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Challenges and Future Trends in Marine Robotics

Enrica Zereik[a], Marco Bibuli[a], Nikola Miskovic[b], Pere Ridao[c], Antonio Pascoal[d]

[a]*CNR - Institute of Marine Engineering, Via De Marini 6, 16149 Genova (Italy)*
[b]*University of Zagreb, Faculty of Electrical Engineering and Computing, Unska 3, 10000 Zagreb (Croatia)*
[c]*University of Girona, 17071 Girona (Spain)*
[d]*Laboratory of Robotics and Engineering Systems / Institute for Systems and Robotics, Instituto Superior Tecnico, Univ. Lisbon, Av. Rovisco Pais, 1 -Torre Norte, 1049-001 Lisboa (Portugal)*

Abstract

Spawned by fast paced progress in marine science and technology, the past two decades have witnessed growing interest in ocean exploration and exploitation for scientific and commercial purposes, the development of technological products for the maritime and offshore industries, and a host of other activities in which the marine environment takes center stage. In this context, marine robotics has steadily emerged as a key enabling technology for the execution of increasingly complex and challenging missions at sea. Intensive research and development in this field have led to major advances and shown unequivocally the effectiveness and reliability of marine robotics solutions in several domains. This progress goes hand in hand with the availability of increasingly sophisticated acoustic networks for multiple, cooperative missions involving surface and underwater robots. At the root of this trend is the fruitful dialogue between robotic systems developers and end-users with the capacity to convert general mission objectives into functional and technical specifications that serve as application-driven requirements for engineering development. The result is the tremendous progress observed in the consolidated methodologies and procedures adopted and the consequent impact on science, industry, and the society at large. In spite of the progress in the area, however many challenges must still be faced and novel applications will continue to set further requirements for future generations of marine robots and their enabling systems. The time is therefore appropriate to overview recent trends in the field of marine robotics and assess their impact on several important application domains. With these objectives in mind, in the present paper we highlight key technological achievements in the field, analyze some of the shortcomings encountered, and indicate specific issues that warrant further research and development effort. To this end, we review a number of highly representative projects in the field, with due account for the theoretical frameworks upon which technological developments build upon. Finally, the paper concludes with an outlook on the future of marine robotics, both from a theoretical and practical standpoint, and describes recently initiated projects that hold promise for the development of advanced tools and systems for ocean exploration and exploitation.

Keywords: marine robotics, field applications, future trends

1. Introduction

The marine environment represents a challenging framework for the exploitation of cutting-edge automation-related methodologies and technologies. The oceans cover more than 70% of the earth's surface and support an estimated 90% of the life forms on our planet. They constitute one of the main resources for food, employment, and economic revenue, and are a potential source of still unknown living and mineral resources, as well as alternative and sustainable energies. From a scientific point of view, the deep ocean is thought to hold the secret to the origin of life. At the same time, the oceans also harbor a vast cultural heritage in the forms of archaeological sites yet to be explored. However, the oceans remain largely unknown, with two thirds of them remaining still unexplored. This is especially true in the case of the deep ocean: deep, dark, vast, and subject to tremendous bar pressure, the bottom of the oceans is the largest component of the surface of our planet and yet it is also the least known.

Clearly, much work remains to be done to have a synoptic view of the open sea and the deep oceans over extended areas of interest and to exploit the resources available in a sustainable manner. This will require the development of new methods and tools for ocean exploration and exploitation and the reinforcement of strong cooperative links among universities, research institutes, companies, and stakeholders worldwide to meet this goal.

In line with the above trend, there is currently worldwide interest in the development of new tools to support the exploration, observation, sampling, and persistent monitoring of the marine environment.The types of operations required are difficult to be accomplished solely through sheer human effort. Thus the quest for the use of advanced technological tools such as remotely operated vehicles and fully autonomous robots to improve the capability to enhance the human knowledge on such a wide and mysterious environment.

Maritime and naval applications such as ship monitoring and maintenance, emergency operation support, offshore inspections and other related activities can also benefit from scientific and technological improvements on advanced technologies for ocean exploration.

As in the case of space exploration, the ocean environment places formidable challenges to the development of autonomous and/or persistent systems for exploration and sampling. In fact, engineers and scientists must strive to meet the extremely tight design constraints imposed by the harsh conditions that both surface and underwater platforms have to face. Among these, the following are worth stressing:

1. high pressures and low temperatures related to extremely deep or harsh environments (e.g., abyssala and polar areas) require suitable components and water-tight containers and equipment.
2. underwater communications mandate the use of acoustic devices that in challenging operational scenarios are plagued with intermittent communication losses and multi-path effects and exhibit reduced bandwidth and low reliability,
3. long range missions require that the vehicles be equipped with proper power supply systems (also relying on alternative technologies such as fuel cells, biological batteries, solar panels, etc.) and efficient energy management systems.

The use of autonomous vehicles requires also the design and implementation of advanced guidance, navigation, motion control, and mission control systems, together with acoustics-based communication networks in order to afford vehicles acting in isolation or in a group the high level of reliability required to accomplish complex missions. Marine system development embraces many theoretical and practical issues that include dynamical systems theory, automatic control, networked systems, identification and estimation, computer vision, communications, and sensing and measurements, to name but a few.

This strong inter-disciplinarity underpins the importance of fostering interest in the topics related to the marine and maritime fields, as well as the importance of encouraging scientists and engineers with different backgrounds to connect, exchange ideas, and define possible avenues for joint research and development work.

As a contribution to bringing attention to many of the above topics, in this paper we overview recent trends in the field of marine robotics and assess their impact on several important application domains. We highlight key technological achievements in the field, analyze some of the shortcomings encountered, and indicate specific issues that warrant further research and development effort. In the process, we review a number of highly representative projects in the field and establish connections with theoretical frameworks upon which technological developments build upon. We also provide an outlook on the future of marine robotics, both from a theoretical and practical standpoint, and describe recently initiated projects that hold promise for the development of advanced tools and systems for ocean exploration and exploitation.

The paper is organized as follows: Section 2 contains a brief description of the most important domains in marine robotics. The state of the art in the field is analysed in Section 3 through an extensive overview of some of the most influential projects. Section 4 summarizes some still open challenges and a number of primary emerging trends for future developments in marine robotics. Finally, Section 6 contains the main conclusions.

2. Domain Overview

Marine robotics encompasses an extremely wide range of topics that are usually defined as application domains. In each domain, autonomous marine systems play a key-role in the achievement of specific challenging scientific, commercial, and societal goals. The latter can only be met through committed research and development work leading to cutting-edge methodologies and technologies that are steadily affording marine robots the capability to address increasing complex problems. A brief introduction to the main application domains and related challenges are reported next with a view to giving a broad vision of the broad scope of marine robot applications.

2.1. Scientific

Since its very first achievements, involving demonstrations in the field, robotics has been viewed as an extremely promising field with tremendous potential for the development of advanced systems capable of affording scientists the means to monitor the ocean and its living and non-living resource at unprecedented temporal and spatial scales. Tasks such as water sampling, monitoring and exploration are extremely simplified by the exploitation of robotic teams of heterogeneous and complementary agents, implying also great improvements in results with less effort in terms of time and human resources and being able to obtain better performance in terms of accuracy on gathered data. The trend observed over the last few years consists of relying on teams of cooperative robots, all of which can perform specific and specialized tasks to achieve an overall common goal; several approaches have been proposed in literature to guide the team and allow it to achieve the requested goals, from simpler formation control with preassigned tasks, to cognitive-based reconfiguration and adaptive behavior with on-line optimization of task distribution according to varying conditions (both of the environment dynamics and of the robotic system itself, which could have to deal with failures, robot re-configuration, as well as changes in mission goals). These systems can be employed with the same effectiveness to fulfill different scientific goals: from water quality monitoring to geophysical and geo-technical surveys, from oceanography and biology-guided missions (such as deep ocean research to identify new marine species and to better characterize their behaviours) to the evaluation and demonstration of bio-inspired systems to enhance the prevalence and the productivity of robotic platforms in everyday life.

2.2. Industrial

During the last decades the Unmanned Underwater Vehicles (UUVs) have been routinely used for inspection and intervention tasks. ROVs are currently the work-horse being routinely used for inspections of harbors, dams, ships, and submerged infrastructures. Definitively, when the task involves the use on Underwater Vehicle Manipulation Systems (UVMS), teleoperated system are the unique alternative available in the market. Nowadays AUVs have become an excellent tool for seafloor mapping using cameras [1] and/or sonar [2]. AUVS have been used for dam inspection [3], marine geology [4] and deep water archeology [5] within other applications. However, commercial of the shelf AUVs are only able follow trajectories at a certain depth or at a fixed altitude from the bottom. Although inspections AUVs are now used routinely for pipe/cable inspection, they are not able to operate in areas with strong 3D relief. Field operations for intervention in offshore infrastructures, as well as for 3D inspections are still done using ROVs. In the next sections we explore the recent research done in these areas to overcome this situation.

2.3. Transport

In a world characterized by an automation level which increases at fast pace, transportation means and infrastructures are also subjected to innovation. The concept of shipping itself is rapidly changing, moving the consolidated commercial traffic that we experience everyday towards a twofold disruptive approach, having on one side the unmanned ship as a goal and, on the other hand, the employment of autonomous marine agents extending the capabilities of the ship (in terms of perception of the environment, remote observation, self-maintenance). In recent years a number of projects has been proposed with the aim of firstly evaluate the major issues and current technological limitations towards the employment of self-navigating autonomous ships, such as the MUNIN project [6]. Being not currently possible to experimental test autonomous navigation for real ships in large scenarios, the activity has focused developing suitable and reliable infrastructures aiming at trials at least confined in constrained and controlled areas.
As previously specified, autonomous shipping does not focus only on self-navigation of the ship itself, but the concept embraces the extension of common operations through the exploitation of (cooperative) autonomous agents capable of

extending the operational range of the ship, allowing wide-range sensing (to enlarge the knowledge of the surrounding environment), outboard interaction (exploration and intervention in the operating scenario), self-maintenance (with autonomous agents operating within the ship).

2.4. Human Interaction

Although the already high level of autonomy reached by current marine robotic platforms, there is still an impressive number of scenarios and applications that requires the skills and adaptation capabilities towards unpredictable conditions that only expert human operators can provide. Application scenarios such as ship or offshore structure maintenance, biological habitat protection or archaeological site assessment require a number of operations (which depend on the current conditions and occurrences) that make unfeasible the exploitation of autonomous platforms, given the huge number of variables and situations to be taken into account by a pre-programmed agent. Anyway, the need of human presence in the operational scenario does not exclude the exploitation of robotic agents which can act as support platforms for the actions carried out by human operators. In this view, autonomous agents capable of guiding the operators in the environment (that can be characterized by low visibility, underwater sea currents, etc.), as well as carrying out tedious or dangerous tasks, provide an added value thanks to the gained efficiency and cost-effectiveness of the operations. Furthermore, the autonomous capability of monitoring the execution of the human operations can turn into a dramatic enhancement towards safety improvement, giving the chance to provide support and aid before accident occurrences.

