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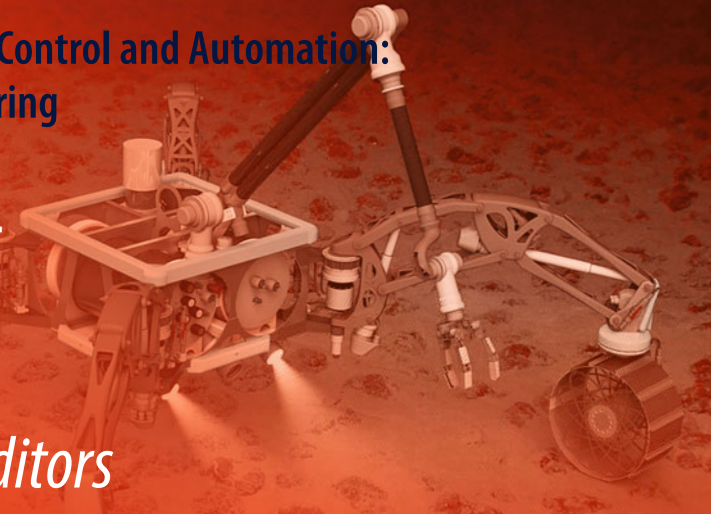
Science and Engineering



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AI Technology for Underwater Robots

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This book provides comprehensive insight in all disciplinary aspects-from system design, communication, AI and machine learning, mapping and coordination, to adaptive mission planning for next generation robotic underwater technologies and structures.

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Preface

Data is the oil of the twenty-first century: This is the key phrase that describes and explains the enormous success of AI technologies that we have witnessed over the last decade. This book is trying to outline the possibilities for AI in a field that for now has been left pretty much untouched by these technologies but that offers great potential for the field of AI as well as it will profit enormously from these applications, especially in combination with modern robotic technologies.

We assembled a group of AI-experts from various areas of artificial intelligence and associated disciplines in a 2-day workshop in Bremen, Germany, August 27–28, 2018.

The idea behind the workshop was to confront these scientists with the field of underwater technologies, applications, and maritime science and to identify what impact this environment would have on the methods, tools, and theories that they are so successfully using, applying, and developing in the terrestrial domain.

In the first part of the workshop, colleagues from the area of maritime science and industrial maritime application presented their work and the challenges they are facing when using existing technology in the maritime but especially the underwater domain.

It turned out to be an eye-opening experience for all participants that deploying and using even the simplest and most robust mechanical tools is presenting a challenge and is often associated with an enormous amount of preparation, continuous monitoring, and maintenance. When it comes to use more sophisticated electromechanical components, or even systems, the amount of preparation and maintenance rises exponentially with the complexity, in terms of number of connected mechatronical parts, of the components or systems. As a result, the price for any activity that is carried out in this environment rises accordingly as the only way to ensure safe and reliable operation of technology in the maritime—and especially the underwater, environment is to increase the amount of manpower for preparation and maintenance. Interestingly enough this is true, though on different scales, for scientific endeavors as well as for industrial undertakings. The notion of price in this context also has an ecological implication. If one calculates the amount of fuel that is burned by a standard offshore maintenance vessel in a single day it is straightforward to see that a single day spared instead by modern robotics and AI technology significantly reduces the ecological footprint of such operations.

The first part outlines some of the challenges that experimenters and operators are confronted with while carrying out marine science or offshore (e.g., Oil and Gas, Wind power) projects. Fischer gives an insight into the world of underwater science and introduces the beauty but also the fragility of the underwater world and outlines the possibilities for future marine science using intelligent underwater systems. Motta et al. provide another view on the underwater environment by describing the requirements that are needed to exploit the rich resources available in this domain as they put the focus on the need to be able to act minimally invasive in order to carry out exploitation without massive intervention.

