaminants, which may alter the capacitance readings. Additionally, they may struggle in high-pressure scenarios, limiting their application in deep-sea operations.

2.3. Piezoelectric Tactile Sensors

Piezoelectric tactile sensors use materials that generate an electrical charge when subjected to mechanical stress [12,13]. When a force is applied to the sensor, the piezoelectric material deforms, producing a voltage output proportional to the applied pressure. This mechanism enables the detection of dynamic forces and vibrations, making piezoelectric sensors effective for capturing transient interactions during manipulation.

In underwater settings, piezoelectric sensors excel at detecting rapid changes in force, making them ideal for applications involving quick or repetitive tasks. They are also less susceptible to drift over time compared to other sensor types. However, they may not provide accurate readings for static forces, as the generated charge dissipates once the stress is removed, which can be a drawback in tasks requiring continuous pressure monitoring.

2.4. Piezoresistive Tactile Sensors

Piezoresistive tactile sensors operate by changing their electrical resistance when subjected to mechanical pressure [14–16]. These sensors typically consist of a conductive material that exhibits a change in resistance as it deforms under load. This change can be measured and used to infer the amount of force being applied to the sensor's surface.

In underwater applications, piezoresistive sensors are advantageous due to their robustness and ability to provide continuous readings under varying conditions. They are relatively simple to integrate and can be used in a variety of manipulation tasks. However, their performance may be influenced by temperature and humidity variations, and they can be less sensitive compared to capacitive or piezoelectric sensors, particularly in detecting subtle touch interactions.

2.5. Visual-Tactile Sensors

Visual-tactile sensors combine visual data from cameras with tactile feedback from other sensors to enhance their environmental perception [17–19]. This integration allows robots to make more informed decisions by correlating visual cues with tactile information, improving performance in object recognition and manipulation tasks.

In underwater scenarios, visual-tactile sensors can significantly enhance a robot's ability to interact with complex and dynamic environments, such as identifying and handling fragile marine life. However, the effectiveness of visual sensing can be hampered by the low-visibility conditions commonly found underwater, such as turbidity or varying light levels. Additionally, the complexity of processing both visual and tactile data may require advanced algorithms, which can increase computational demands and system costs.

2.6. Force Sensors

Force sensors measure the magnitude and direction of forces exerted on the manipulator, providing critical feedback for control systems [20–23]. These sensors can operate based on various principles, including strain gauges and piezoelectric materials, to capture real-time force data during manipulation tasks.

In underwater applications, force sensors are essential for achieving precise control in delicate operations, allowing manipulators to adjust their grip dynamically based on the force exerted. They enhance safety by preventing damage to objects and the manipulator itself. However, their performance can be affected by the harsh underwater environment, including pressure variations and potential fouling. Moreover, depending on the type of force sensor used, there may be limitations in measuring static forces or detecting subtle changes in force, which could impact their effectiveness in certain tasks.

2.7. Tactile Sensors in Underwater Environments

Despite extensive research on tactile sensors in electronic and robotic systems, their successful implementation in underwater robotic applications remains limited. Table 1 summarizes fundamental information regarding the underwater tactile sensors developed in recent years. This table includes details on various sensor types, sensing methods, and specific applications, providing a comprehensive overview of the advancements in tactile sensing technology for underwater environments.

Table 1. Overview of underwater tactile sensors.

Sensing Methods	References	Year	Applications	Sensor Types
Strain gauge, PVDF	[12]	1997	Underwater gripper	Force sensors, Piezoelectric tactile sensors
PVDF	[13]	2000	Underwater teleoperated manipulator	Piezoelectric tactile sensors
Strain gauge	[24]	2006	Underwater dexterous hand	Force sensors
Optical fiber	[17]	2008	Underwater robots	Visual-Tactile sensors
Strain gauge	[20,21]	2010	Underwater manipulator	Force sensors
Strain gauge	[22,23]	2013	Underwater gripper	Force sensors
Optical reflection	[18,19]	2014	Underwater gripper	Visual-Tactile sensors
Optical fiber, PVDF, strain gauge	[25–31]	2015	Underwater gripper	Visual-Tactile sensors, Force sensors, Piezoelectric tactile sensors
Capacitive	[10,11]	2015	Underwater manipulator	Capacitive tactile sensors
Suction flow	[32]	2015	Underwater mobile manipulation	Force sensors
Piezoresistive	[14,15]	2018	Underwater dexterous hand	Piezoresistive tactile sensors
Piezoresistive	[16]	2020	Underwater manipulator	Piezoresistive tactile sensors
Suction flow	[33]	2020	Submerged dexterous manipulation	Force sensors
Triboelectric	[34]	2022	Underwater autonomous target grasping	Force sensors
Force sensing using flex sensors	[35]	2022	Underwater soft robotic applications	Force sensors
Force sensing using Hall effect sensors	[36]	2023	Deep-sea exploration	Force sensors
Triboelectric, Visual-Tactile	[37]	2023	Underwater manipulation	Force sensors, Visual-Tactile sensors
Piezoresistive	[38]	2024	Underwater dexterous hand	Piezoresistive tactile sensors
Piezoresistive	[39]	2024	Underwater force sensing	Piezoresistive tactile sensors
Optical fiber	[40]	2024	Underwater grasping	Visual-Tactile sensors

Compared to terrestrial environments, underwater conditions present distinct challenges for tactile sensing. High hydrostatic pressures at greater depths can significantly affect the behavior and performance of sensors by altering their structural integrity and calibration. For instance, capacitive sensors may experience changes in dielectric properties, piezoresistive sensors may show variations in resistance, and fiber-optic sensors may encounter wavelength shifts, all leading to measurement inaccuracies. Kampmann and Kirchner [25,26] demonstrated that optical tactile sensors can effectively determine object geometry even under pressures up to 600 bar, highlighting the need for specialized designs to withstand extreme underwater conditions. Material deformation and sealing issues under pressure further complicate sensor performance. Waterproof sealing is critical to prevent water ingress and potential sensor failure. Muscolo and Cannata [10,11] proposed a novel tactile sensor for deep-sea environments that utilizes a deformable membrane and oil-filled structure to address waterproofing challenges and improve pressure tolerance. Additionally, water turbidity can impact vision-based sensing methods, necessitating the exploration of various sensing mechanisms and materials to overcome these challenges. Similarly, Zhang et al. [39] developed a flexible underwater tactile sensor based on waterproof graphene/carbon nanotube/polydimethylsiloxane (GR/CNT/PDMS) composites, which demonstrated excellent pressure resistance and structural durability.

Suction-based tactile sensors detect contact through changes in suction flow or pressure differentials. Although they can enhance underwater grasping stability, their performance may degrade under high-pressure environments due to flow instability or seal deformation. Research by Stuart et al. [32,33] indicated that suction can significantly improve underwater grasping performance. Triboelectric tactile sensors exploit the triboelectric effect to generate electrical signals proportional to mechanical stimulation, offering high sensitivity and low power consumption, though they may be affected by changes in environmental humidity. Mu et al. [37] developed a bionic electronic finger (EM-Finger) that combines triboelectric and visual-tactile sensing for underwater human–robot interaction.

In addition to sensor-specific challenges, environmental factors such as water turbidity can impact vision-based sensing methods, while temperature variations may alter sensor calibration, particularly for piezoresistive and piezoelectric sensors. Kirchner et al. [25–31] addressed some of these limitations by developing a deep-sea hydraulic three-fingered hand called SeeGrip, equipped with multimodal sensors, including piezoelectric, strain gauge, and fiber-optic sensors, and capable of operating at depths of up to 6 km. These designs demonstrate the importance of pressure-resilient structures and adaptive calibration techniques for deep-sea applications.

Underwater tactile sensors have diverse applications across various fields. In underwater object recognition and localization, tactile sensors provide valuable information about an object's shape, texture, and hardness. Tactile sensors are essential for underwater grasping and manipulation, offering feedback on grasping force, contact position, and slip detection. Aggarwal et al. [26,31] proposed a tactile object recognition and localization system that operates effectively in noisy underwater environments.