On the other hand, mixed teams of human and robotic agents can cooperate with greater effectiveness within emergency situations as in a search and rescue context, as well as within scientific missions in harsh environments, as in Polar expeditions.

Moreover, heterogeneous multi-agent systems can be exploited in both professional (e.g. archaeological) and recreational scenarios; in the specific cases robotic platforms can relieve divers from difficult, tricky or dangerous tasks, as well as monitor their health condition (e.g. preventing accidents by detecting early stage signs of panic or of nitrogen narcosis) and guide them through their overall mission, being able to issue a prompt alarm whenever required.

3. Relevant Projects

Following the application domain classification, a number of relevant projects related to each domain are briefly described next. In the process, we highlight their innovative features aimed at improving single and multiple vehicle systems performance, reducing costs, and enhancing operational safety.

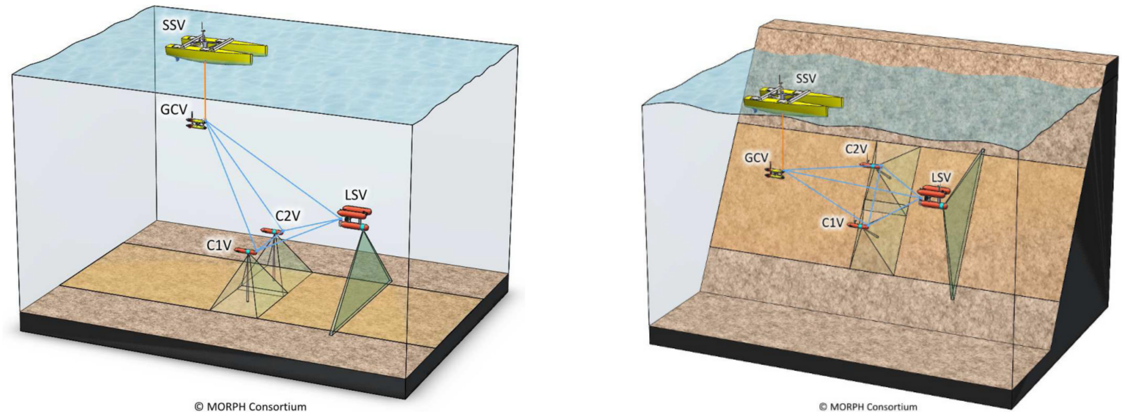
3.1. Scientific

As suggested above, the applications in the scientific domain are multi-purpose and the methodologies and technologies used can often be adapted to meet different requirements. Some broad categories, each one including several different yet comparable projects, can be identified.

The first one includes research activities aimed at exploration and mapping the marine environment with different goals in mind: for instance, the *MORPH* project [7], [8] was devoted to the development of an effective underwater autonomous robotic system composed by many heterogeneous nodes to carry out different tasks such as seabed mapping and species (e.g. coral reefs) monitoring, oil & gas inspection, as well as harbour protection. Similar objectives were pursued by the *ROBUST* [9] and *WiMUST* [10], [11], [12] projects, focused respectively on cooperative robots equipped with distributed acoustic devices for geophysical survey devoted to exploitation and geo-technical applications, and on vast terrain mapping through robotic technology for mineral and raw material detection and exploitation. Geological and mineralogical information gathering was also the main goal of the *UNEXMIN* project [13], [14], employing robotic systems for the autonomous exploration and mapping of European flooded mines. The concept of responsible exploitation of the marine environment, assuring its long-term preservation through a cost-effective ocean glider, was addressed in the *BRIDGES* project [15]. Much effort has been (and still is) devoted to the increasing of robotic capacity of operating in a real-world scenario without requesting (or minimizing such requests) help from humans: the *PANDORA* project [16], [17] aimed at developing and evaluate smart computational methods to make robots persistently autonomous, where as the *NOPTILUS* project [18] faced the execution of real-life complex

situation-awareness operations. Robotic technology has been widely used also to deploy and retrieve data-gathering sensors and equipment, as in the *AUTODROP* project, where a dedicated new-concept UUV [19] has been developed, or in the *DIGITAL OCEAN* project [20], aiming at discovering the ocean depth and making it interactive through robotics, 3D imagery and mixed reality.
A second category is made up of projects relative to environmental and infrastructure monitoring, in which different aspects are considered and different goals are pursued. In particular, the development of suitable technological platforms for water quality monitoring were addressed by *HYDRONET* [21], which employed small-scale robots and an ambient intelligence framework. The *SHOAL* project [22] aimed at introducing a bio-mimetic concept into environmental monitoring procedure, in particular exploiting a robotic fish swarm to search for contaminants and pollutants. Multi-robot systems were also employed in the pioneering *Co3AUVs* project [23], dealing with both monitoring of critical underwater infrastructures and interaction with humans during commercial and scientific dives. Underwater and surface vessels for maritime and offshore operations are employed also by the very recent *SWARMs* project [24], particularly focusing on seabed mapping, pollution monitoring and plume detection & tracking.
Very important initiatives are represented by infrastructures and networks created with the main purpose to allow collaborative networking among marine stations, institutions, researchers and all personnel involved in ocean and marine related activities. For instance, both the *Autonomous Ocean Sampling Network (AOSN)* [25] and the *AOSN II* [26] fuse realistic ocean models with advanced robotics and sensor systems to observe and better predict ocean behaviours. Similar objectives are pursued by the MARS Network [27], representing the European version of AOSN, and fostering collaboration among European marine stations on basic research and environmental issues. A family of networks and research infrastructures particularly devoted to climate change monitoring and effects (that is one of the main societal challenges, with very high priority, devised by the European scientific community) has been established. Many governments of the world signed an agreement to form the *Global Earth Observation System of Systems (GEOSS)* [28], while in Europe the *Copernicus* [29] network arose, being dedicated to global monitoring of environment and security. GEOSS and Copernicus are in charge of providing measurements suitable to predict the influence of global change on weather, climate, water, energy, health and disasters. The components of GEOSS that are oriented to climate and ocean are *Global Climate Observing System (GCOS)* [30], *Global Ocean Observing System (GOOS)* [31] and the European declination of GOOS, *EuroGOOS* [32]. All these networks and infrastructures are sustained by international initiatives such as the *Argo programme* [33], which was started as a pilot project on climate and which now boasts an array of more than 3500 instruments that are deployed over the world ocean and that can gather data about subsurface ocean properties. The European contribution to such equipped structure is offered by *Euro-Argo* [34], dealing with European interests such as high latitudes, bio-geochemical measures and depths greater than 2000 m.

Over the last years, great efforts were invested in enhancing training of early–stage researchers in the area of marine robotics, as well as consolidating available research infrastructures in order to bring it closer to the wide scientific community.
One of the early examples is European training network FREESUBNET that had the main objective of providing European–wide excellence in quality training to young and experienced researchers in the field of cooperative autonomous intervention underwater vehicles, [35]. The main result was the succesful training of a number of researchers who created a cohesive mass of capability within the European Union in the area of autonomous underwater vehicle development. As a following step, the Marine UAS European innovative training network was formed, [36]. This EU–funded doctoral program had a high impact on the training of individual researchers and their knowledge, skills and their future careers in the area of on autonomous unmanned aerial systems for marine and coastal monitoring. With the increasing need to perform scientific and economic exploration of the ocean, an innovative training network Robocademy [37] funded by the European Commission through the FP7 Marie Curie Programme was formed with the goal to establish a network of European competence centers in sub-sea robotics, to form experts in sub-sea robotics, and to develop advanced robotic technologies needed for the exploration of the oceans, [38].
As the need of extending the know–how in the area of marine robotics increased over time, two projects were initiated by the European Commission with the objective of additionally enhancing scientific and technology capacity of marine robotics research centres in Croatia and Portugal, through twinning projects EXCELLABUST [39] and STRONGMAR [40].
Bringing together the European research fleets owners to enhance their coordination and promote the cost–effective use of their facilities was successfully conducted as part of EUROFLEETS and EUROFLEETS 2 infrastructure



(a) flat terrain (b) cliff with 60° slope

Figure 1: MORPH 3D environment mapping using a multiple vehicle formation.

projects [41], while EUMarineRobots [42], an access infrastructure, was very recently established, to include aerial, surface and subsurface marine robots thus representing a big potential for R&D in marine robotics across Europe. The extremely huge effort needed to set up such comprehensive networks and research infrastructures should underline the importance of a worldwide spread collaboration among all the actors involved in climate, ocean and emerging related topics.

3.1.1. MORPH project

The key objective of the MORPH project was to develop efficient methods and tools to map the underwater environment in situations that are not easily addressed by current technology. Namely, missions that involve underwater surveying and marine habitat mapping of rugged terrain and structures with full 3D complexity, including vertical cliffs. As explained in [8], potential applications include the "study of cold water coral reef communities, ecosystems in underwater canyons, pipeline and harbor monitoring, or the inspection of offshore wind and wave energy harvesting infrastructures". The project advanced the novel concept of an underwater robotic system consisting of a number of mobile robot modules (nodes), carrying complementary sensors suites for environment perception. Instead of being physically coupled, the modules are connected via communication links that allow for the flow of information among them. Without rigid links, the so-called MORPH Supra-Vehicle can reconfigure itself and adapt to the environment and mission goals, in reaction for example to terrain shape and the presence of nearly vertical cliffs. This flexibility is instrumental to enable optimal positioning of each sensor, increased number of simultaneous viewpoints, and high-resolution data collection in an effective manner."
The research and development work undertaken in the scope of MORPH led naturally to systems that were instrumental in reaching a landmark in September 2014 in the Azores sea, Portugal. Here, for the first time, five autonomous marine robots from distinct partners, equipped with advanced systems for cooperative motion programming, control, and navigation performed a series of missions that illustrated the concerted operation of the so-called upper and lower segments of the MORPH supra-vehicles, see the illustrations in Figure 1. In this set-up, one autonomous surface vehicle labeled SSV played the role of master vehicle and acted as a reference to be tracked by two underwater vehicles, labeled GCV and LSV, playing the role of anchors (upper segment). The latter, in turn, served as a moving baseline to guide the motion of two underwater vehicles (equipped with cameras), named C1V and C2V, moving close to the seabed and establishing a desired geometric formation with the anchors by measuring their ranges to the latter (lower segment). The set-up adopted allowed for geo-referencing of the data acquired by the two camera vehicles.