The second part puts the focus on basic technologies required to achieve the kind of intelligent systems that have been postulated in the chapter "A Survey of Challenges and Potentials for AI Technologies". The requirements range from perspectives from material science in Bachmayer et al. that discuss the possibilities of new and advanced materials and production strategies to enable more robust systems exploiting properties like self-healing instead of withstanding the harsh underwater environment, to, e.g. Hildebrandt et al. who presenting approaches to modularity and reconfigurability with the focus on improving the usability, versatility, and deployment costs of underwater systems. Bachmayer et al. focus on a different, however, very important technology by providing insights into the possibilities to design new thrusters that will allow to maneuver and control underwater vehicles with a precision and accurateness that actually reflects the possibilities of the underlying control algorithms.

Another very basic requirement is that of communication. While electromagnetic wave propagation is limited by the physics to a very narrow bandwidth, Wübben et al. provide insight into alternative ways to communicate by exploiting semantic concepts as new communication paradigm in the face of limited bandwidths. Finally, Bartsch et al. focus on another important ability of future underwater robots by introducing new concepts for underwater manipulation by trying to exploit concepts from terrestrial actuator design and control to underwater high-performance, scalable actuators.

In the third part, the authors focus on system functionality and performance as well as possibilities to represent the environment structure and dynamics. De Gea et al. are analyzing the possibilities of machine learning to model and control the increasing structural complexity of underwater robots for precise and intelligent manipulation. In order to apply these techniques effectively, a precise ability of the robot to recognize and represent the environment is required, which is in the focus of Köser et al. who use modern AI technologies for environment recognition and representation. Kampmann et al. put the focus on a very important subsystem for underwater manipulation by looking at the gripper system itself. These authors emphasize the need for dexterous manipulation and exploit new and innovative pressure-tolerant sensor technologies to achieve adaptive dexterous gripping abilities in underwater robots. An extremely difficult case is the modeling of the system dynamics in the water column. Using straightforward mathematical approaches has very narrow boundaries as it comes to changing properties of the medium as well as changing dynamics in the system itself. De Gea et al. are analyzing the possibilities of deep learning technologies to approximate a model of the dynamics of an underwater robot even in the case of a highly complex mechanical structure. Kampmann et al. finally emphasize the need for new sensor technology by specifically exploiting a concept that is long since established in terrestrial applications and that exploits different modalities to integrate into more precise, more robust, and finally more reliable information gathering from the environment.

In the fourth part, authors look at the possibilities to integrate new intelligent robots in actual underwater scenarios. Frese et al. explore the possibilities of navigating especially in confined spaces. Unlike navigation in open water, confined spaces need probabilistic approaches to model and predict both, the environment as well as system dynamics, in order to compute a self-localization hypothesis as well as an environment map. One important drawback of probabilistic methods is that they require training data in order to converge to—in the end—optimal solutions. This information cannot efficiently be acquired in real-world tests. Therefore, a possible approach giving today's simulation tools and approaches is exploited in the chapter "Towards a Simulation Framework for Underwater Intervention Analysis and Training" in Teschner et al. by exploring the possibilities for simulation frameworks for underwater intervention to train and optimize the performance of systems in the real world. No matter how much training in realistic or simulated scenarios we will be able to perform, in the end, when it comes to apply these new kinds of systems in marine science or marine industry scenarios, a verification protocol will be needed that describes and to some extent guarantees the function of the system. Lüth et al. are concerned with this issue when they explore new and existing techniques to prove the correctness of software and hardware of underwater robotic systems. After all, we will not be able and it is not intended to actually replace the human operator when it comes to apply intelligent robots in underwater environments. Actually, these new systems will be extended tools for human operators that will help them to improve the quality of the job they do, or that will allow them to do things they could not do so far, or that will allow them to do things that they already did but with less or no destructive interventions and finally it will allow the human operators to gather much more information about this fragile yet unforgiving and harsh environment. In any case, humans and robots need to interact efficiently, which is the focus of Kirchner et al. when they describe new and innovative techniques to interact with underwater robotic systems.