Overall, underwater tactile sensing technology has made significant strides, leading to the development of various sensors with unique characteristics and capabilities. These sensors have found applications in underwater robotics, including object recognition, grasping, manipulation, and environmental exploration. However, challenges remain, such as improving reliability and durability in high-pressure, low-temperature, and highly corrosive underwater environments. Future research directions include the development of novel sensing materials and multimodal sensing technologies to enhance sensitivity, resolution, and perceptual capabilities. Additionally, integrating artificial intelligence and machine learning algorithms into tactile data processing holds promise for improving the intelligence of underwater robotic tasks. Continued advancements will drive the evolution of underwater robotics, enabling operations in more complex and challenging environments, thus contributing to human exploration and utilization of ocean resources.

3. Touching-Based Robot Control

The control methods of UVMSs are critical for ensuring precision and adaptability in manipulating underwater objects. To provide a comprehensive overview, this chapter is divided into two main subsections: manipulator control methods and gripper and hand control methods. The first subsection explores the control strategies employed for overall manipulator systems, while the second focuses specifically on the techniques used for controlling grippers and hands, which are crucial for delicate interactions.

3.1. Manipulator Control Methods

Existing commercial underwater manipulator systems often exhibit limited control capabilities and a lack of automation. While high-quality sensors and actuators are employed, the control mechanisms are frequently inadequate, leading to low precision, repeatability, and control loop frequencies. Historically, these systems have been designed primarily as remote-controlled devices, rather than as fully autonomous robotic arms. Figure 4 illustrates a typical UVMS control framework, showcasing the integration of sensing, planning, and actuation modules. This framework highlights how modern UVMS designs are evolving to address these basic control components by improving the task priority, adaptability, and force and coordinate control in underwater manipulation tasks.

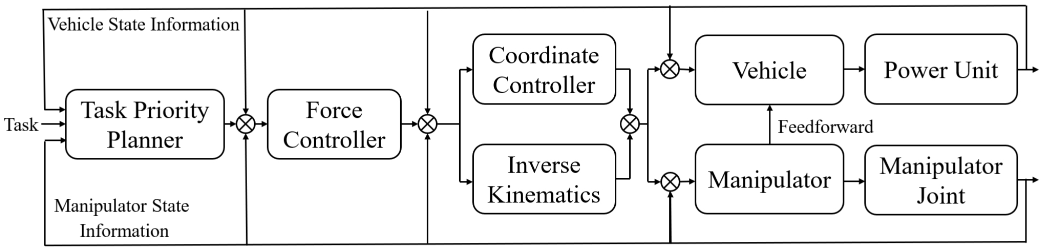

Figure 4. Typical UVMS control framework.

One of the early efforts to tackle force interaction in underwater manipulators was undertaken by Lane et al. [41], who developed a hydraulic-driven manipulator and proposed a hybrid position and force control scheme. This approach was both theoretically developed and tested on real hardware [42]. Lane's method involved decoupling the force and position into independent subspaces, applying position control in unconstrained operational directions and force control in constrained directions. Following this, the AMADEUS project further advanced the field by developing a UVMS and creating a series of robust force control algorithms designed to enhance performance in unstructured environments and varying stiffness conditions [12,43,44].

Recent studies have focused on extending hybrid position–force control to adaptive and model-based approaches to better handle dynamic disturbances in underwater environments. Examples include integrating machine learning techniques for adaptive force regulation and predictive force control schemes that anticipate environmental variations [45,46]. These methods are particularly effective for tasks requiring continuous adaptation to unpredictable underwater currents or uneven terrain.

In contrast to earlier models focusing solely on base dynamics, researchers like Cui et al. have developed comprehensive dynamic equations for the entire UVMS and designed impedance control algorithms [47]. They later introduced a hybrid control algorithm combining fuzzy impedance control with force–position control, which enabled smooth contact transitions and effective force trajectory tracking [48]. This integration of advanced control techniques highlights the evolution in the design of underwater manipulators, facilitating more nuanced interactions.

Simultaneously, researchers have conducted simulation-based studies to explore the complex dynamics of underwater manipulators. For example, Kajita et al. [49] modeled the interaction forces generated during the operation of a manipulator's end-effector by compensating for forces exerted by the base ROV's thrusters. They developed a force control algorithm to maintain these interaction forces effectively. Similarly, Lapierre et al. [50] installed a force sensor between the manipulator's base and the vehicle to estimate the torque exerted on the platform, allowing for stabilization during manipulator operations [51].

Building on these foundational approaches, various researchers have expanded the control methods available for UVMSs. Antonelli et al. [52] designed an admittance control algorithm by establishing the force–position relationship between a UVMS and its environment. In parallel, Bilodeau et al. [53] and Sekhavat et al. [54] focused on hydraulic-driven manipulator joints, conducting dynamic modeling and designing impedance control algorithms, with Sekhavat validating their algorithms on physical hardware [55]. Lemieux et al. [56] constructed a testing platform to validate UVMS force control algorithms, providing a crucial link between theoretical development and practical application.

Recent advancements have also seen the development of various hybrid control strategies. Barbalata created a series of hybrid force–position control algorithms using sliding mode control [57–59]. Following this, Dai et al. [60] designed an impedance control algorithm based on sliding mode control, while Cieslak et al. [46] developed an adaptive admittance control algorithm integrated with a task priority framework. Notably, in 2023, they further refined an adaptive admittance control algorithm specifically for detecting underwater structural corrosion [61].

The versatility of control methods is exemplified by Seki et al. [62], who designed a UVMS equipped with dual three-degree-of-freedom manipulators, creating an impedance control algorithm that integrates task priority motion control. Cetin et al. [63] introduced an adaptive force control algorithm capable of seamlessly transitioning between contact and non-contact states for underwater facility inspections. Additionally, Konoplin et al. [64,65] focused on tool utilization, designing a hybrid force–position control algorithm for various underwater manipulator tasks.

Heshmati-Alamdari et al. [66] made strides in collaborative manipulation by implementing a force control that converts force signals into velocity commands for a UVMS. Their work included several algorithms for multi-UVMS collaboration, such as an impedance control algorithm [67], a distributed impedance control algorithm [68], and a model predictive control algorithm for dual UVMS systems [69]. They later developed a collaborative impedance control algorithm that facilitates object manipulation without the need for direct communication between systems [70].

The advancement of admittance and impedance control algorithms has also led to the development of task-priority-based frameworks, which allow manipulators to prioritize multiple objectives, such as avoiding obstacles while maintaining force stability during operations [46,71]. These frameworks are increasingly important in real-world applications, where multiple constraints must be handled simultaneously.

In the realm of teleoperation, significant advancements have also been made in force control algorithms. Kwon et al. [72] designed an adaptive sliding mode controller with a disturbance observer for force feedback teleoperation, addressing the challenges posed by underwater disturbances. Khabit et al. developed the humanoid underwater robot Ocean One [73–75], creating a whole-body teleoperation control algorithm that enables bilateral force feedback for underwater archaeological tasks [76]. Furthermore, Wang et al. [77] developed a six-axis underwater manipulator based on ROS 2 control, successfully testing the teleoperation of an admittance control algorithm in underwater environments.

In summary, the field of force control for underwater manipulators has made remarkable progress, with a variety of control strategies being developed to enhance performance in complex underwater settings. Ongoing research and innovation are crucial for addressing the remaining challenges and expanding the capabilities of underwater robotic systems.

3.2. Gripper and Hand Control Methods

Similarly to other actuators in underwater manipulator systems, grippers are also controlled through a master–slave control system using a miniature master arm. Most grippers are hydraulically driven and operate using open-loop rate control. Operators predefine the opening and closing speeds of the gripper in the main controller settings and activate the grip function by squeezing a textured band on the master arm's wrist. Some underwater manipulators use closed-loop servo position control for grippers, where sensor feedback, typically provided by linear variable differential transformers (LVDT), enables precise control. However, only a few experimental prototypes developed in laboratories have implemented grip force control and force feedback.