3.1.2. ROBUST project

ROBUST aimed at exploiting cost-effective and reliable technology to be devoted to vast terrain mapping, to assess the presence of minerals and raw material. Currently such exploration is usually performed by ROVs and crew members; ROBUST project proposed to employ a laser-based technology to analyze terrain merged with a robotic

AUV performing seabed 3D mapping. The final objective consisted in locate mineral deposits underwater and to position suitable instruments completing qualitative as well as quantitative surveys.

3.1.3. WiMUST project

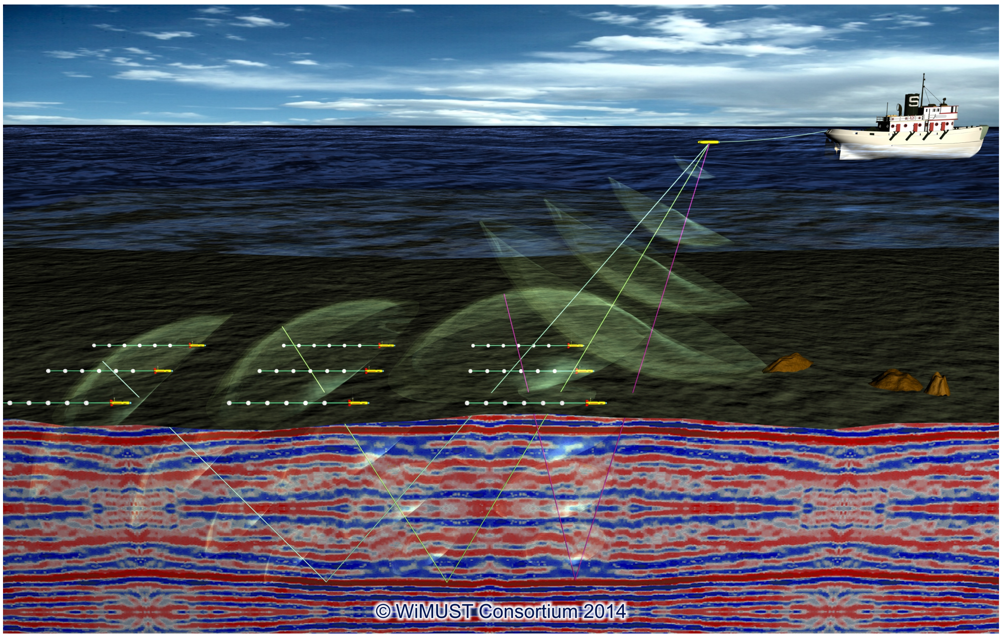


Figure 2: The WiMUST concept: cooperative autonomous marine robots for geotechnical surveys.

The WiMUST (Widely scalable Mobile Underwater Sonar Technology) project aimed at ”expanding and improving the functionalities of current cooperative marine robotic systems, effectively enabling distributed acoustic array technologies for geophysical surveying with a view to exploration and geotechnical applications” [10], [11], [12]. The rational for the project stemmed from the realization that there is vast potential for groups of marine robots acting in cooperation, sharing data over an underwater acoustic network, to drastically improve the methods available for ocean exploration and exploitation. Traditionally, seismic refection surveys are performed using vessels that tow streamers equipped with hydrophones and acquire acoustic signals that originate in one or more acoustic sources (towed or installed onboard the support vessel) and are reflected and refracted by the seafloor and the subbottom. Processing of the data acquired allow for proper identification of conspicuous features with geological relevance. In this context, geotechnical surveying for civil and commercial applications (e.g., underwater construction, infrastructure monitoring, mapping for natural hazard assessment, environmental mapping, etc.) aims at sea floor and sub-bottom characterization using towed streamers of fixed lengths that are extremely cumbersome to operate because they are connected to a support vessel. In other words, acoustic sources and receivers are coupled. The major achievement of WiMUST was to physically separate the sources and streamers: the first were installed on two autonomous surface robots while the latter, with a maximumm length of 6 m, were towed by a group of 5 autonomous vehicles (of which 4 underwater). Advanced cooperative control / navigation systems enabled by an acoustic communication and positioning network enabled the marine robots (both at the surface and submerged) to interact by sharing information and maneuver in a desired, possibly time-varying formation while acquiring geotechnical data. In this respect, the global WiMUST system may be viewed as the combination of acoustic sources and an adaptive variable geometry acoustic array. The final tests in Sines, Portugal in January 2018 demonstrated the efficacy of the system in acquiring geotechnical data in a completely autonomous manner.

3.1.4. UNEXMIN project

Mineralogical data is sought also in the UNEXMIN project, aiming at achieve valuable surveys on the status of European flooded mines, through the employment of an autonomous robotic explorer with 3D mapping capabilities.

Information coming from these exploration activities can be strategically exploited for making decision on the re-opening of abandoned mines: actualized data is difficult to be obtained with other methodologies. Hence, the idea to perform surveys with robotic technology, that in the last years experienced big progress in autonomy research; in spite of this last fact, many challenges are still to be faced, particularly concerning platform miniaturization and suitability to operate at big depth, as well as the capability to effectively interpret geoscientific data.

3.1.5. BRIDGES project

Responsible exploitation, monitoring capability enhancing and further understanding of the marine environment are fundamental steps towards the long-term preservation of our oceans. The main goal of the BRIDGES project has been identified in the development of glider technology to allow long-term autonomous exploration at high depths, involving vast areas and high frequency of survey. Different domains can benefit from such technology: from the oil & gas industry, to the deep sea mining industry and the environmental monitoring activity (foreseen by the Marine Strategy Framework Directive) to allow for a smart and adequate eco-system management plan. Hence the system should be endowed with the essential abilities to execute unmanned underwater operations, to work in the deep ocean, and to assess the environmental impact of the maritime economy.

3.1.6. NOPTILUS project

NOPTILUS tackled the problems related to the still not achieved full autonomy of marine robots: currently multi-vehicle systems are employed in many applications but they still lack an actual and effective capability to take over human operators in real-world complex activities that require situation-awareness. Such cases need advanced reasoning and decision-making: that's why, usually, human operators are integrated in the loop. Anyway, their involvement does not necessarily assure good performance: they can be overwhelmed with too much information, their performance can be degraded by fatigue, they can very hardly achieve a proper vehicle coordination, and they cannot guarantee operation continuity. In order to be able to remove the human operator from the control loop and, at the same time, achieve a suitable autonomous behaviour for the system, advancements in many robotics abilities have to be pursued: perception and learning motion control, cognitive-based situation understanding, cooperative and cognitive communications, smart motion strategies. When deploying such a system in a realistic environment, great effort has to be concentrated in robustness, dependability, adaptability and flexibility, especially to be able to deal with unknown complex underwater environments and situations that have not been taught or considered before.

3.1.7. AUTODROP project

A specific attention on the development of an improved methodology to accurately and cost-efficiently deploy and retrieve seabed sensors and equipment was shown by AUTODROP. In particular, the employment of an *ad hoc* developed UUV was planned. Technicalities about the hydrodynamic design, navigation capability (also to assure a gentle landing of the sensors) and the possibility to change buoyancy properties (thus allowing the equipment retrieval) were addressed and implemented during the project. The correct retrieval of previously deployed equipment was supported by a service vessel, receiving the GPS coordinates of the AUTODROP UUV.

3.1.8. DIGITAL OCEAN project

Robotic technology and devices were also exploited, in the DIGITAL OCEAN project, to improve discovery of the ocean, not only from its surface, but through all its depths and in real-time, making a virtual diving in real time possible. The employed smart robots collected underwater digital data to generate undersea scenes in 3D interactive imagery and these preprocessed background productions are then merged through mixed reality, and diffused on-line. Such technological application offer to all people the possibility to freely virtually roam in the ocean realm.

3.1.9. HYDRONET project

Fair exploitation, protection and preservation of the waters were the main topics addressed by HYDRONET. The project aimed at employing a network of small-scale robots embedded in an Ambient Intelligence framework to devise and implement new strategies and technologies for the assessment and improvement of water quality (in terms of chemical and ecological status). Exploitation of mathematical models describing the pollutants transport in water bodies, as well as knowledge discovery processes aiming at extracting and increasing knowledge on water management, enhanced the integrated response of the system.

3.1.10. SHOAL project

Environmental monitoring was the main purpose also of the SHOAL project, which planned to employ biomimetic approaches to the problem: a shoal of robotic fishes is devoted to the analysis and real-time mapping of the presence in water of contaminants and pollutants. Group coordination and swarm intelligence strategies were applied to allow the multi-agent system to be adaptive with respect to environmental changes. The capability of search for pollutants both on the surface and underwater (discovering dissolved chemicals in the water) was studied and implemented for the developed fish robots, to be able to react to several sources of contamination (underwater leaks from vessel submerged hull or from underwater pipelines).

3.1.11. SWARMs project

Offshore activity was addressed by the SWARMs project: current operations are mainly executed by divers performing dangerous missions. Since their possibility to work is limited, the offshore industry is highly compromised. A solution to this problem is represented by the exploitation of AUVs and ROVs, but their deployment is usually very expensive due to the difficulties and specific skills required to operate them, as well as their characteristic of being tailored for specific tasks. Hence, SWARMs planned to extend the access to AUVs and ROVs to more users through: i) assuring re-usability by enabling such systems to cooperatively work, combining capabilities of heterogeneous non-specialized vehicles; and ii) increasing autonomy for AUVs and usability for ROVs. Positive outcomes of such new operating modes can be applied to different scenarios, among which: offshore infrastructure inspection, maintenance and repair; pollution monitoring; offshore construction activities.