Bremen, Germany Frank Kirchner
June 2019

Contents

Part I
Underwater Robots: Challenges and Applications

This part outlines some of the challenges that experimenters and operators are confronted with while carrying out marine science or offshore projects, like oil, gas, and wind power. Chapter 1 explores the potential and challenges of AI technologies in the domain of underwater technology, where autonomy is a crucial factor in order to tackle important aspects of future maritime system application.

Chapter 2 gives an insight into the world of underwater science and introduces the beauty but also the fragility of the underwater world and outlines the possibilities for future marine science using intelligent underwater systems. The actual state and the challenges in using state-of-the-art IT-based sensor technology in shallow water areas are summarized as well as the main shortcomings and pitfalls when modern sensor technology meets the rough conditions of coastal areas in temperate and polar waters. A significant part of the marine biological recruitment, production, and biodiversity is related to the shallow water areas down to 50 m water depth along the World's coastal zones where light penetrates to the bottom producing a highly diverse benthic community and a baseline for marine life. Chapter 3 provides another view on the underwater environment by describing the requirements that are needed to exploit the rich resources available in this domain as they put the focus on the need to be able to act minimally invasive in order to carry out exploitation without massive intervention. Industries are continuously looking for new technologies to turn their business more environmental friendly while being profitable and safer at the same time. The environmental technological challenges are discussed and an integrated multidisciplinary strategic long-term plan to increase the technology maturity and its general applicability is proposed.

A Survey of Challenges and Potentials for AI Technologies

Frank Kirchner

Abstract Artificial Intelligence (AI) has received much attention lately for various achievements in areas like face recognition, natural language understanding and production as well as in medical fields like tumor classification, heart failure prediction, and even depression diagnosis, e.g. in Chockley and Emanuel (J Am Coll Radiol 13(12):1415–1420, 2016, [1]). The fields of application for AI Technologies are currently expanding rapidly into pharmacy, finance, and of course security in all its forms and shapes. What all the above-mentioned areas have in common is the fact that we can apply a specific kind of AI Technologies that are grounded in statistical analysis of massive amounts of data. These are the so-called data-driven machine learning techniques that increase exponentially in performance with the amount of data that is available for statistical analysis. It is easy to forget that Artificial Intelligence in fact is a much broader field that dates back to the beginning of the last century when scientists from a much broader spectrum of disciplines were focused on the question of modelling intelligent behavior. One key player in this field was Alan Turing himself, who was attracted to the question as a result of his work in the field of computation theory that resulted in the Turing machine as an universal mechanism/theory to efficiently computable functions. It was just consequential that he would start thinking about the set of functions that would not fall into the above-mentioned class and from there it is a small step to discuss intelligence and what mechanisms may be underlying. Figure 1 depicts the origin of Artificial Intelligence as being in the middle of a spectrum of disciplines that range from Engineering and Mechatronics via Computer Science to Cognitive Science, Neuroscience and even Linguistics and Psychology. Artificial Intelligence therefore represents a field that is of great interest for applications especially those that require a huge degree of autonomy like the underwater domain does.

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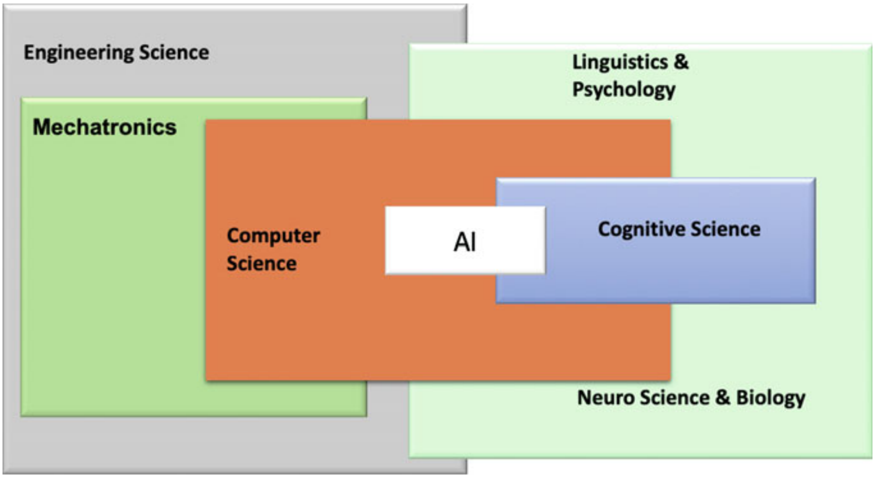