More advanced gripper control methods now integrate multi-modal sensing, combining force, pressure, and tactile feedback to improve grasp stability and adaptability [39,78]. These methods are particularly useful for applications involving fragile or irregularly shaped objects. The use of soft robotic grippers, designed with flexible materials, further enhances compliance and reduces the risk of damage during manipulation.

Sensing, particularly tactile sensing, is crucial for autonomous grip force control. However, reliable tactile sensing in underwater environments is challenging. This is due to the limited availability of underwater tactile sensing solutions and the fact that only a few have been tested under high-pressure conditions. In the AMADEUS project [79], Lane et al. equipped grippers with tactile sensors [80,81] and designed a simple PI force control algorithm [82]. Zhang et al. developed an adaptive fuzzy impedance control algorithm for gripper force control using pressure sensors [83]. Khabit et al. implemented a force feedback teleoperation control algorithm for the gripper in the Ocean One system [84,85]. Han et al. designed an adaptive fuzzy impedance control and a parameter-identification-based impedance controller [86], which is less sensitive to the inner position loop's response speed, providing better robustness.

Recent developments in adaptive control schemes, such as variable stiffness control and bio-inspired designs, enable grippers to handle both rigid and deformable objects effectively [37]. These improvements address challenges related to unpredictable underwater environments and complex manipulation tasks.

Reports suggest that the quality of tactile information obtained from underwater tactile exploration is lower than that from aerial exploration. Therefore, tactile data may require appropriate processing before they can be used for grip force control. Additionally, some researchers have designed grippers with compliant properties inherent in their soft structures to perform compliant manipulation tasks. Relevant research on soft underwater grippers can be referenced in Park et al.'s review [78] on the subject.

4. Underwater Manipulation

Researchers have achieved tremendous progress in underwater manipulation studies. In this section, we mainly summarize studies on three key topics: (1) levels of underwater manipulation autonomy, discussing the varying degrees of autonomy in manipulation tasks; (2) basic tasks of underwater manipulation, which outlines the fundamental actions required for effective interaction; and (3) applications of underwater manipulation, which showcases real-world use cases in diverse settings.

4.1. Levels of Underwater Manipulation Autonomy

UVMS manipulations can be categorized based on the different levels of intervention autonomy: fully teleoperated manipulation, shared autonomy manipulation, and fully autonomous manipulation. This classification is necessary to account for the varying levels of human involvement, system capability, and environmental complexity in underwater tasks. Different autonomy levels allow an UVMS to be tailored to specific mission requirements, ensuring flexibility, safety, and efficiency in operation. The basic information of these modes and force control requirements is shown as Table 2.

Table 2. Comparison of manipulation modes and force control requirements.

Type	Characteristics	Force Control Requirements	Limitations
Teleoperated	Real-time control, high precision, operator-dependent.	Low-latency communication, rapid feedback, manual adjustments.	Operator fatigue, skill dependency, communication delays.
Shared Autonomy	Hybrid control—routine tasks automated, complex tasks supervised.	Autonomous force compensation, manual supervision for complex forces.	Skilled supervision required, communication constraints.
Autonomous	Fully automated, detects objects, plans actions, executes tasks.	Pre-programmed algorithms, real-time sensing, impedance/admittance control.	Limited adaptability, complex algorithm requirements.

In fully teleoperated manipulation, two operators directly control the underwater manipulator and ROV in real-time, which typically requires high precision and adaptability to complex, dynamic environments [87,88]. Human decision-making is critical in this mode, enabling quick responses to unpredictable situations. However, fully teleoperated manipulation places substantial physical and cognitive demands on the operator, due to the need for continuous control. For force control, this mode relies on the operator's input to manage the manipulator's interaction forces, demanding rapid feedback and low-latency communication to achieve fine-tuned adjustments in force.

Communication delays caused by the constraints of underwater acoustic channels pose significant challenges to teleoperated systems, especially in deep-sea environments. Recent advancements, including hybrid acoustic-optical communication systems, multi-hop relay networks, and predictive control algorithms, have been explored to address these limitations and improve real-time feedback performance. While such developments are highly relevant to underwater operations, this review focuses specifically on touching-based perception, control, and manipulation. Relevant research on underwater communication technologies and time delay mitigation can be found in Quattrini Li et al.'s review [89] on the subject.

In shared autonomy manipulation, control is distributed between the human operator and the autonomous system [73–75,77,90,91]. Here, the UVMS autonomously handles routine or low-level tasks, such as maintaining a stable position or compensating for disturbances, allowing the operator to focus on more complex, task-specific actions. This approach reduces the operator's workload and improves efficiency, while retaining human oversight of critical decision-making. In terms of force control, shared autonomy requires the UVMS to handle basic force adjustments autonomously, particularly in maintaining stability and adapting to minor disturbances, while the operator handles force-intensive tasks. This hybrid approach helps balance the force control requirements between the system and the operator, though it remains constrained by communication limitations.

In fully autonomous manipulation, the UVMS performs underwater operations entirely independently, detecting objects, planning actions, and executing manipulations without user intervention [61,70]. This mode is ideal for repetitive or well-defined tasks in stable environments. For force control, fully autonomous manipulation depends on pre-programmed algorithms and real-time sensor feedback to manage interaction forces. Advanced force control algorithms, such as impedance or admittance control, are essential to enable the manipulator to adapt to varying object stiffnesses and environmental conditions without human input. However, fully autonomous manipulation can be challenged in highly dynamic or uncertain environments, where real-time decision-making for force control is crucial.

This range of autonomy levels in UVMS manipulation allows for a flexible approach to underwater tasks, accommodating the specific demands of force control depending on the required human involvement and environmental complexity.

4.2. Basic Tasks of Underwater Manipulation

When performing underwater manipulation, UVMSs face a range of challenges depending on the task type, and the basic features of these tasks are shown in Table 3. The complexity of the underwater environment—characterized by factors such as limited visibility, dynamic water currents, and uncertain contact forces—requires the system to handle various operational issues. Below is an analysis of common underwater tasks and the unique challenges associated with each.

Table 3. Basic Features of Underwater Manipulation Tasks.

Task	Key Requirements	Challenges	Applications
Grasping	Tactile sensing, force feedback, adaptive control.	Irregular shapes, high currents, fragility.	Object retrieval, sample collection.
Valve-turning	Torque control, hybrid force–position algorithms.	Alignment, torque precision in dynamic conditions.	Pipeline maintenance, infrastructure repair.
Force Regulation	Real-time sensing, compliance control.	Surface variations, dynamic stability.	Cleaning, inspections, sampling.
Cooperative Manipulation	Multi-robot communication, distributed control.	Synchronization, load sharing, delays.	Assembly tasks, object transportation.

Underwater grasping is complicated because of the lack of precise visual feedback due to murky water and low-light conditions, as well as the unpredictable dynamics of floating or drifting objects [83,86]. UVMSs must rely on tactile and force sensors to securely grasp objects, while avoiding damage to delicate items. Additionally, buoyancy and water resistance affect the force and stability of the grasp, making it difficult to control the manipulator's movements precisely.

Valve-turning tasks, common in underwater infrastructure maintenance, demand high precision and controlled force application [90]. Water resistance can cause feedback delays, making it challenging for the manipulator to maintain a steady grip and apply rotational force accurately. Furthermore, the force required to turn a valve must be carefully regulated to avoid over-torquing, which could damage the valve or connected systems. Hydrodynamic effects may also destabilize the manipulator's position during these fine tasks.

Tasks that require precise force regulation, such as drilling or cutting, are particularly challenging in underwater environments [46,59,60]. The interaction between the manipulator and the environment is harder to control due to unpredictable water currents, drag forces, and the compliance of underwater materials. UVMSs must integrate advanced force feedback control algorithms to maintain an appropriate contact force, preventing tool slippage or excessive pressure that could lead to failures or damage to the structure being worked on.

In cooperative manipulation tasks, where multiple UVMSs or manipulators on the same platform must work together, synchronization becomes a major challenge [69,70,92]. The underwater environment exacerbates communication delays, and coordinating the motion and force application of multiple manipulators can be difficult due to the influence of water currents and external forces. Maintaining stability and control over both manipulators, while ensuring precise interaction with the task object, requires advanced control strategies, robust feedback systems, and accurate coordination algorithms.