3.2. Industrial - Autonomous Intervention

Intervention operations require the use of Underwater Vehicle Manipulator Systems. While Commercial of the Shelf (COTS) work class ROVs are used routinely by the Oil & gas industry, researchers are making an effort to develop the I-AUV (Intervention AUV), the Autonomous counterpart of the work class ROV. Figure 3 shows the evolution of this research field. Pioneering works include 1 DOF I-AUV developments like the MBARI OTTER vehicle[43] and the ODIN [44]. More challenging was the UNION EU project [45] which was the first attempt to operate autonomously a vehicle equipped with a 7 DOF arm. At this point the technology of electrically driven underwater arms was not yet ready. The first robust 7 DOF electrical robot arm was developed in the AMADEUS EU project [46] where a robust 6DOF electrically driven robot was developed. The arm, initially used for cooperative object manipulation fixed in an structure of an underwater work-cell, was later on integrated in the SAUVIM I-AUV [47]. The first autonomous intervention demonstration arrived in 2003, in the context of a milestone EU project, ALIVE [48]. The project, lead by Cybernetix, finalized with a demonstration where the I-AUV homed and docked to a subsea intervention panel to perform a valve turning task (fixed base manipulation). The first free floating intervention was done in the context of another milestone project, SAUVIM [47]. In this case, the robot navigated to a target area identified using a DIDSON imaging sonar, where the robot used the camera to identify a simple target easily identifiable using computer vision. SAUVIM used a 7 DOF to grasp the object while floating (Free-floating manipulation). Two years later, a significantly lighter I-AUV was designed and developed at the university of Girona [49], the GIRONA 500. It was the result of the Spanish project RAUVI, [50], where a 4 DOF electrically driven robot arm was mounted on the GIRONA 500 AUV conforming and I-AUV of less than 200 Kg, 1 order of magnitude less than SAUVIM and ALIVE. The project demonstrated free-floating object recovery, using visual-servoing while doing station keeping. The concept was extended later on in a wider European project named TRIDENT [51, 52]. In this case a 7 DOF robot arm equipped with a 3 finger robot hand were mounted on GIRONA 500 [53]. TRIDENT used a multipurpose manipulation strategy in two steps. First the I-AUV performed an optical survey of the area of interest building a photo-mosaic. Next, an user selected a target object and the robot was send to recover it autonomously. Subsea panel intervention while docked was later on reproduced in the TRITON Spanish project [54] , where a visual-servoing based method for docking was employed. Besides turning a valve, it was also demonstrated how to autonomously plug and unplug a connector using fixed-base manipulation. Valve turning in free flotation was first demonstrated in [55] using learning by demonstration techniques, and later on in [56] using the task priority approach, and later on in [57] using real time path planning techniques to deal with fixed virtual fixed obstacles. The last work also demonstrated free-floating connector plugging and unplugging. Dual arm manipulation using a fixed base underwater work-cell was early demonstrated in [58] using the AMADEUS arm. An ongoing project involving

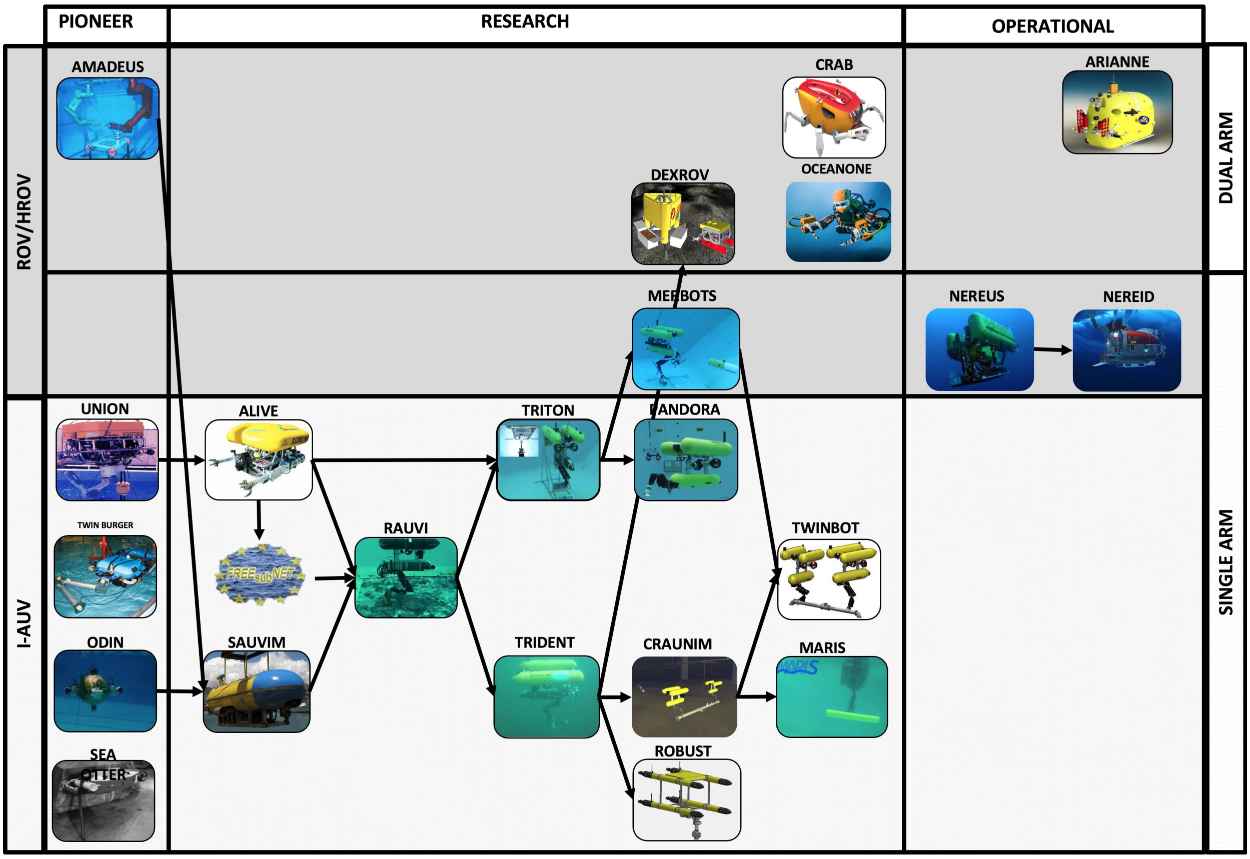


Figure 3: Evolution of Autonomous Intervention Projects

the implementation of a dual arm system is DEXROV [59], where a satellite based teleoperation of an intervention ROV in presence of significant time delays is targeted. In a different line, recent projects related to Underwater Vehicle Manipulator Systems (UVMS) included the design and development of bio-mimetic designs. One example is the CRABSTER UVMS [60] which is a legged underwater robot whose two frontal legs can be used for bi-manual manipulation. Another interesting project is the Ocean One [61] where a humanoid robotic avatar is used for ocean exploration and intervention. In [62], a bio-mimetic long-fin propulsion system is used to control an I-AUV equipped with a 4 DOF arm.

Recently, projects like ROBUST are proposing the use of I-AUVs for field applications , like deep mining [63] . This, together with the recent apparition on the scientific HROV systems [64, 65], which from the hardware point of view are equivalent to I-AUVs, is expected to foster new field application in the near future.

3.2.1. ALIVE project

ALIVE is an open frame AUV equipped with a 7 DOF hydraulic manipulator and 2 hydraulic grasps used for docking the vehicle to the bars of a subsea panel. The vehicle weights 3.5 Ton and can be deployed from a non DP vessel. It features acoustic based homing capabilities and vision based docking. Once docked, the system becomes fixed-base manipulation system, simplifying the problem since there is no join control of the vehicle and the manipulator. ALIVE represents what could be the evolution of the current work class ROV.

3.2.2. SAUVIM project

SAUVIM was a project funded by the Office of Naval Research in the USA. The project was developed at the University of Hawaii. While ALIVE targeted subsea panel intervention with fixed base manipulation approach, SAUVIM goal was object recovery in free flotation. The main concept of SAUVIM was the use of a low mass arm (65 kg)

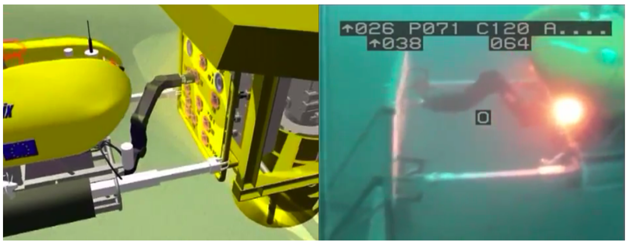


Figure 4: ALIVE project, particular of AUV operations

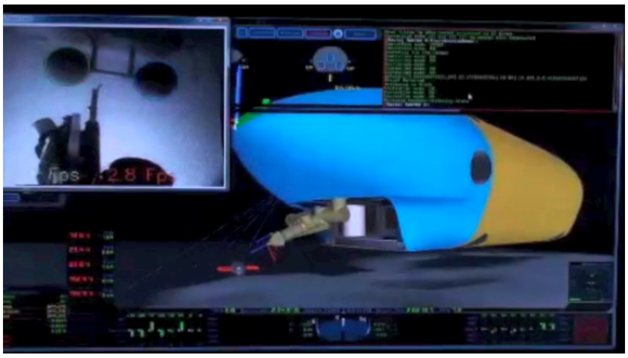


Figure 5: SAUVIM project, test campaign

mounted on a large mass AUV (6 Ton) to avoid arm to base perturbations, making possible the use of uncoupled controllers for the AUV and the arm. SAUVIM was the first project to demonstrate autonomous object recovery in a complex experiment including the use of an multibeam imaging sonar to detect the target area and a camera with a simple visual servoing system to detect the target. Manipulation was carried out in station keeping using the robot arm.

3.2.3. TRIDENT project

The TRIDENT concept (Figure 6) is base on a 2 step methodology to achieve multipurpose intervention capabilities. During the first phase, and ASC and an AUV work in tandem. The AUV performs an optical survey of the seafloor, while the ASC performs as a navigation and communication gateway. When this phase is completed, the AUV is recovered and a photomosaic of the seafloor is built. Next, the user specifies an object in the map to be recovered and the I-AUV is send for recovery. Since the object pose is now know, the robot navigates to the target position. When the object appears in the field of view of the camera, the object is identified and tracked. Next, a grasp planer selects the best grasping and a task priority framework is used to jointly control the AUV and the arm to complete the grasping.