Fig. 1 Artificial Intelligence is the interface between Engineering and Cognitive Science trying to implement intelligent functions in technical systems

The Case for AI and Robotics

In the domain of underwater technology, autonomy is a crucial factor to be able to tackle important aspects of future maritime system application. The oceans and especially the bottom of the oceans is a kingdom largely still unknown to humanity. As has been pointed out many times before we know much less about the bottom of our oceans as we do know about the surface of Mars. On the other hand, it is more than obvious that humanity does need the resources that the oceans provide. These resources are vast and range from the production of energy to the production of rare earth minerals and to the production of food for a population that is said to reach 9 billion in only the next 20 years. However, if we do accept the fact that these resources are needed, we must as well accept the fact that we must make use of this natural resource in a way that guaranties the existence of this resource also for future generations, thus technologies are required that allow for a sustainable exploitation of the oceans as a vital resource for mankind (Fig. 2).

Artificial Intelligence and robotic technologies are assets that we have already mastered to a great amount and they can be used to achieve a sustainable exploitation of maritime resources. However, these technologies must be expanded and further developed to be truly applicable in the domain of underwater applications.

This expansion and development will pose some serious research questions on the side of the current AI and Robotic technologies and methods however, the solutions to those questions will on the other hand not just expand AI and robotics, moreover it will actually allow us to formulate new directions of research and therefore answer some pressing questions on the perspectives for Artificial Intelligence itself (Figs. 3 and 4).

Fig. 2 The Waste-Shark. A study of an autonomous robot to collect floating waste in harbours and other confined maritime environments

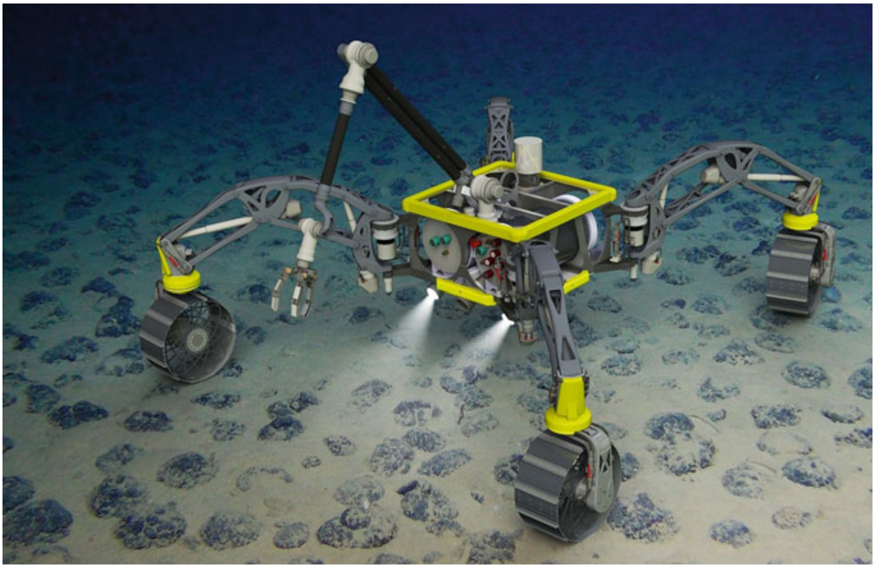

Fig. 3 A design study of the underwater mobile manipulation system Sherpa-UW that was designed and built at the Robotics Innovation Center of DFKI in Bremen