These task-specific challenges highlight the complexity of UVMS operations underwater, where environmental factors and the physical limitations of underwater robotics must be carefully managed to ensure successful task execution.

4.3. Applications of Underwater Manipulation

UVMSs are widely employed across the various underwater applications shown in Table 4, including underwater archaeology [93–96], construction [97–100], aquaculture [101,102], maritime rescue [103–108], and deep-sea exploration [109–112]. Their ability to perform precise tasks in challenging underwater conditions makes them essential for a wide range of operations, enhancing the efficiency, safety, and accuracy in these demanding environments.

Table 4. Applications of underwater manipulation.

Application	Key Tasks	Challenges
Archaeology	Excavation, artifact recovery, mapping.	Fragile artifacts, sediment disturbance.
Construction	Welding, assembly, inspection, repair.	Visibility, currents, precision assembly.
Aquaculture	Cage cleaning, feeding, monitoring.	Biofouling, marine disturbance, debris.
Rescue	Recovery, damage assessment, salvage.	Time constraints, hazardous conditions.
Exploration	Sampling, mapping, ecosystem studies.	Pressure, temperature, reliability.

In underwater archaeology, UVMSs are used for the delicate recovery and preservation of submerged artifacts, shipwrecks, and historical sites. They can perform tasks such as excavating sediments, handling fragile objects, and documenting discoveries with minimal disturbance to the surrounding environment. Their precise control and ability to access hard-to-reach areas make them ideal for archaeological missions in deep and shallow waters alike.

For underwater construction, such as building offshore structures or repairing underwater pipelines, UVMSs are employed to manipulate heavy objects, install components, and perform inspections. They can be used to weld, cut, and drill materials at great depths, where human divers face limitations due to pressure and safety concerns. UVMSs ensure safer and more efficient construction operations in these hazardous conditions.

In the aquaculture industry, UVMSs can automate the monitoring and maintenance of underwater fish farms. They are capable of feeding fish, cleaning nets, and inspecting fish health and farm infrastructure. By reducing the need for human divers, UVMSs increase operational efficiency, improve safety, and provide real-time data to enhance the management of marine farms.

UVMSs are also crucial in maritime rescue operations, where they can assist in locating and retrieving sunken vessels, debris, or even trapped survivors. Equipped with advanced sensors and manipulators, they can conduct search-and-recovery missions in dangerous or unreachable areas, such as deep ocean zones or areas with strong currents, ensuring timely and effective rescue efforts.

In deep-sea exploration, UVMSs are used to explore the ocean floor, collect samples, and perform geological surveys. They can take sediment and biological samples from extreme depths, contributing to research in marine biology, geology, and environmental studies. Their ability to function in high-pressure environments allows scientists to discover new species, resources, and underwater ecosystems, pushing the boundaries of human knowledge in deep-sea exploration.

UVMSs' versatility across these diverse fields demonstrates their crucial role in advancing underwater technologies and improving operational capabilities in challenging and often dangerous environments.

5. Future Research Challenge

As UVMSs continue to evolve, significant advances are expected in both tactile sensing and force control, aimed at addressing the unique challenges posed by the underwater environment. The following detailed trends are anticipated to shape the future of UVMS capabilities in these areas.

- **Development of high-resolution, pressure-resistant underwater tactile sensor arrays.** These can provide precise, multi-dimensional feedback in real time. Current tactile sensors often struggle with the high-pressure conditions at greater ocean depths, temperature fluctuations, and biofouling, which reduces their performance over time. Future sensors are expected to leverage advanced materials such as flexible piezoelectric polymers, nanomaterials, and soft sensing technologies. These materials will allow for enhanced sensitivity to shear forces, pressure, and texture. Additionally, bio-inspired designs, such as those mimicking the sensing capabilities of marine organisms, are being explored to improve adaptability and durability. Tactile sensor surfaces may also integrate self-cleaning or anti-biofouling coatings to maintain long-term operations in marine environments.
  To further enhance the functionality of these sensors, researchers are investigating multimodal tactile sensors capable of detecting not only surface textures but also the physical properties of objects, such as stiffness, compliance, and temperature. This would enable UVMSs to differentiate between various types of materials underwater, such as metals, corals, or biological tissues, leading to more precise manipulation strategies.
- **Exploiting machine learning for the interpretation of tactile data.** By training ML models on large datasets of underwater manipulation tasks, future UVMSs will be able to recognize patterns in tactile sensor feedback more accurately and in real time. For instance, a system could autonomously adjust its manipulation strategy based on the texture or compliance of the object it is interacting with. Techniques such as deep learning and reinforcement learning will likely be applied to process noisy tactile data, extract meaningful insights, and improve decision-making in unstructured underwater environments. Furthermore, real-time processing of tactile data in conjunction with force control would enable continuous refinement of grip force and object handling, especially in tasks requiring fine motor control, such as grasping fragile objects or performing repairs to delicate structures.
  Moreover, machine learning techniques can also address challenges caused by communication delays in remote operations by enabling predictive feedback systems that anticipate operator actions and environmental changes. These systems can preprocess incoming sensor data locally to reduce transmission delays, ensuring smooth and responsive manipulation even under constrained communication conditions.
- **Advanced adaptive and predictive control methods for UVMSs.** Traditional force control algorithms, which rely on rigid models, often fail in dynamic environments. As a solution, new approaches based on adaptive control techniques are being developed.

These methods adjust the applied forces in real time by continuously monitoring feedback from both internal force sensors and external environmental sensors. Predictive models, such as those built on model-predictive control (MPC) frameworks, will enable UVMSs to anticipate changes in current and pressure, adjusting manipulator movements before disturbances occur.

In addition, force feedback will increasingly be integrated with position control systems, enabling hybrid force–position control strategies. This integration is essential for tasks that require both precise positioning (such as aligning tools) and controlled force application (such as drilling or fastening). Research is also focusing on developing controllers that can autonomously switch between force control and position control modes, depending on the task requirements, to enhance the overall operational efficiency of UVMSs.

Moreover, adaptive and predictive control methods can mitigate the impact of communication constraints by compensating for time delays and disturbances. By integrating predictive strategies into control loops, UVMSs can maintain precise force regulation and positioning, even with delayed feedback. This approach is particularly beneficial for remote operations, where low-latency communication may not always be feasible.

- **Visual and haptic interface for teleoperation.** For UVMSs in semi-autonomous or teleoperated modes, providing human operators with realistic haptic feedback will be a key research focus. Current systems lack detailed force feedback, making it difficult for operators to sense the exact conditions underwater. Future developments may aim to create more intuitive haptic interfaces, allowing operators to feel the texture, stiffness, and resistance of objects through force feedback gloves or joysticks. This direct feedback loop will improve the precision of teleoperated manipulation, particularly in complex or delicate tasks such as archaeological artifact recovery or the repair of fragile underwater infrastructure.

  To achieve this, researchers are investigating low-latency transmission methods for haptic data, which will reduce the lag in delivering tactile and force feedback to operators working remotely. This is especially important for deep-sea operations, where communication delays due to depth and distance can impair real-time control. Advanced signal processing and compression techniques will be critical for transmitting detailed sensory data in real time, ensuring the operator receives accurate haptic feedback despite the challenging underwater communication environment.
- **Data fusion approaches to integrate different modality data from UVMSs and improve the autonomous manipulation capability.** The future of UVMS tactile and force control research will increasingly involve sensor fusion, where tactile, force, vision, and acoustic data are combined to provide a more comprehensive understanding of the underwater environment. By fusing tactile and force information with visual data, UVMSs will be able to better perceive the objects they are manipulating, even in low-visibility conditions. This multimodal approach will enhance object recognition, improve manipulation accuracy, and enable more adaptive control strategies in dynamic environments.