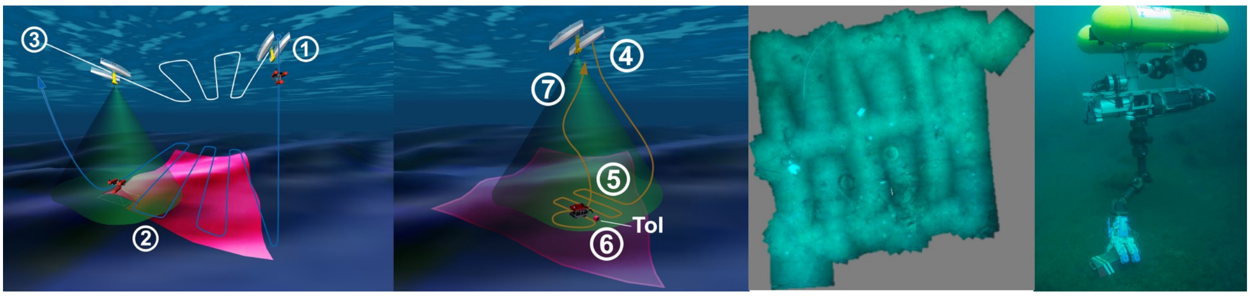


Figure 6: TRIDENT concept: (From left to right) Survey Phase Concept; Intervention Phase Concept; Seafloor P TRIDENT I-AUV

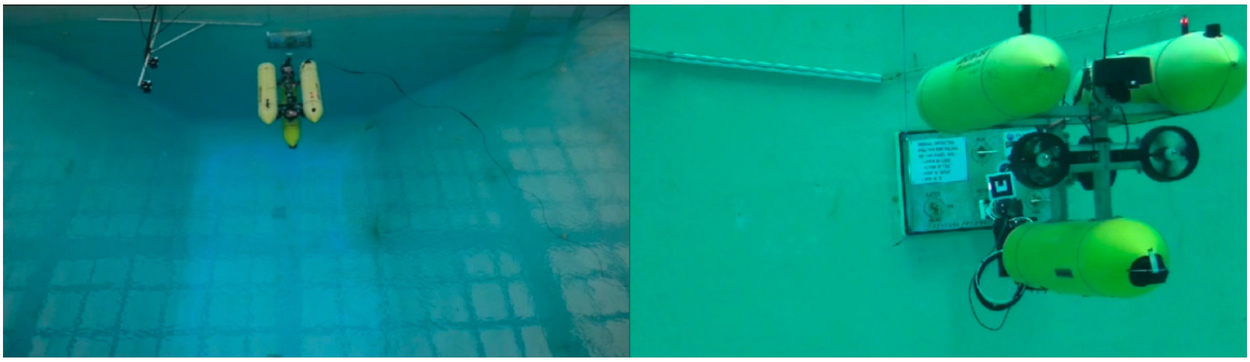


Figure 7: PANDORA project, particular of an intervention mission

3.2.4. PANDORA project

This project aimed at developing technologies to achieve persistent autonomy. Three themes were targeted: (1) describing the world for detecting failures in the task execution; (2) directing and adapting intentions by means of planning for responding to failures; and (3) acting robustly mixing learning and robust control for making actions indifferent to perturbations and uncertainty. The project tackled scenarios related to the Oil & Gas Industry including riser and mooring chain inspection and valve turning. PANDORA developed methods to: 1) control an I-AUV using learning by demonstration; 2) Task planning and dispatch using PDDL[1] integrated with the AUV control architecture, 3) Fault detection and restoring. The project demonstrated (Figure 7) a 3 hours autonomous intervention mission turning valves in a water tank including perturbation currents, blocked valves and panel occlusions achieving a 80 % success rate.

3.2.5. OCEAN ONE

OCEAN ONE is an underwater robotic avatar jointly developed by Standford University, the King Abdullah University of Science and Technology and the Red Sea Research Center in Saudi Arabia, and Meka Robotics in California. It is a bimanual underwater humanoid ROV-like robot using haptic feedback to allow a human pilot to perform challenging intervention operations underwater. In collaboration with the French Departement des recherches archologiques subaquatiques et sous-marines (DRASSM), the robot was used to explore La Lune, a 17th shipwreck located off the coast of Toulon (France). The contribution of OCEAN ONE to underwater manipulation lies in the use of haptic interfaces with force feedback to exhibit advance manipulation capabilities. Interestingly, Ocean One has been designed to draw on the complementary strengths of both humans and robots, As such, it is truly a quantum leap in the development of a new class of robots capable of performing delicate operations underwater, including many of interest to marine scientists and researchers specialized in the preservation of cultural heritage [66].

3.3. Transport

Autonomous marine robots can play multiple roles within the marine and maritime domain: from water monitoring, to safety increase in transport and underwater intervention activities (including assembly, manipulation, decommissioning).
In the last two decades, industry has remarkably benefited from marine robot exploitation, thanks to the technological transfer from pioneering research to professional service applications.
Today, research is again ready to transfer its new cutting-edge results and consolidate its experience through the

[1]Planning Domain Definition Language

Figure 8: The OCEAN ONE underwater robot.

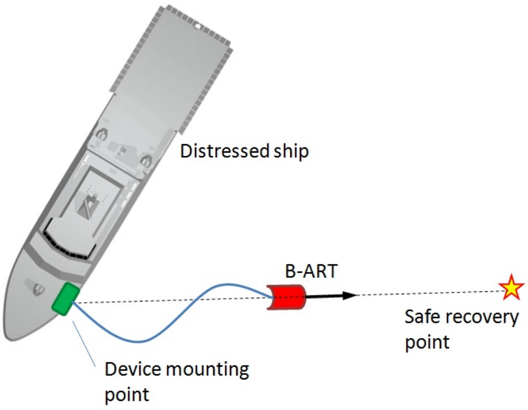
deployment of effective systems within civil and industrial applications. However, there are obstacles to such deployment of different nature: i) technical (e.g. autonomous anti-collision systems, underwater communications, vision & localization, persistence in terms of both energy support and decisional autonomy); ii) non-technical (e.g. lack of a legal framework regulating autonomous marine robot behaviour in presence of other agents).
Therefore, robotics research community, industrial stakeholders and end-users should work together in a solid way to push policy makers, public administrations, standards and certification organizations to acknowledge and incorporate consolidated research results into precise *ad hoc* regulations.
Specifically dealing with maritime transportation, one of the major requirements is that of increasing people and goods safety while reducing costs. CART [67] and MINOAS [68] are representative projects addressing safety issues in maritime transport.

3.3.1. CART project

The *CART* project proposed a new robotics concept for salvage operations of distressed ships at sea, particularly focusing on linking on the emergency towing system of ships in emergency to towing vessel (a very high-risk operation usually performed by humans).
The proposed concept was demonstrated through the development of cooperative robotic technologies able to (semi-)automatically recover the towing system; it proved to be able to optimize the operations for safeguarding the environment, typically preventing oil pollution at sea, while minimizing the risk for human life. In Figure 9, the project concept is shown: the B-ART vehicle moves away from distress ship carrying the messenger line and the ART vehicle safely ties it to allow ship towing. This avoids that the towing vessel approach the distressed ship at relatively short range, which can be very dangerous in the case of rough sea conditions.

3.3.2. MINOAS project

Ships and vessels are still today heavily employed for the cost and time efficient transport of goods and humans. Hence, they require increasingly high safety standards.
Towards this goal, technology and automation can endow vessels with tools and equipment to monitor the ”safe operational” criteria, achieving less effort required, lower level of uncertainty and higher accuracy. The *MINOAS* project developed an integrated product, based on autonomous robotics technology, to be exploited for the inspection related procedures of the maritime industry. In particular, the project resulted in an increase of the inspection procedure quality, as well as in leveraging the engineering and cost performance required, through the standardization of the number and the sequence of the tasks involved in the inspection procedure. Figure 10 shows some of the robotic platforms employed within the project.



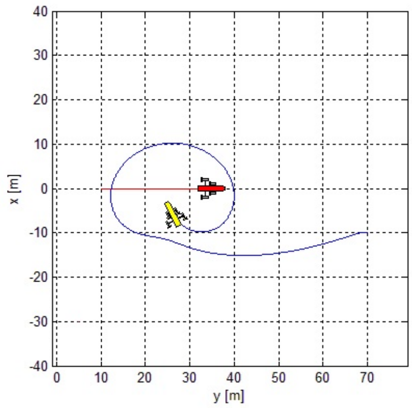


Figure 9: CART concept

Figure 10: Some of the robotic platforms exploited in MINOAS

3.3.3. RITMARE Italian Flagship project

RITMARE is an Italian collaborative framework that aims at developing the concepts of extended ship and system of systems. The overall and long-term goal of the project is the enforcement of competitive and globalization capabilities of the Country towards technological changes in the marine and maritime sectors, including environmental related challenges such as climate change, marine environment degradation, maritime security and energetic sustainability. Within this huge and challenging framework the project faces the challenge of autonomous shipping with the development of a heavy size autonomous surface vehicle capable of deploying/recovering unmanned underwater robots, performing cooperative tasks, thus evolving the capabilities of intelligent marine agents. Moreover, a number of complementary actions are carried out in order to enhance the overall system performance pointing at:

- cost planning and reduction in the life-cycle of the ship system;
- modeling of the human perception with respect to comfort factors;
- agent based technologies and explorable 3D models for onboard people and goods management;
- development of innovative autonomous vehicles;
- adaptive navigation, guidance and control systems coupled with intelligent data gathering modules;
- innovative instrumentation for mobile platforms;
- Small Waterplane Area Twin Hull (SWATH) design and development.

3.4. Human-Robot Interaction

In spite of autonomy required to all robotic platforms, Human-Robot interaction is an essential component of all applications in relevant environments, at least at some level; to this aim, suitable methodologies and interfaces should be developed to allow such interaction. In detail, there are different types of possible interactions between humans and robots: from a human operator controlling and monitoring robot activities, to an actual integration of human beings in the loop, allowing a real cooperation. Required robotic features in the different cases are varying: from a classical visual interface including all relevant information and controls [69], to more complex interfaces and structures enriched with multi-modal sensory information and augmented reality [70], [71], [72], as well as to the development of communication based on more "natural" interaction methodologies, such as speech and/or gestures [73].
A classical kind of human-robot interaction in the marine and maritime domain is required by subsea operations by ROVs; the *OceanRINGS* suite [74] is a good example of control and navigation framework for offshore commercial ROVs. Usually, these technologies are applicable to off-shore oil and gas sector, for inspection and maintenance, and can also be exploited for future deployment, monitoring, and maintenance of ocean energy devices. Such system facilitates ROV operations, reducing ship time and cost and increasing safety; moreover, it provides a suitable platform to researchers that can develop, evaluate and test advanced control algorithms, both in simulation and in real world.
The topic concerning Human-Robot interaction is somehow "cross-domain", since robotic systems up-to-date deployed in real world require human intervention, at some level.
Recent research activities, also conducted in EU-funded projects, have investigated, with mostly success, the possibility to integrate humans and robots in very comprehensive and effective systems (such as in search & rescue applications), as well as adopting new and "more natural" interaction strategies (e.g. exoskeleton, gestures . . .).
The pioneering research work conducted in the *CO3AUVs* project [23], dealing with the development of an advanced multi-robot system for underwater environments, led the marine robotics community to investigate mixed human-robot multi-agent systems with increasingly stronger effort.
Mixed team of humans and robots have been employed also in a search & rescue context: the *DARIUS* and *ICARUS* projects [75], [76], [77] dealt with the exploitation of comprehensive unmanned search and rescue tools, including specifically-adapted unmanned platforms (air, ground and maritime), to support human crisis managers and to assist search and rescue teams. These tools are suitably integrated into the C4I (Command, Control, Communications, Computers and Intelligence) equipment used by crisis managers, in such a way to be effective in real operations and in enhancing the safety of humans. Also the German project *AGaPaS* [78] aimed at demonstrating the added value brought by robotics platforms in search & rescue operations at sea.