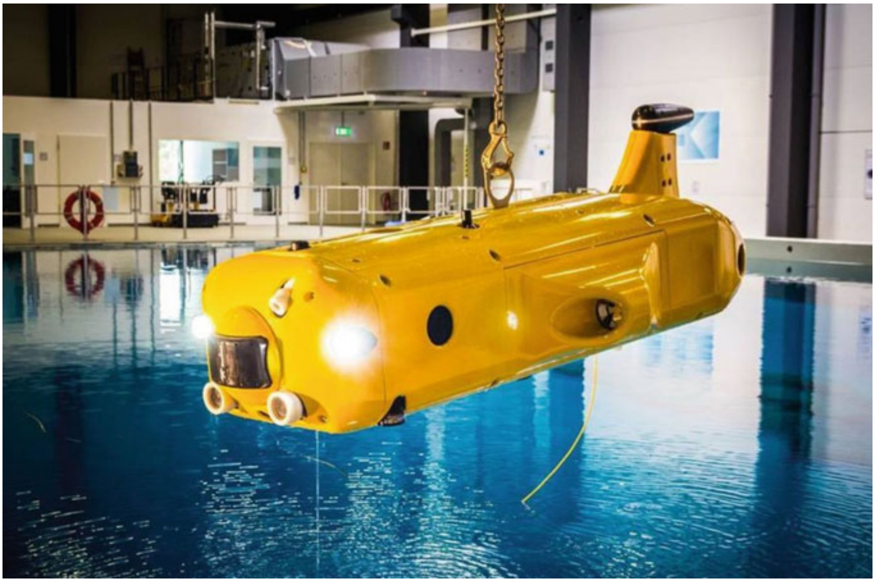

Fig. 4 The underwater autonomous vehicle Flatfish that was designed and built in a cooperation project with DFKI Bremen and SENAI-Salvador, Brasil [2]

If we take a look at the life cycle of e.g. an underwater production site (see Fig. 5) we can outline the need for intelligent technology support during each phase of the cycle. During the exploration and prospection phase in a typical offshore

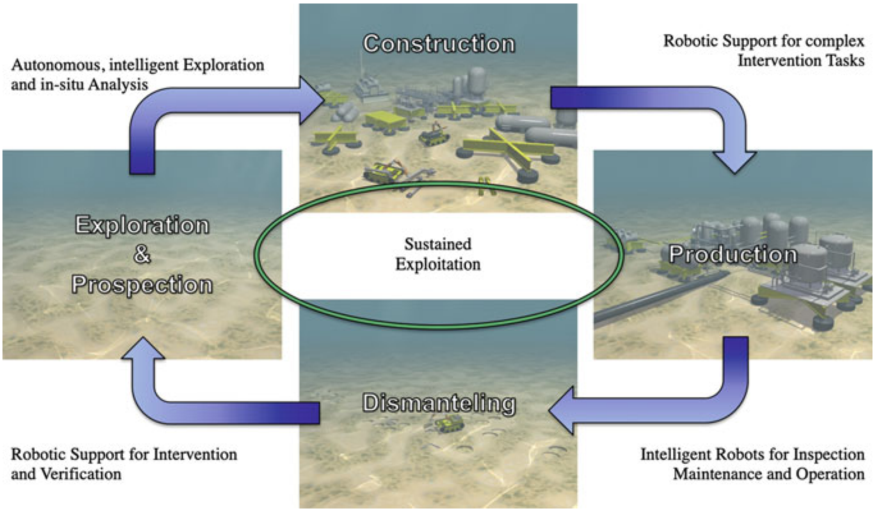

Fig. 5 Sustainable Exploitation life cycle of underwater production site

production project, intelligent and especially autonomous robotic systems can collect data of higher quality to identify suitable sites with fewer consumption of energy. An autonomous system needs significantly less surface support than does a typical cable-driven remotely operated vehicle (ROV), thus the size of the surface vessel and the crew head count can be decreased significantly, which results in lower exploration costs–one should note that reduced exploration costs also mean a reduced ecological footprint. At the same time the quality of the data can be increased as the intelligent robot is capable to take significantly more samples in the same amount of time as can be done with an ROV, which is a result of intelligent path and mission planning derived from AI Technologies in the field of formal planning and execution control [3].