  Additionally, data fusion approaches can help compensate for communication constraints by enabling local processing and integration of sensor data, reducing the need for high-bandwidth communication during remote operations. Machine learning algorithms can also be used to predict environmental changes and refine sensor data, improving the robustness and reliability of autonomous manipulation tasks.

  Future research will focus on creating robust algorithms capable of integrating these diverse data streams and translating them into actionable insights for real-time manipulation. This requires advancements in both hardware, to ensure that the sensors can function in harsh underwater conditions, and software, to process and integrate the sensor data in real time. Machine learning techniques will also play a key role in sensor fusion, helping UVMSs extract the most relevant information from noisy and incomplete datasets.

In summary, future research in tactile sensing and force control for UVMSs will be directed towards improving sensor accuracy, adaptability, and robustness, while developing more advanced control algorithms to handle the complexities of underwater environments. These advancements will significantly enhance systems' manipulation capabilities and autonomy, allowing for more sophisticated and precise underwater operations.

6. Conclusions

In this review, we explored touching-based underwater robotic perception and manipulation, reviewing and analyzing the current state of research from the perspectives of sensor hardware, force control algorithms for underwater manipulators and grippers, and related operational tasks. Unlike previous reviews, our focus was primarily on the emerging field of underwater manipulation when contact occurs and discussing how to improve manipulation capabilities with tactile sensors. Based on the identified limitations, we highlighted several key challenges and proposed future research directions aimed at enhancing UVMS operational capabilities and expanding the scope of their applications.

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References

1. Ridao, P.; Carreras, M.; Ribas, D.; Sanz, P.J.; Oliver, G. Intervention AUVs: The next challenge. *Annu. Rev. Control* **2015**, *40*, 227–241. [CrossRef]
2. Aldhaheri, S.; De Masi, G.; Pairet, È.; Ardón, P. Underwater robot manipulation: Advances, challenges and prospective ventures. In Proceedings of the OCEANS 2022, Chennai, India, 21–24 February 2022; pp. 1–7.
3. Kumar, S.; Rastogi, V.; Gupta, P. Recent developments in modeling and control of underwater robot manipulator: A review. *Indian J. Sci. Technol.* **2016**, *9*, 8. [CrossRef]
4. Simetti, E. Autonomous underwater intervention. *Curr. Robot. Rep.* **2020**, *1*, 117–122. [CrossRef]
5. Youakim, D.; Ridao, P. Motion planning survey for autonomous mobile manipulators underwater manipulator case study. *Robot. Auton. Syst.* **2018**, *107*, 20–44. [CrossRef]
6. Wang, Z.; Cui, W. For safe and compliant interaction: An outlook of soft underwater manipulators. *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.* **2021**, *235*, 3–14. [CrossRef]
7. Morgan, E.; Carlucho, I.; Ard, W.; Barbalata, C. Autonomous underwater manipulation: Current trends in dynamics, control, planning, perception, and future directions. *Curr. Robot. Rep.* **2022**, *3*, 187–198. [CrossRef]
8. Sivčev, S.; Coleman, J.; Omerdić, E.; Dooly, G.; Toal, D. Underwater manipulators: A review. *Ocean Eng.* **2018**, *163*, 431–450. [CrossRef]
9. Mazzeo, A.; Aguzzi, J.; Calisti, M.; Canese, S.; Vecchi, F.; Stefanni, S.; Controzzi, M. Marine robotics for deep-sea specimen collection: A systematic review of underwater grippers. *Sensors* **2022**, *22*, 648. [CrossRef]

10. Muscolo, G.G.; Cannata, G. A novel tactile sensor for underwater applications: Limits and perspectives. In Proceedings of the OCEANS 2015, Genova, Italy, 18–21 May 2015; pp. 1–7.
11. Muscolo, G.G.; Moretti, G.; Cannata, G. SUAS: A novel soft underwater artificial skin with capacitive transducers and hyperelastic membrane. *Robotica* **2019**, *37*, 756–777. [CrossRef]
12. Lane, D.M.; Davies, J.B.C.; Casalino, G.; Bartolini, G.; Cannata, G.; Veruggio, G.; Canals, M.; Smith, C.; O'Brien, D.J.; Pickett, M.; et al. AMADEUS: Advanced manipulation for deep underwater sampling. *IEEE Robot. Autom. Mag.* **1997**, *4*, 34–45. [CrossRef]
13. Dennerlein, J.; Howe, R.; Shahoian, E.; Olroyd, C. Vibrotactile feedback for an underwater telerobot. In Proceedings of the Robotics and Applications; Robotic and Manufacturing Systems Recent Results in Research, Development and Applications International Symposium, Sacramento, CA, USA, 9–11 April 2000; pp. 244–249.
14. Zhang, J.; Liu, W.; Gao, L.; Zhang, Y.; Tang, W. Design, analysis and experiment of a tactile force sensor for underwater dexterous hand intelligent grasping. *Sensors* **2018**, *18*, 2427. [CrossRef] [PubMed]
15. Jianjun, Z.; Weidong, L.; Yiwen, Z.; Weijiang, T. Tactile Force Sensor of Underwater Dexterous Hand Based on Micro Electromechanical System. *J. Shanghai Jiaotong Univ.* **2018**, *52*, 76.
16. Lin, M.; Vatani, M.; Choi, J.W.; Dilibal, S.; Engeberg, E.D. Compliant underwater manipulator with integrated tactile sensor for nonlinear force feedback control of an SMA actuation system. *Sensors Actuators A Phys.* **2020**, *315*, 112221. [CrossRef] [PubMed]
17. Tan, D.z.; Wang, Q.m.; Song, R.h.; Yao, X.; Gu, Y.h. Optical fiber based slide tactile sensor for underwater robots. *J. Mar. Sci. Appl.* **2008**, *7*, 122–126. [CrossRef]
18. Palli, G.; Moriello, L.; Scarcia, U.; Melchiorri, C. An intrinsic tactile sensor for underwater robotics. *IFAC Proc. Vol.* **2014**, *47*, 3364–3369. [CrossRef]
19. Palli, G.; Moriello, L.; Melchiorri, C. Performance and sealing material evaluation in 6-axis force-torque sensors for underwater robotics. *IFAC-Pap.* **2015**, *48*, 177–182. [CrossRef]
20. Liang, Q.; Zhang, D.; Chi, Z.; Ge, Y. Fingertip force/torque sensor with high isotropy and sensitivity for underwater manipulation. In Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Montreal, QC, Canada, 15–18 August 2010; Volume 44120, pp. 743–752.
21. Liang, Q.; Zhang, D.; Song, Q.; Ge, Y. A potential 4-D fingertip force sensor for an underwater robot manipulator. *IEEE J. Ocean. Eng.* **2010**, *35*, 574–583. [CrossRef]
22. Sanz, P.J.; Penalver, A.; Sales, J.; Fornas, D.; Fernández, J.J.; Pérez, J.; Bernabe, J. Grasper: A multisensory based manipulation system for underwater operations. In Proceedings of the 2013 IEEE International Conference on Systems, Man, and Cybernetics, Manchester, UK, 13–16 October 2013; pp. 4036–4041.
23. Fernández, J.J.; Prats, M.; Sanz, P.J.; García, J.C.; Marin, R.; Robinson, M.; Ribas, D.; Ridao, P. Grasping for the seabed: Developing a new underwater robot arm for shallow-water intervention. *IEEE Robot. Autom. Mag.* **2013**, *20*, 121–130. [CrossRef]
24. Meng, Q.; Wang, H.; Li, P.; Wang, L.; He, Z. Dexterous underwater robot hand: HEU hand II. In Proceedings of the 2006 International Conference on Mechatronics and Automation, Luoyang, China, 25–28 June 2006; pp. 1477–1482.
25. Kampmann, P.; Lemburg, J.; Hanff, H.; Kirchner, F. Hybrid pressure-tolerant electronics. In Proceedings of the 2012 Oceans, Hampton Roads, VA, USA, 14–19 October 2012; pp. 1–5.
26. Aggarwal, A.; Kampmann, P.; Lemburg, J.; Kirchner, F. Haptic Object Recognition in Underwater and Deep-sea Environments. *J. Field Robot.* **2015**, *32*, 167–185. [CrossRef]
27. Kampmann, P.; de Frank, K. A Tactile Sensing System for Underwater Manipulators. In Proceedings of the Workshop on Advances in Tactile Sensing and Touch Based Human-Robot Interaction, Boston, MA, USA, 7–12 October 2012; Association for Computing Machinery: New York, NY, USA, 2012.
28. Kampmann, P.; Kirchner, F. Towards a fine-manipulation system with tactile feedback for deep-sea environments. *Robot. Auton. Syst.* **2015**, *67*, 115–121. [CrossRef]
29. Lemburg, J.; Kampmann, P.; Kirchner, F. A small-scale actuator with passive-compliance for a fine-manipulation deep-sea manipulator. In Proceedings of the OCEANS'11 MTS/IEEE KONA, Waikoloa, HI, USA, 19–22 September 2011; pp. 1–4.
30. Aggarwal, A.; Kampmann, P. Tactile sensors based object recognition and 6d pose estimation. In Proceedings of the Intelligent Robotics and Applications: 5th International Conference, ICIRA 2012, Montreal, QC, Canada, 3–5 October 2012; Springer: Berlin/Heidelberg, Germany, 2012; pp. 406–416.
31. Aggarwal, A.; Kirchner, F. Object recognition and localization: The role of tactile sensors. *Sensors* **2014**, *14*, 3227–3266. [CrossRef] [PubMed]
32. Stuart, H.S.; Bagheri, M.; Wang, S.; Barnard, H.; Sheng, A.L.; Jenkins, M.; Cutkosky, M.R. Suction helps in a pinch: Improving underwater manipulation with gentle suction flow. In Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, Germany, 28 September–2 October 2015; pp. 2279–2284.
33. Nadeau, P.; Abbott, M.; Melville, D.; Stuart, H.S. Tactile sensing based on fingertip suction flow for submerged dexterous manipulation. In Proceedings of the 2020 IEEE International Conference on Robotics and Automation (ICRA), Paris, France, 31 May–31 August 2020; pp. 3701–3707.