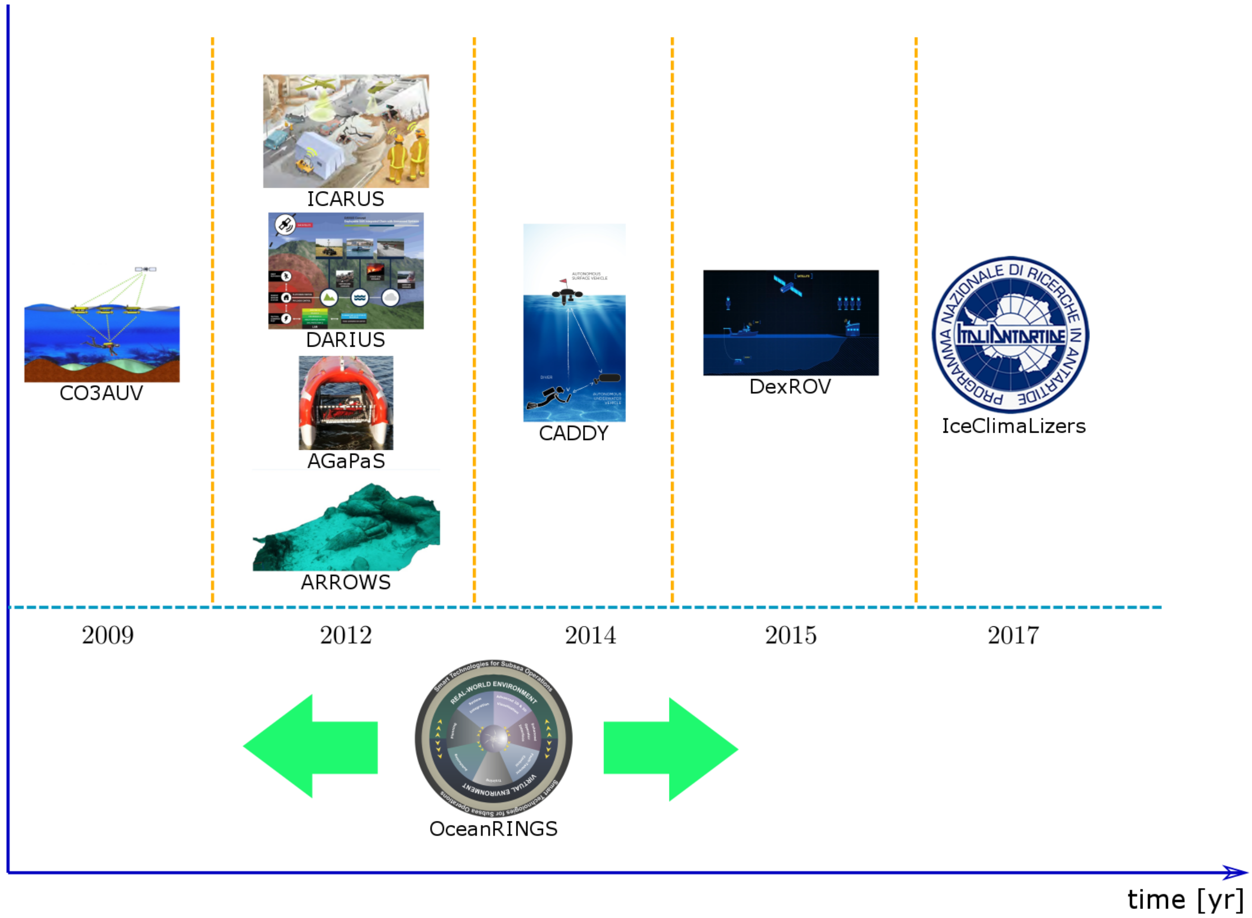


Figure 11: Timeline of the mentioned main projects dealing with Human-Robot Interaction

The first starting idea of robot assisting divers during missions, introduced in the *CO3AUVs* project, has been then resumed and widely extended by the *CADDY* project [79]. This last accomplished its main goal to achieve an effective robotic system to monitor, guide and obey to human divers during their missions, through a "natural" interaction based on diver gestures.
Another particular form of interaction is developed in the on-going *DexROV* project [80] which plans to exploit a double advanced arm and hand force feedback exoskeleton [81] as interface to assure dexterity to the ROV pilot.
Dexterous control could be also exploited in the underwater archaeology domain, having to deal with fragile and precious finds. Important research in the field has been conducted within the *ARROWS* project [82], [83], which aimed at adapting and developing low cost autonomous underwater vehicle technologies to cover the full extent of archaeological campaign, reducing cost of operations.
An excellent level of dexterity and precise control is required also in the on-going (and just started) Antarctic project *IceClimaLizers* [84], which aims at investigating the role of selected species of bioconstructors as proxies for climate changes; skillful manipulation of fragile bio-organisms will be essential for the project success and will be performed via suitable teleoperation.
Figure 11 depicts relationship in time among the mentioned projects focusing on Human-Robot Interaction; note how the application domains are different (from archaeology, to search & rescue and human safety, as well as support to industrial activities and to scientific research in harsh and remote environment). Note also how results from a project like *OceanRINGS*, dealing with technologies to ease ROV piloting and operations, are important and shared among all the domains.

3.4.1. CO3AUVs project

At the time the *CO3AUVs* was proposed, as well as still today, autonomous underwater platforms was and still are among the most exciting challenges of robotics research. Difficulties arising from the unstructured environment, in terms of perception, decision, control and communication issues, require that robotics go far beyond the current approaches and methodologies.
The main purpose of the project consisted in enabling advanced cognitive systems for coordinated and cooperative control of a team of AUVs, capable of both seamlessly performing monitoring tasks (e.g. of underwater infrastructures, also detecting anomalous situations) and of acting as companion/support platforms for humans (e.g.during scientific and commercial dives).

3.4.2. ICARUS and DARIUS projects

ICARUS and *DARIUS* projects were devoted to the exploitation of mature robotic technology in search & rescue applications.
In particular, the *ICARUS* project proposed to employ unmanned platforms and tools as support for first responders working on search & rescue during a major crisis, with the final goal to reduce costs in terms of human lives and money. The addressed technology concerns assistive unmanned air, ground and sea vehicles, in charge of both the first exploration of the considered area and providing support (as well as enhancing their safety) to human personnel. The complementary *DARIUS* project aimed at adapting and integrating already developed technologies for situation awareness into complex multi-national and/or multi-agency search & rescue operations. In particular, it focused on the achievement of effective levels of interoperability to make these systems effectively useful to be shared between several organizations.

3.4.3. CADDY project

Divers operate in harsh and poorly monitored environments in which the slightest unexpected disturbance, technical malfunction, or lack of attention can have catastrophic consequences. They maneuver in complex 3D environments and carry cumbersome equipment while performing their missions. To overcome these problems, the EU Project CADDY [85] aims to establish an innovative set-up between a diver and companion autonomous robots (underwater and surface) that exhibit cognitive behavior through learning, interpreting, and adapting to the diver's behavior, physical state, and actions.
The CADDY project replaces a human buddy diver with an autonomous underwater vehicle and adds a new autonomous surface vehicle to improve monitoring, assistance, and safety of the diver's mission. The resulting system plays a threefold role similar to those that a human buddy diver should have: i) the buddy "observer" that continuously monitors the diver; ii) the buddy "slave" that is the diver's "extended hand" during underwater operations performing tasks such as "do a mosaic of that area", "take a photo of that" or "illuminate that"; and iii) the buddy "guide" that leads the diver through the underwater environment.

3.4.4. ARROWS project

The main purpose of the *ARROWS* project consisted in the adaptation and development of low-cost underwater technologies aimed at supporting archaeological campaign activities, like mapping, diagnosis and excavation tasks. In particular, some of the pursued objectives regarded: multi-modal sensing through customized AUVs for fast and low-cost horizontal surveys of wide areas; high resolution maps through precise image reconstruction and accurate AUV localization; soft excavation tools to deal with fragile objects; virtual exploration of archaeological sites through mixed-reality environments.

3.4.5. DexROV project

The *DexROV* project focuses on ROV operations and on how to effectively reduce their time and costs. Operating ROV usually requires significant off-shore dedicated manpower, while the project aims at mainly gathering manned effort for operations in a *ad hoc* control room on-shore. This is possible through a real-time simulator able to both exploit ROV sensor data to model the environment, and respond to operators' commands.
Interaction with human operator is foreseen through a double advanced arm and hand force feedback exoskeleton, which can enable dexterous manipulation.

3.4.6. IceClimaLizers project

The just started *IceClimaLizers* project aims to identify bioconstructional areas in Terranova Bay, since they are responsible for the increasing in Antarctic biodiversity, and to investigate the relation between climate changes and varying properties of bioconstructors (i.e. organisms that builds a structure that survives the death of the organism itself).
The novelty the proposed approach consists in directly correlating the biomineral characteristics of the species with the environmental parameters experienced during the last year species growth.
In such a way to be able to handle such fragile and precious organisms in a harsh and remote Polar environment, the required robotic manipulation activity will be performed exploiting classical teleoperation technique by a human expert operator.