Provided the capabilities of future robotic systems in terms of on-board sample taking in situ and on-board, real-time analysis, we will be able to optimize the exploration and prospection missions even further as we can better and quicker predict the suitability of the site. These capabilities originate from the possibility of implementing high performance computation devices that allow for the use of data-driven deep neural network technologies. At the same time, the system will be able to implement data analysis methods to qualify environmental parameters, as bio-diversity and ecological value of the site, which are parameters that do not necessarily enter the equation in today's approaches to use a given site for production. If these parameters are obtained at all nowadays, than they typically have to be acquired in a separate mission that comes weeks or months later with additional surface vessels and underwater equipment, again increasing the ecological footprint. Intelligent robotic technology can do this in a single sweep and with much higher precision often even qualitatively better than a human operator could do this due to fatigue and error prone visual inspection by humans.

During the production phase of such a project, which lasts about 30+ years, intelligent robotic systems based on AI technology can enormously increase security and safety of the production site. Future intelligent robotic systems can be subsea resident, which means they are deployed once and then stay on site for months or even years. This is possible because the site either produces energy or is connected to an energy source, which allows for the implementation of underwater power supply and data-exchange facilities (garage). As modern probabilistic navigation technology will enable the robots to autonomously find their way to the garage, they can recharge any time and use the physical connection to the garage to establish high band-with communication links with an operator central. This communication link can be used to upload information that the system has acquired during its mission and to receive new mission parameters for the next trip. It should be noted that the operator central could actually be located anywhere on the globe as it will be possible to use satellite communication links from a surface buoy or from an onshore facility that is connected via underwater cable to the production or scientific site. Not just the amount of data that the onshore operators will receive will be increased to a great extent, also the quality of the data and thus the quality of the integrity monitoring will be raised drastically relative to today's standards. The systems will

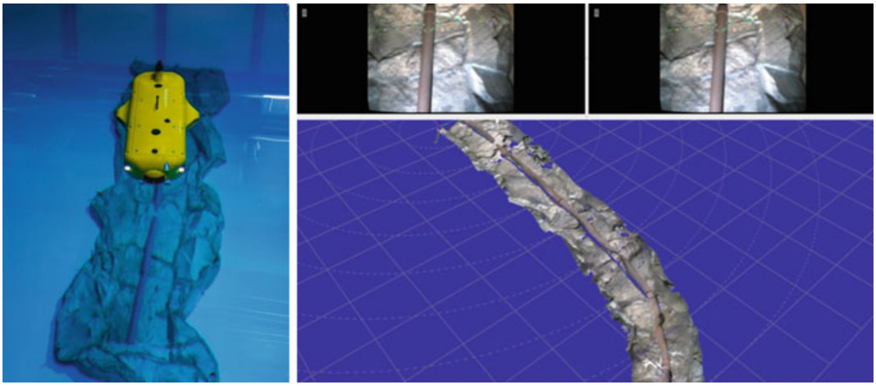

Fig. 6 The Flatfish robot during a 3D Reconstruction task (left) and the results of scanning an underwater pipe as 3D Model (right)

use modern 3D reconstruction technologies based on AI-methods known from terrestrial systems, like structure from motion [4], 3-D vision, and multi-modal (laser and ultrasound) scanning techniques [5] to deliver perfect 3D reconstructions of the underwater installations which will show even the smallest deformations in structures or defects in mechanical parts before they can cause a serious problem (Fig. 6).

Again, deep neural networks will actually be able to identify those spots autonomously so that human operators are not required to watch hours of video material to identify possible spots of future danger. In fact, we can make use of modern learning and AI-Techniques to predict the occurrence of failure, a technique that is called predictive maintenance that is used e.g. in train systems already today [6] to reduce the costs (ecological footprint) and improve safety.