34. Xu, P.; Liu, J.; Liu, X.; Wang, X.; Zheng, J.; Wang, S.; Chen, T.; Wang, H.; Wang, C.; Fu, X.; et al. A bio-inspired and self-powered triboelectric tactile sensor for underwater vehicle perception. *Npj Flexible Electron.* **2022**, *6*, 25. [CrossRef]
35. Subad, R.A.S.I.; Saikot, M.M.H.; Park, K. Soft multi-directional force sensor for underwater robotic application. *Sensors* **2022**, *22*, 3850. [CrossRef] [PubMed]
36. Liu, S.; Zhang, D.; Fu, X.; Mo, L.; Miao, Q.; Huang, R.; Huang, X.; Guo, W.; Li, Y.; Zheng, Q.; et al. Tactile Sensing for Soft Robotic Manipulators in 50 MPa Hydrostatic Pressure Environments. *Adv. Intell. Syst.* **2023**, *5*, 2300296. [CrossRef]
37. Mu, S.; Li, S.; Zhao, H.; Wang, Z.; Xiao, X.; Lin, Z.; Song, Z.; Tang, H.; Xu, Q.; Wang, D.; et al. A platypus-inspired electro-mechanosensory finger for remote control and tactile sensing. *Nano Energy* **2023**, *116*, 108790. [CrossRef]
38. Zhang, J.; Han, P.; Liu, Q.; Li, S.; Li, B. The design of underwater tactile force sensor with differential pressure structure and backpropagation neural network calibration. *Meas. Control* **2024**, *57*, 124–138. [CrossRef]
39. Zhang, Z.; Xiang, F.; Mei, D.; Wang, Y. Waterproof and Flexible Aquatic Tactile Sensor with Interlocked Ripple Structures for Broad Range Force Sensing. *Adv. Mater. Technol.* **2024**, *9*, 2301513. [CrossRef]
40. Guo, N.; Han, X.; Liu, X.; Zhong, S.; Zhou, Z.; Lin, J.; Dai, J.; Wan, F.; Song, C. Autoencoding a Soft Touch to Learn Grasping from On-Land to Underwater. *Adv. Intell. Syst.* **2024**, *6*, 2300382. [CrossRef]
41. Lane, D.M.; Dunnigan, M.W.; Quinn, A.; Clegg, A.C. Motion planning and contact control for a tele-assisted hydraulic underwater robot. *Underw. Robot.* **1996**, *3*, 159–177.
42. Dunnigan, M.; Lane, D.; Clegg, A.; Edwards, I. Hybrid position/force control of a hydraulic underwater manipulator. *IEE Proc.-Control. Theory Appl.* **1996**, *143*, 145–151. [CrossRef]
43. Lane, D.; Dunnigan, M.; Clegg, A.; Dauchez, P.; Cellier, L. A comparison between robust and adaptive hybrid position/force control schemes for hydraulic underwater manipulators. *Trans. Inst. Meas. Control* **1997**, *19*, 107–116. [CrossRef]
44. Clegg, A.C.; Dunnigan, M.W.; Lane, D.M. Self-tuning position and force control of an underwater hydraulic manipulator. *IFAC Proc. Vol.* **2001**, *34*, 149–154. [CrossRef]
45. Jamali, N.; Kormushev, P.; Viñas, A.C.; Carreras, M.; Caldwell, D.G. Underwater robot-object contact perception using machine learning on force/torque sensor feedback. In Proceedings of the 2015 IEEE International Conference on Robotics and Automation (ICRA), Seattle, WA, USA, 26–30 May 2015; pp. 3915–3920. [CrossRef]
46. Cieślak, P.; Ridao, P. Adaptive admittance control in task-priority framework for contact force control in autonomous underwater floating manipulation. In Proceedings of the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain, 1–5 October 2018; pp. 6646–6651.
47. Cui, Y.; Podder, T.K.; Sarkar, N. Impedance control of underwater vehicle-manipulator systems (UVMS). In Proceedings of the 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems, Human and Environment Friendly Robots with High Intelligence and Emotional Quotients (Cat. No. 99CH36289), Kyongju, Republic of Korea, 17–21 October 1999; Volume 1, pp. 148–153.
48. Cui, Y.; Sarkar, N. A unified force control approach to autonomous underwater manipulation. *Robotica* **2001**, *19*, 255–266. [CrossRef]
49. Kajita, H.; Kosuge, K. Force control of robot floating on the water utilizing vehicle restoring force. In Proceedings of the 1997 IEEE/RSJ International Conference on Intelligent Robot and Systems, Innovative Robotics for Real-World Applications, IROS'97, Grenoble, France, 11 September 1997; Volume 1, pp. 162–167.
50. Lapierre, L.; Fraisse, P.; M'Sirdi, N.K. Hybrid position/force control of a ROV with a manipulator. In Proceedings of the IEEE Oceanic Engineering Society, OCEANS'98, Conference Proceedings (Cat. No. 98CH36259), Nice, France, 28 September–1 October 1998; Volume 2; pp. 931–935.
51. Lapierre, L.; Fraisse, P.; Dauchez, P. Position/force control of an underwater mobile manipulator. *J. Robot. Syst.* **2003**, *20*, 707–722. [CrossRef]
52. Antonelli, G.; Sarkar, N.; Chiaverini, S. Explicit force control for underwater vehicle-manipulator systems. *Robotica* **2002**, *20*, 251–260. [CrossRef]
53. Bilodeau, G.; Papadopoulos, E. A model-based impedance control scheme for high-performance hydraulic joints. In Proceedings of the 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems, Innovations in Theory, Practice and Applications (Cat. No. 98CH36190), Victoria, BC, Canada, 17 October 1998; Volume 2, pp. 1308–1313.
54. Sekhavat, P.; Sepehri, N.; Wu, Q. Asymptotic force control of hydraulic actuators with friction: Theory and experiments. In Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Anaheim, CA, USA, 13–19 November 2004; Volume 47063, pp. 405–412.
55. Sekhavat, P.; Wu, Q.; Sepehri, N. Impact control in hydraulic actuators. *J. Dyn. Syst. Meas. Control* **2005**, *127*, 197–205. [CrossRef]
56. Lemieux, S.; Beaudry, J.; Blain, M. Force control test bench for underwater vehicle-manipulator system applications. In Proceedings of the IECON 2006-32nd Annual Conference on IEEE Industrial Electronics, Paris, France, 6–10 November 2006; pp. 4036–4042.