4. Challenges

Marine robots fall into two major categories; remotely operated and autonomous. The first include Remotely Operated Vehicles (ROVs), while a representative group of the latter consists of Autonomous Underwater Vehicles (AUVs), often referred to as Unmanned Underwater Vehicles (UUVs). In the last 20 years, ROVs and AUVs have steadily become the work-horses of scientific/commercial underwater exploration and exploitation, leaving the use of manned submersibles for very particular and specialised tasks. ROVs and AUVs have significantly increased their presence in the market since they became more affordable. More recently, new categories of autonomous marine vehicles have appeared with great success. Gliders have become the oceanographic tool per excellence and Autonomous Surface Vehicles (ASCVs), also known as Autonomous Surface Craft (ASC), have become relevant for hydrographic and surveillance mission and to work in tandem with AUVs, playing the role of navigation aids and communication relays. Long Range AUVs have demonstrated the capability to travel thousands of kilometers. The marine robotics community has also witnessed the appearance of new vehicle concepts such as HROVs, which may perform either as ROVs or AUVs depending on the needs, underwater and wave gliders, intervention AUVs, micro-AUVs, precursors of AUV swarms, and cooperative multiple-vehicle teams. In the upcoming years, the flexibility of hybrid vehicles, scuh as HROVs, with multifaceted applications, will increase their visibility and protagonism in the marine robotics scene. Small and micro AUVs will also strengthen their presence in the oceans due to their increasing affordability, making them accessible to a large community of end users. This will naturally lead to an increase in multiple vehicle operations beyond those in defense areas. Nevertheless, there still remain significant challenges in the way of making AUVs increasingly more autonomous with a view to widen their spectrum of applications.
Also, marsupial robotics and morphology-changing modular vehicles are quite new trends in marine robotics applications, exploiting their suitable and unique capability to transform and adapt to missions and the environment, and to carry heterogeneous and complementary payloads and sensors in order to meet a variety of scientific and commercial mission requirements. Indeed, in exploration and environment monitoring applications, the employment of robotic networks is at the cutting-edge of today research. This is because *heterogeneous* robots have higher chances to successfully achieve complex missions; such networks strongly leverage heterogeneity to perform their assigned tasks. Particularly, marsupial systems exploit the so called ”marsupial relationship” [86], the physical interaction occurring among a *carrier robot* and its one or more *passenger robots*: the carrier, beside making available its own capabilities to the overall robotic system, can provide faster deployment of passengers. Thanks to their high flexibility, marsupial robots can be exploited for complex missions in harsh and dangerous environments but, in any case, they need new methodologies and brand-new concepts in perception, control and communication, being this a big still open challenge.

Navigation in unconfined environments (beyond the coverage of acoustic transponder networks) remains one of the milestone problems yet to be solved. Terrain based navigation [87, 88], with so many implementations already reported in the literature has not found its path towards routinary application, because it requires accurate a priori available maps which are not always available. SLAM arises as a key technology to solve this problem during the next years. Many SLAM implementations have been recently reported in the literature using bathymetries [89, 90], occupancy maps [91, 92], forward looking sonar imagery [93], visual SLAM [94, 95, 96, 97, 98], etc... Nevertheless, very few of them have been employed in realtime to control AUVs [91]. SLAM algorithms require that the trajectory excuted by the robot goes through an area of the environment where the local observations are informative enough to discriminate its pose. For instance, even the best terrain based algorithm will fail if the robot flies all the time through a uniformly flat bottom. For this reason it is necessary to develop active localization algorithms to allow the robot complete their mission traversing informative regions of the environment in order to bound the drift. Of particular interest are those SLAM methods where the map representation allows for an easy categorization of the space into ’free’, ’occupied’ and ’unknown’ [91, 92]. These methods are easily integrated with path planning algorithms allowing the robot to trace safe routes between way points through the free-space. It is necessary to research the best metrics to be applied for motion planning depending on the applications needs. Should the robot trace the short distance route towards a goal way point or the one that would allow it to reach the target with the smallest uncertainty in its pose? Of course the answer is application-dependent.

Another important challenge is related to achieve 3D mapping capabilites of high interest for the scientific and industrial applications. While during the last decade there has been a significant advance in the techniques for 3D mapping (stereo, structure from motion, visual SLAM) very little work has been done on the development of the algorithms and methodologies required to bring the AUVs close enough to the 3D structures in order to gather optical imagery [99]. In most of the 3D optical maps reported in the literature the data has been acquired with ROVs, since state of the art AUVs are not able to navigate close to areas with strong relieves. Nevertheless, recent results in motion planning for AUVs have demonstrated experimental results circunavigating an small ireland at a constant depth while gathering optical imagery [100]. Explicitly knowing the boundary between the ’mapped’ and ’unknown’ area allows for the use of view planning algorithms [101] to expand the horizon of the ’known’ area as well as to ensure full coverage of complex 3D structures. It is worth noting the requirement to simultaneously solving the online path planning and the SLAM problems, since they are actually coupled.

There are also formidable challenges in the general area of Cooperative Motion Planning, Navigation and Control using a Networked Systems Approach. The motivation for this theme stems from the fact that worldwide, there is a tremendous surge of interest in the development of the methodologies and technologies required to enable groups of robotic vehicles linked via communication networks to collectively inspect, survey, and map challenging underwater environments, while affording humans access to the data collected as a cooperative mission unfolds. From a theoretical standpoint, this entails the study of algorithms for distributed cooperative motion planning, navigation, and control in the presence of external disturbances, time-varying communication topologies, and stringent communication constraints imposed by the water medium [102], [103], [104], [105], [106], [107]. Many of these issues have been the subject of intensive research addressing extremely interesting problems in networked systems theory, control, filtering, and optimization. A representative example is the problem of combined surface and underwater vehicle operations, leading to algorithms capable of making the vehicles follow predetermined spatial paths while keeping a desired geometric formation and executing compliant formation control in reaction to unexpected obstacles or episodic events detected on line [108]. See also [109] for interesting connections to research in similar themes in the area of autonomous air vehicles. In this context, a research topic that has recently come to the fore is the development of cooperative control strategies that are robust against temporary communication losses and have the potential to reduce drastically the amount of data exchanged among the vehicles by exploiting techniques that have recently come to the fore (e.g., event triggered and self-triggered control and communications) [110], [111], [109].

From a practical standpoint, besides the requirements for increasingly sophisticated sensors, actuators, and embedded computer systems, there is a need to enhance the technology for underwater data exchange among mobile and/or stationary network nodes that may include autonomous surface vehicles (ASVs), autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and benthic stations. The data exchanged are crucial in a number of applications that include cooperative, distributed multiple vehicle navigation and control, mission status assessment, and environmental sensing [112], [113]. Meeting the above goals will require the exploitation of the underwater acoustic and optical channels simultaneously and the development of strategies to dynamically adapt the topology of the communications network and the geometric configuration of the group of vehicles in real-time. This exciting avenue of research is being made possible by the availability of new types of optical modems for communications at short range [114], [113], [115], [116] and networks of high performance acoustic modems and positioning devices equipped with high precision atomic clocks [112], [117].

Another essential issue consists of developing a system capable of executing long-range missions, eventually reaching the stage where it can be permanently deployed in a particular site or area (sustained presence at sea). To this end, many different achievements are needed: from energetic considerations (minimization of power consumption and losses, optimization of required tasks and robot lifetime, generation of power from the working environment), to decisional autonomy avoiding human intervention (capability to conveniently plan and re-plan missions, to react and adapt to changes in mission goals and environment conditions, autonomous management of failures), till the capability to store perception about both the world and the robotic system itself, process and propagate such knowledge in such a way that learning behaviours and construction of a semantic mapping and representation of the working environment can thrive.

All the mentioned achievements should be included within a multi-robot logic: to accomplish long and complex missions, also facing changing conditions and failure, heterogeneous vehicles carrying complementary payloads and abilities are to be employed, being able to react to bad situation and guaranteeing robustness for the overall system. Huge coordination and cooperation abilities should be developed, both among vehicles and in a mixed human-robot team framework (with all the concerning safety issues).

Significant advancements in all these aspects will strengthen robotic deployment and its effectiveness in scientific, social and industrial applications. One example among many others is represented by the intervention domain: a robust and reliable system performing an intervention or inspection mission would require skills such as dual-arm manipulation, cooperative behaviours and decisions, *ad hoc* motion planning and semantic mapping.

Marsupial robotics is earning great interest, for its feature of allowing heterogeneous collaboration among different robots in charge of different tasks, able to nicely adapt even to harsh and complex environments (for instance Polar regions). Moreover, the possibility to further change the system morphology through modular design and reconfiguration pushes the marine robotics frontier beyond what seemed not achievable just a few years ago.

One of the emerging and most intriguing future trends in the robotic community consists in the development of effective robotic teams to be deployed in harsh and remote environments for complex autonomous operations to be cooperatively performed by agents. This goal completion strongly depends on achievements in all the topics above mentioned. Indeed, many challenges have to be addressed to obtain a robotic colony able to autonomously survive in the environment: persistence, in terms of both decisional autonomy and ability to gather energy from environment; cognitive ability to be able to adapt to changes in both environment and mission objectives; ability to evolve suitably to survive in the environment and to be able, at the same time, to perform useful tasks...

Recently, some EU-funded projects have dealt with the development of smart teams of heterogeneous robots, focusing on different aspects and adopting various points of view. An excellent example is the *CoCoRo (Collective Cognitive Robots)* project [118], aiming at creating a swarm of interacting, cognitive, autonomous underwater vehicles (AUVs) for the execution of tasks such as ecological monitoring, searching, maintaining, exploring and harvesting resources in underwater habitats. Agents in the swarm, by interaction and information exchange, resulted in a cognitive system aware of the surrounding environment, as well as of goals and threats (both local individual and global at swarm level). Moreover, also the emergence of artificial collective pre-consciousness was investigated, enabling self-identification and improvement of collective performance; this represents a key step for improving the robustness, flexibility and efficiency of such systems and empowering their actual deployment and exploitation in real world applications.

Another essential (and still on-going) project on robotic colonies is *SubCULTron (Submarine Cultures Perform Long-Term Robotic Exploration of Unconventional Environmental Niches)* [119], whose main purpose consists in creating an artificial society underneath the water-surface to the service of a human society above the water. In particular, challenges concern the achievement of long-term autonomy in a learning, self-regulating, self-sustaining underwater society/culture of robots.

Results achievable by these pioneering research activities will enable future robotic systems able to self-organize, survive and evolve as independent societies of individuals sharing a common sense and joint life goals.

5. Future Trends

This section is a brief summary of four extremely innovative, forward looking projects in the USA, India, Norway, and Korea, that hold considerable promise for the development of cutting edge technologies in marine robotics.