Moreover, as the systems are subsea resident, an operator in an onshore installation could command the robot online to go to a specific site and provide real and 3D reconstructed imagery in real time, which will actually allow the operator to walk through his underwater installation, which may be thousands of miles away and thousands of feet below the surface. In case the operator will observe an imminent threat to the installation, he might want to prevent more serious things from happening by intervention tasks. Meaning that a valve has to be closed or a handle to be turned. The future underwater robotic systems will be equipped with AI-enabled manipulator technology that will allow the operator to do just this in a multi-modal approach. Multi-modality in this case refers to the fact that the operator will not just be able to see and hear what is happening but he will also be able to feel it, too. Haptic feedback will be provided to the operator, which is a crucial information in human controlled manipulation tasks [7] as can be witnessed by anybody who ever tried to screw a nut on a bolt. Note that we can be running the system in a supervised autonomy mode. In this mode, the systems run many tasks autonomously but these can be overwritten by the human operator if needed (Fig. 7).

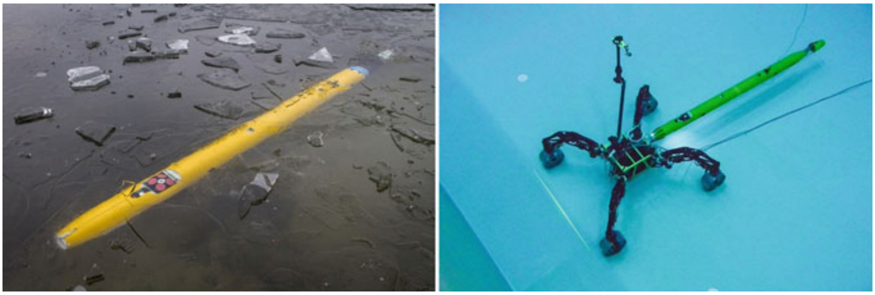

Fig. 7 The Underwater Robot Leng. The system is actually a study to explore the depths of extraterrestrial oceans (study for the german space administration) but has been used here to simulate multi robot scenarios. The right picture shows the robot Leng docking to the robot Sherpa-UW in an attempt to exchange huge amounts of data, which is inefficient to do via radio link in water

In the third phase of the life cycle, the site needs to be dismantled. This is the phase when intervention is actually required on a big scale. Things need to be taken apart. Things need to be carried from one place to another and things need to be lifted into transportation buckets to retrieve them at the surface. Here the advanced AI-based manipulation capabilities of future underwater robots will play a crucial and important role for the overall sustainability of underwater exploitation of maritime resources. First of all, it needs to be mentioned that today underwater manipulation technology is actually very crude. For the most part, heavy duty, hydraulic manipulators are used that have enormous force but very little brains.

Actually, the brains are completely located in the human operators that teleoperate the systems via a cable connection from a surface vessel. It usually requires years of training and several operators to turn shifts (due to fatigue) to simply connect a plug [7] (Fig. 8).

Modern underwater robots will be able to use their advanced AI-methods for environmental representation to obtain highly accurate 3D representations of the structures and items to be handled. They will possess manipulators and grippers that are not just structurally capable to actually perform dexterous and delicate manipulation and gripping tasks but that also provide the computational power to run algorithms that will allow them to improve their manipulation and gripping techniques over time as they can learn from previous examples via the use of machine learning techniques. These systems actually do not require to replace precision by shear force as they can determine the best way to grab an object and even to maintain a stable grip without just squeezing the object by applying more force.

These systems will operate much more like a human would handle the task by shifting the grip or adjusting the center of mass of the object in its hands. In fact, two or more such robots will be able to handle very big objects in a team as they can use AI Technologies from multi-agent systems [8] to coordinate their work and cooperate in an intelligent and task-oriented way.