57. Barbalata, C. Modelling and Control of Lightweight Underwater Vehicle-Manipulator Systems. Ph.D. Thesis, Heriot-Watt University, Edinburgh, UK, 2017.
58. Barbalata, C.; Dunnigan, M.W.; Petillot, Y. Coupled and decoupled force/motion controllers for an underwater vehicle-manipulator system. *J. Mar. Sci. Eng.* **2018**, *6*, 96. [CrossRef]
59. Barbalata, C.; Dunnigan, M.W.; Petillot, Y. Position/force operational space control for underwater manipulation. *Robot. Auton. Syst.* **2018**, *100*, 150–159. [CrossRef]
60. Dai, P.; Lu, W.; Le, K.; Liu, D. Sliding Mode Impedance Control for contact intervention of an I-AUV: Simulation and experimental validation. *Ocean Eng.* **2020**, *196*, 106855. [CrossRef]
61. Pi, R.; Cieślak, P.; Esteba, J.; Palomeras, N.; Ridao, P. Compliant Manipulation With Quasi-Rigid Docking for Underwater Structure Inspection. *IEEE Access* **2023**, *11*, 128957–128969. [CrossRef]
62. Seki, Y.; Sagara, S.; Ambar, R. Impedance control of dual-arm 3-link underwater robot: In the case of grasping a fixed object lightly with one hand. In Proceedings of the 2018 International Conference on Information and Communication Technology Robotics (ICT-ROBOT), Busan, Republic of Korea, 6–8 September 2018; pp. 1–4.
63. Cetin, K.; Zapico, C.S.; Tugal, H.; Petillot, Y.; Dunnigan, M.; Erden, M.S. Application of adaptive and switching control for contact maintenance of a robotic vehicle-manipulator system for underwater asset inspection. *Front. Robot. AI* **2021**, *8*, 706558. [CrossRef] [PubMed]
64. Konoplin, A.; Krasavin, N. Approach to Perform Contact Manipulation Operations by AUV with Multilink Manipulators. In Proceedings of the 2023 International Conference on Ocean Studies (ICOS), Vladivostok, Russia, 3–6 October 2023; pp. 65–68.
65. Konoplin, A.; Krasavin, N.; Yurmanov, A.; Piatavin, P.; Vasilenko, R.; Panchuk, M. Development of a Control System for Underwater Vehicles with Multilink Manipulators Performing Contact Manipulation Operations. *J. Mar. Sci. Eng.* **2024**, *12*, 1126. [CrossRef]
66. Heshmati-alamdari, S.; Nikou, A.; Kyriakopoulos, K.J.; Dimarogonas, D.V. A robust force control approach for underwater vehicle manipulator systems. *IFAC-PapersOnLine* **2017**, *50*, 11197–11202. [CrossRef]
67. Heshmati-Alamdari, S. Cooperative and Interaction Control for Underwater Robotic Vehicles. Ph.D. Thesis, National Technical University of Athens, Athens, Greece, 2018.
68. Heshmati-Alamdari, S.; Bechlioulis, C.P.; Karras, G.C.; Kyriakopoulos, K.J. Decentralized impedance control for cooperative manipulation of multiple underwater vehicle manipulator systems under lean communication. In Proceedings of the 2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV), Porto, Portugal, 6–9 November 2018; pp. 1–6.
69. Heshmati-Alamdari, S.; Karras, G.C.; Kyriakopoulos, K.J. A distributed predictive control approach for cooperative manipulation of multiple underwater vehicle manipulator systems. In Proceedings of the 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 20–24 May 2019; pp. 4626–4632.
70. Heshmati-Alamdari, S.; Bechlioulis, C.P.; Karras, G.C.; Kyriakopoulos, K.J. Cooperative impedance control for multiple underwater vehicle manipulator systems under lean communication. *IEEE J. Ocean. Eng.* **2020**, *46*, 447–465. [CrossRef]
71. Cataldi, E.; Chiaverini, S.; Antonelli, G. Cooperative object transportation by two underwater vehicle-manipulator systems. In Proceedings of the 2018 26th Mediterranean Conference on Control and Automation (MED), Zadar, Croatia, 19–22 June 2018; pp. 161–166.
72. Kwon, D.S.; Ryu, J.H.; Lee, P.M.; Hong, S.W. Design of a teleoperation controller for an underwater manipulator. In Proceedings of the 2000 ICRA, Millennium Conference, IEEE International Conference on Robotics and Automation, Symposia Proceedings (Cat. No. 00CH37065), San Francisco, CA, USA, 24–28 April 2000; Volume 4, pp. 3114–3119.
73. Khatib, O.; Yeh, X.; Brantner, G.; Soe, B.; Kim, B.; Ganguly, S.; Stuart, H.; Wang, S.; Cutkosky, M.; Edsinger, A.; et al. Ocean one: A robotic avatar for oceanic discovery. *IEEE Robot. Autom. Mag.* **2016**, *23*, 20–29. [CrossRef]
74. Yeh, X. Development of an Underwater Humanoid Robotic Diver. Ph.D. Thesis, Stanford University, Stanford, CA, USA, 2017.
75. Brantner, G. *Human-Robot Collaboration in Challenging Environments*; Stanford University: Stanford, CA, USA, 2018.
76. Brantner, G.; Khatib, O. Controlling Ocean One: Human–robot collaboration for deep-sea manipulation. *J. Field Robot.* **2021**, *38*, 28–51. [CrossRef]
77. Wang, F.; Liu, H.; Cao, L.; Xie, F.; Song, G.; Song, A. A Novel Lightweight Underwater Manipulator Based on ROS2 for Reliable Intervention. In Proceedings of the 2024 9th International Conference on Automation, Control and Robotics Engineering (CACRE), Jeju Island, South Korea, 18–20 July 2024; pp. 345–349.
78. Subad, R.A.S.I.; Cross, L.B.; Park, K. Soft robotic hands and tactile sensors for underwater robotics. *Appl. Mech.* **2021**, *2*, 356–382. [CrossRef]
79. Lane, D.M. Introduction to the Special Issue of the International Journal of Systems Science on the AMADEUS dextrous underwater grasping system. *Int. J. Syst. Sci.* **1998**, *29*, 445–454. [CrossRef]
80. O'Brien, D.J.; Lane, D. Force and explicit slip sensing for the AMADEUS underwater gripper. *Int. J. Syst. Sci.* **1998**, *29*, 471–483. [CrossRef]