5.1. The Mesobot project, Dana Yoerger, WHOI, USA

The Woods Hole Oceanographic Institution, the Monterey Bay Aquarium Research Institute, Stanford University, and the University of Texas Rio Grande Valley are developing an autonomous underwater robot, Mesobot, with new

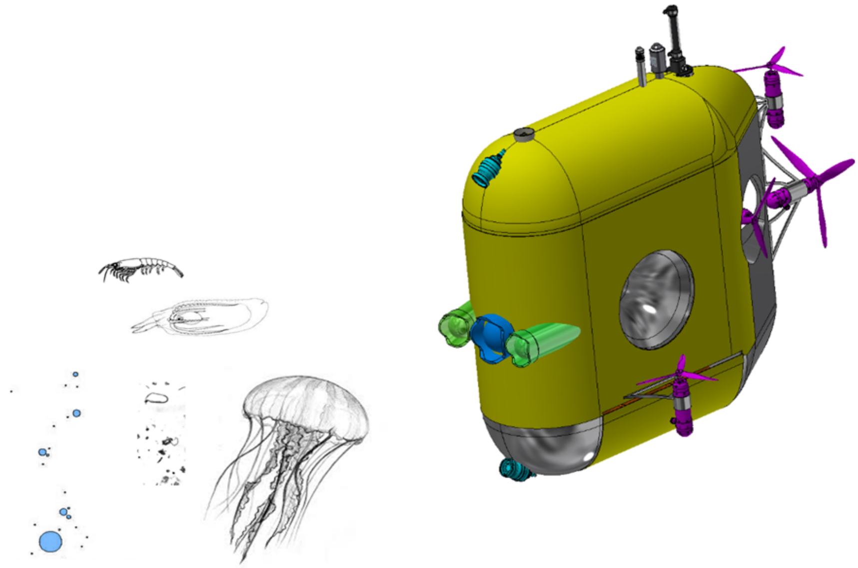


Figure 12: Mesobot: an AUV to study life in the midwater ocean. Photo Courtesy of D. Yoerger, WHOI.

capabilities for understanding the unique and abundant life in the midwater ocean or ”twilight zone”. The twilight zone, which extends from about 200m to 1000m depth, may harbor more fish biomass than all other fisheries worldwide. Many twilight zone animals undergo diel or daily migration, spending daylight hours hundreds of meters deep and rising to near surface waters in the evening to feed. While largely invisible to us, this daily worldwide movement of animals is by far the largest migration on our planet and likely a major mechanism for moving organic material from near-surface waters to the deep ocean, thereby playing an important role in our planet’s climate by sequestering carbon.

Mesobot will use its stereo cameras to follow midwater animals as they migrate, documenting their behavior for periods exceeding a full diel cycle. Mesobot missions will begin using a tether, allowing a human pilot on the surface to identify targets, after which the tether will be released and Mesobot will track the target autonomously. In addition to the monochrome stereo cameras, Mesobot will carry a highly sensitive color 4K video and still camera. Mesobot will be equipped with white lights for high-quality scientific imagery and red lights to minimize both avoidance and attraction. Simultaneously, Mesobot will be able to obtain up to a dozen samples of filtered seawater, allowing researchers to characterize the environment from geochemical and genetic perspectives. Mesobot will use a combination of thrusters and a variable buoyancy system to follow the animals with minimal disturbance. Like its targets, Mesobot will be nearly Lagrangian. Mesobot will displace about 200kg and can be launched from a variety of vessels.

5.2. The C-Bot project, Pramod Maurya, CSIR-NIO, Goa, India

Given the reality of climate change, with the consequent warming effects in India, there exists an urgent need in the country to develop the proper means to monitor, detect, and predict in a timely fashion local phenomena that may be reliable indicators of this trend. Coral reef monitoring is considered by most climate scientists as a reliable proxy indicator of climate change because corals are sensitive to small changes in temperature. Recent studies published by the India National Curriculum Framework (NCF) have revealed that nearly 50 % of the Indian reefs exhibit bleaching, an irreversible whitening process where the reefs begin to die. Thus the question: how does one monitor and survey large areas of coral beds in an efficient manner?

Present day methods employ an experienced diver and buddy with camera equipment to survey coral reef beds along

straight line transects and halting at locations along the transects to image any corals undergoing suspected bleaching. Given the high cost and strenuous human effort involved, only a few straight line transects a year are considered adequate under current monitoring protocols. The data thus acquired are not adequate to truly assess the impact of climate change on the quality of living living in coastal areas and often the policies adopted to address this problem are very conservative. The wildlife wardens are looking for a solution that will allow then to collect high resolution images of the coral reefs in a given area periodically with a view to obtain and accurate information upon which to base government policies.
A larger number of transects a year is desirable, and this is best addressed by the new technology of low flying autonomous underwater vehicles with cameras and sensors as payloads. For example, a low flying reef robot cruising at 0.5m/s will be able to image suspect corals in a mere 33 minute mission to cover a 1 km line transect. The conventional diver approach would probably take more than 2 hours to accomplish the job, with extra time to resurface, change air tanks, and resume the mission. The start of our millennium has witnessed a paradigm shift in oceanographic observations that began with the use of Autonomous Underwater Vehicles and profiling robots for spatial and depth based sampling respectively at various targeted locations in the seas. Over the past 15 years, the Marine Instrumentation Group at CSIR-NIO has acquired expertise and field experience in building underwater robots. The roadmap offered by these available technological tools reduces both cost and human intervention.
The focus of the Coral Bot (C-bot) project is to build a robot to monitor coral reefs in shallow waters. A C-Bot is a much needed development that will fulfill an important objective embodied in the United Nations proclamation of a Decade of Ocean Science for Sustainable Development (2021-2030) using new technologies.
The challenges in the design and development of the C-Bot are several. The C-Bot is planned to replace human divers for monitoring work and will only involve coral reef personnel to plan and program a robot mission (including the definition of the transects) and to launch and retrieve the robot. The C-Bot will be dropped on top of the coral reefs, after which it will find bu itself a suitable sand patch location to land. Thereafter, based on the mission specifications. the C-Bot will be in the water for approximately 6 months repeating the transects every months and sleeping on the seabed during the intervals between the transects. The main components of the project are to design, implement, and assess the performance of the systems required to:

- keep the the C-Bot at selected places in the seabed even in the presence of currents
- enable the C-Bot to find suitable locations for landing and execute landing maneuvers
- geo-locate the C-bot underwater
- control the C-Bot in its vertical and horizontal motion, the latter along desired
- record and transmit images and environmental data.

The following functionalities are envisioned for the C-Bot:

- The vehicle will belong to a new generation of one-man deployable/retrievable robot which can be dropped in the water by one person.
- It will be able to sit on the seabed for long periods of time and perform the preprogrammed transects saving on manpower, cost , with the added the benefit of acquiring large datasets over larger sampling areas in a single month (this would yield detailed high resolution maps of the reef beds all tagged with oceanographic properties of the water column).
- The vehicle will be controlled to maintain a height of 1 meter above the coral reef beds while recording high resolution images
- After each mission transect, the C-Bot will resurface and transmit the data acquired using Satellite Modem/Radio/GSM, after which C-Bot will again dive and sit at the bottom and wait for the time to start the next transect

The use of C-Bot is not limited to coral applications. In fact, it holds potential to be used It can be as coastal surveillance robot to monitor all types of noise sources, both natural as well as man-made. This opens up the technology to other useful applications.

5.3. Projects on Autonomous Ships, Vahid Hassani, NTNU, Norway

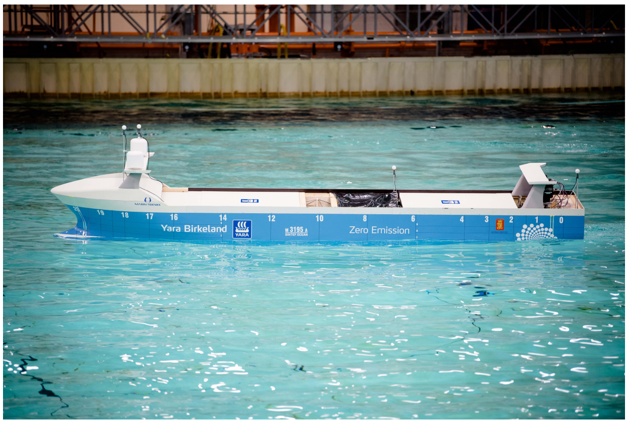


Figure 13: Model testing of YARA Birkeland, the worlds first autonomous ship, in SINTEF Ocean' basin, Norway. Photo courtesy of Ole Martin Wold, SINTEF.

One of the earliest research projects on Autonomous Ships was the European project named "Maritime Unmanned Navigation through Intelligence in Networks (MUNIN)" [120]. MUNIN, co-funded by the European Commission under its Seventh Framework Programme, put forward a new concept for an autonomous ship with the the potential to tackle some of the most challenging problems in the field of autonomous marine transportation such as the significant increase in transport volume, growing environmental requirements, and a shortage of seafarers in the future. Autonomous Shipping allows for more efficient and competitive ship operation and expected to yield a significant decrease in the environmental footprint marine vessels. The concept proposed in the scope of MUNIN received praise from the academia, industries, and civilian authorities [121], [122]. The autonomous shipping concept not only brought new challenges to both industry and academia but also redefined the shipping industry by bringing new players into the picture. The first industrial Autonomous ship project was initiated by YARA AS, a chemical company that ordered the vessel YARA Birkeland, the worlds first fully electric and autonomous container ship, with zero emissions [123]. The vessel will be delivered 2020, and will gradually move from manned operation to fully autonomous operation by 2022. Another recent initiative in the field of autonomous shipping is the "Autoferry project" coordinated by the Norwegian University of Science and Technology (NTNU), aimed at the development of autonomous all-electric passenger ferries for urban water transport [124]. The recent European Commission call for proposal on the topic of autonomous ship aims to develop and demonstrate integrated automation technologies in a real environment [125].

5.4. Development of a multi-purpose autonomous surface vehicle, Jinwhan Kim, KAIST, Korea

The project aims to develop an unmanned surface vehicle (USV) platform and intelligent algorithms for autonomous navigation. A 8-m long USV, called Aragon, was designed and built, focusing on nearshore and coastal applications. Aragon can reach the maximum speed of 45 knots and equipped with various sensors such as a camera, lidar and radar for environmental perception. The vehicle was integrated with intelligent algorithms for high-level vehicle autonomy and a number of field tests were performed in real-sea environments. Aragon can be controlled in either remote control mode or fully autonomous mode. In the fully autonomous mode, the vehicle is capable of automatically detecting nearby obstacles and performing collision avoidance maneuvers while adhering to maritime traffic rules (i.e., COLREGs). The research project has been led by Korea Research Institute of Ships and Ocean Engineering (KRISO) and funded by the Ministry of Oceans and Fisheries, Korea. The Korean Advanced Institute for Science and Technology (KAIST) has been in charge of developing autonomous perception algorithms fusing various sensor data from INS/GPS, camera, lidar, and radar systems

6. Conclusions

The paper gave an overview of some of the most relevant domains in marine robotics with far reaching scientific, commercial, and societal impact. The first part focused on selected pioneering projects in the field and traced the

Figure 14: The Aragon USV (left); Automatic Collision Avoidance Test (right). Photo courtesy of Jinwhan Kim, KAIST.

course of the main objectives accomplished. In the second part, many of the emerging challenges were discussed, highlighting their importance and role in advancing research and development in the field of marine robotics. Some of the primary trends involving cutting edge methodologies and technologies in robotics were presented, together with a broad vision of the next steps to be taken. There has been tremendous progress field, both from a theoretical and practical standpoint. The road ahead is certainly long, but definitely thrilling and challenging.

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