To summarize the areas of improvement of current underwater application the following list gives an overview:

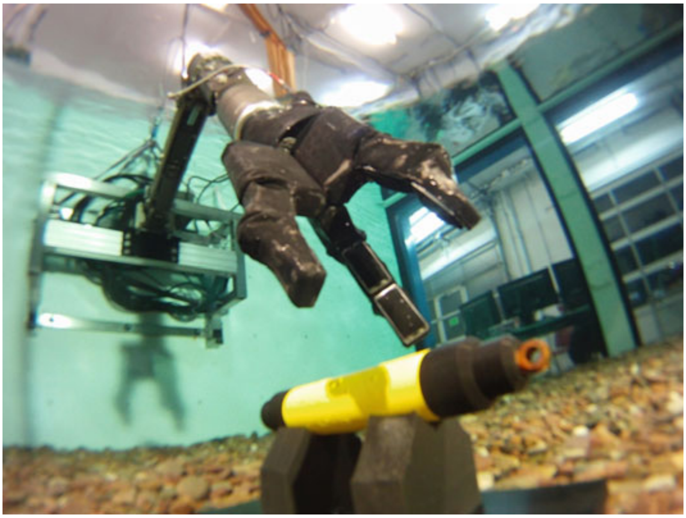

Fig. 8 A standard industry grade manipulator arm from Shilling Robotics, USA reprogrammed and fitted with tactile grippers and cameras during an autonomous object recognition and gripping task

- Intelligent Manipulation
  - Systems to exchange components in an underwater production facility, Closing Connectors, Plugging Operation etc.
  - modular Dual-Arm manipulation systems
  - Intelligent Handling/Exchange systems/-processes
- Intelligent Mobility
  - Minimal invasive Operations
  - Locomotion concepts: Walking, reconfiguration
  - Semi-autonomous platform for handling heavy loads
  - Movement (sea state) compensation at surface.
- Awareness: Intelligent perception
  - Mobile sensor carrier and planning components
  - Combination of acoustic and visual sensor information to enhance navigation capabilities
  - Physically (as) correct (as possible) Simulation of underwater environments
- Human Centered AI
  - AI-based Exploration Planning
  - AI-based Management-system for multi system–production sites
  - Multi-modal Man-Robot Interaction.

Underwater Environment will Help to Improve AI and Robotics

As has been pointed out in the previous paragraph, it is obvious that AI and Robotic technology can improve underwater system performance in a variety of ways and thereby help to design solutions to applications from maritime science to offshore energy production and marine agriculture. The consequences of applying these new technologies in the underwater environment will also allow us to exploit the resources of the oceans in a sustainable way and to save this resource for future generations.

However, maritime research and industry are much more connected with the developments in AI and robotics than it seems at a first glance: the specific challenges of technology in underwater environments impose the tackling of many crucial challenges in the AI and robotics community, as will be outlined in the following.

In the first column, Table 1 shows a list of tasks and challenges that underwater robotic systems must be able to solve in order to be usable for underwater application. In the second column, the table shows the hurdles that the underwater environment presents to the designer of new technologies. As is pointed out by the list in the first column, actually every aspect of technology development is touched: From the design and construction of the physical structure of the system that has to withstand pressures that are so gigantic that they will smash each piece of hardware that tries to withstand it, to its means of mobility in a dense medium that exerts forces on the system that will be difficult or in the worst case impossible to withstand. Also, the way the system is able to perceive the environment via vision, which presents a powerful sensor in terrestrial applications, is severely crippled as the environment provides noise and obstruction in a way hardly known to terrestrial systems. Wireless communication underwater is largely a no-go and navigation techniques have no means of global references which all together increases the need for autonomy to a level that is normally not required in terrestrial or even space applications.

Table 1 Challenges for AI Technology in underwater environments

Technology	Challenge
Design and construction	Extreme pressure (Inflation, Oil compensation)
Mobility	Buoyancy, drag, current
Vision (Sensor input, Image processing)	Sediments, maritime snow, distortion, darkness
Communication (wireless)	Narrow bandwidth to none
Navigation	No global navigation system, acoustic, vision
Control	Semi-autonomous or autonomous