81. O'Brien, D.J.; Lane, D.M. Force and slip sensing for a dextrous underwater gripper. In Proceedings of the 1998 IEEE International Conference on Robotics and Automation (Cat. No. 98CH36146), Leuven, Belgium, 20 May 1998; Volume 2, pp. 1057–1062.
82. O'Brien, D.; Lane, D. The sensing subsystems and force control of the AMADEUS dextrous underwater gripper. In Proceedings of the IEEE Oceanic Engineering Society, OCEANS'98, Conference Proceedings (Cat. No. 98CH36259), Nice, France, 28 September–1 October 1998; Volume 2, pp. 713–717.
83. Chen, Y.; Zhang, Q.; Tian, Q.; Huo, L.; Feng, X. Fuzzy Adaptive Impedance Control for Deep-Sea Hydraulic Manipulator Grasping Under Uncertainties. In Proceedings of the Global Oceans 2020, Singapore, 5–14 October 2020; pp. 1–6.
84. Stuart, H. Robotic Hand Design for Remote Ocean Exploration: Active Selection of Compliance and Contact Conditions. Ph.D. Thesis, Stanford University, Stanford, CA, USA, 2017.
85. Stuart, H.; Wang, S.; Khatib, O.; Cutkosky, M.R. The ocean one hands: An adaptive design for robust marine manipulation. *Int. J. Robot. Res.* **2017**, *36*, 150–166. [CrossRef]
86. Lu, L.; Liu, Q.; Liang, C.; Tang, X.; Xu, D.; Yang, X.; Han, B. Impedance control for underwater gripper compliant grasping in unstructured environment. In Proceedings of the Intelligent Robotics and Applications: 14th International Conference, ICIRA 2021, Yantai, China, 22–25 October 2021; Springer: Berlin/Heidelberg, Germany, 2021; pp. 279–289.
87. Cooke, N.J. Human factors of remotely operated vehicles. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Los Angeles, CA, USA, 20–22 November 2006; Volume 50, pp. 166–169.
88. Capocci, R.; Dooly, G.; Omerdić, E.; Coleman, J.; Newe, T.; Toal, D. Inspection-class remotely operated vehicles—A review. *J. Mar. Sci. Eng.* **2017**, *5*, 13. [CrossRef]
89. Quattrini Li, A.; Carver, C.J.; Shao, Q.; Zhou, X.; Nelakuditi, S. Communication for Underwater Robots: Recent Trends. *Curr. Robot. Rep.* **2023**, *4*, 13–22. [CrossRef]
90. Di Lillo, P.A.; Simetti, E.; De Palma, D.; Cataldi, E.; Indiveri, G.; Antonelli, G.; Casalino, G. Advanced ROV autonomy for efficient remote control in the DexROV project. *Mar. Technol. Soc. J.* **2016**, *50*, 67–80. [CrossRef]
91. Londhe, P.; Mohan, S.; Patre, B.; Waghmare, L. Robust task-space control of an autonomous underwater vehicle-manipulator system by PID-like fuzzy control scheme with disturbance estimator. *Ocean Eng.* **2017**, *139*, 1–13. [CrossRef]
92. Simetti, E.; Casalino, G. Manipulation and transportation with cooperative underwater vehicle manipulator systems. *IEEE J. Ocean. Eng.* **2016**, *42*, 782–799. [CrossRef]
93. Allotta, B.; Costanzi, R.; Ridolfi, A.; Colombo, C.; Bellavia, F.; Fanfani, M.; Pazzaglia, F.; Salvetti, O.; Moroni, D.; Pascali, M.A.; et al. The ARROWS project: Adapting and developing robotics technologies for underwater archaeology. *IFAC-PapersOnLine* **2015**, *48*, 194–199. [CrossRef]
94. Bingham, B.; Foley, B.; Singh, H.; Camilli, R.; Delaporta, K.; Eustice, R.; Mallios, A.; Mindell, D.; Roman, C.; Sakellariou, D. Robotic tools for deep water archaeology: Surveying an ancient shipwreck with an autonomous underwater vehicle. *J. Field Robot.* **2010**, *27*, 702–717. [CrossRef]
95. Hur, B.; Casas, R.; Cervantes, D.A.; Comer, J.R.; De Anda, B.R.; Ledbetter, L.J.; Fly, A.; Tsai, G.E.; Davila, E.L. Small-scale Underwater Robotics Development for Underwater Archaeological Applications. In Proceedings of the 2019 ASEE Annual Conference & Exposition, Tampa, FL, USA, 16–19 June 2019.
96. Scaradozzi, D.; Sorbi, L.; Zoppini, F.; Gambogi, P. Tools and techniques for underwater archaeological sites documentation. In Proceedings of the 2013 OCEANS, San Diego, CA, USA, 23–27 September 2013; pp. 1–6.
97. Browne, T.M.; Collins, T.J.; Garlich, M.J.; O'Leary, J.E.; Heringhaus, K.C. *Underwater Bridge Repair, Rehabilitation, and Countermeasures*; Technical Report; Federal Highway Administration, Office of Bridge Technology: Washington, DC, USA, 2010.
98. Surojo, E.; Putri, E.D.W.S.; Budiana, E.P. Recent developments on underwater welding of metallic material. *Procedia Struct. Integr.* **2020**, *27*, 14–21. [CrossRef]
99. Nauert, F.; Kampmann, P. Inspection and maintenance of industrial infrastructure with autonomous underwater robots. *Front. Robot. AI* **2023**, *10*, 1240276. [CrossRef]
100. Vijay, A.; Radhika, N. A comprehensive review on underwater welding: Methods, property evaluations and challenges. *Adv. Mater. Process. Technol.* **2024**, *10*, 923–959. [CrossRef]
101. Daoliang, L.; Jianhua, B. Research progress on key technologies of underwater operation robot for aquaculture. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 1–9.
102. Wu, Y.; Duan, Y.; Wei, Y.; An, D.; Liu, J. Application of intelligent and unmanned equipment in aquaculture: A review. *Comput. Electron. Agric.* **2022**, *199*, 107201. [CrossRef]
103. Matos, A.; Martins, A.; Dias, A.; Ferreira, B.; Almeida, J.M.; Ferreira, H.; Amaral, G.; Figueiredo, A.; Almeida, R.; Silva, F. Multiple robot operations for maritime search and rescue in euRathlon 2015 competition. In Proceedings of the OCEANS 2016, Shanghai, China, 10–13 April 2016; pp. 1–7.
104. Venkatesan, S. AUV for Search & Rescue at sea-an innovative approach. In Proceedings of the 2016 IEEE/OES Autonomous Underwater Vehicles (AUV), Tokyo, Japan, 6–9 November 2016; pp. 1–9.

105. Abi-Zeid, I.; Morin, M.; Nilo, O. Decision Support for Planning Maritime Search and Rescue Operations in Canada. In Proceedings of the International Conference on Enterprise Information Systems (ICEIS), Heraklion, Greece, 3–5 May 2019.
106. Jorge, V.A.; Granada, R.; Maidana, R.G.; Jurak, D.A.; Heck, G.; Negreiros, A.P.; Dos Santos, D.H.; Gonçalves, L.M.; Amory, A.M. A survey on unmanned surface vehicles for disaster robotics: Main challenges and directions. *Sensors* **2019**, *19*, 702. [CrossRef] [PubMed]
107. Queralta, J.P.; Taipalmaa, J.; Pullinen, B.C.; Sarker, V.K.; Gia, T.N.; Tenhunen, H.; Gabbouj, M.; Raitoharju, J.; Westerlund, T. Collaborative multi-robot search and rescue: Planning, coordination, perception, and active vision. *IEEE Access* **2020**, *8*, 191617–191643. [CrossRef]
108. Qingqing, L.; Taipalmaa, J.; Queralta, J.P.; Gia, T.N.; Gabbouj, M.; Tenhunen, H.; Raitoharju, J.; Westerlund, T. Towards active vision with UAVs in marine search and rescue: Analyzing human detection at variable altitudes. In Proceedings of the 2020 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), Abu Dhabi, United Arab Emirates, 4–6 November 2020; pp. 65–70.
109. Simetti, E.; Campos, R.; Di Vito, D.; Quintana, J.; Antonelli, G.; Garcia, R.; Turetta, A. Sea mining exploration with an UVMS: Experimental validation of the control and perception framework. *IEEE/ASME Trans. Mechatron.* **2020**, *26*, 1635–1645. [CrossRef]
110. Sartore, C.; Campos, R.; Quintana, J.; Simetti, E.; Garcia, R.; Casalino, G. Control and perception framework for deep sea mining exploration. In Proceedings of the 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Macau, China, 4–8 November 2019; pp. 6348–6353.
111. Sartore, C.; Simetti, E.; Wanderlingh, F.; Casalino, G. Autonomous deep sea mining exploration: The EU ROBUST project control framework. In Proceedings of the OCEANS 2019, Marseille, France, 17–20 June 2019; pp. 1–8.
112. Di Vito, D.; De Palma, D.; Simetti, E.; Indiveri, G.; Antonelli, G. Experimental validation of the modeling and control of a multibody underwater vehicle manipulator system for sea mining exploration. *J. Field Robot.* **2021**, *38*, 171–191. [CrossRef]