TRIDENT: A Framework for Autonomous Underwater Intervention Missions with Dexterous Manipulation Capabilities

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Abstract: TRIDENT is a STREP project recently approved by the European Commission whose proposal was submitted to the ICT call 4 of the 7th Framework Program. The project proposes a new methodology for multipurpose underwater intervention tasks. To that end, a cooperative team formed with an Autonomous Surface Craft and an Intervention Autonomous Underwater Vehicle will be used. The proposed methodology splits the mission in two stages mainly devoted to survey and intervention tasks, respectively. The project brings together research skills specific to the marine environments in navigation and mapping for underwater robotics, multi-sensory perception, intelligent control architectures, vehicle-manipulator systems and dexterous manipulation. TRIDENT is a three years project and its start is planned by first months of 2010.

Keywords: Autonomous marine vehicles, dexterous manipulation, multirobot cooperation.

1. INTRODUCTION

Nowadays, a significant number of field operations are carried out with unmanned underwater vehicles (UUVs) in applications like marine rescue, marine science and offshore, need manipulative capabilities in order to perform the desired task. In such scenarios, most of the intervention operations are undertaken by manned submersibles or by Remotely Operated Vehicles (ROVs), both equipped with robotic arms.

Manned submersibles have the advantage of placing the operator in the field of the mission with a direct view of the object being manipulated. Their drawbacks are the reduced time for operation, the human presence in a dangerous and hostile environment, and a very high cost associated to the supply and oversee equipment needed. Work class ROVs, are probably the more standard technology for deep intervention. They can be remotely operated for days without problems. Nevertheless, they still need an expensive oceanographic vessel with a heavy crane, an automatic Tether Management System (TMS) and a Dynamic Position system (DP). Another issue is the cognitive fatigue of the ROV's pilot who has to take care of the umbilical and the ROV while cooperating with the operator in charge of the robotic arms. For all these reasons, very recently some researchers have started to think about the natural evolution of the intervention ROV, the Intervention Autonomous Underwater Vehicle (I-AUV). Without the need for the TMS and the DP, light I-AUVs could theoretically be operated from cheap vessels with the opportunity of reducing the cost considerably. With the fast development of battery technology, and by removing the operator from the control loop, we can even think about manipulative operations lasting for several days, where the ship is only needed the first and the last day for launch and recovery operations, and can be used to perform other tasks. For operations in inland waters or near the shoreline, it is even possible to replace the oceanographic ship by an Autonomous Surface Craft (ASC), which dramatically reduces the operational costs. With such a heterogeneous team of marine robots with complementary skills, the ASC and the I-AUV form together a powerful tool for conducting underwater surveys and/or manipulative tasks, being also of great interest for ocean operations. The team can be deployed from an oceanographic vessel to autonomously perform a mission while other scientific operations are being carried out from the ship in a different area. By means of the ASC, conveniently equipped with an Ultra Short Baseline (USBL), an acoustic modem and a radio-modem, it is possible to geo-reference the I-AUV position, as well as to establish a communication link to allow for a remote tracking and supervision by the end user.

This fascinating scenario comes at the cost of endowing the vehicles with the intelligence needed to keep the operator out of the control loop. Although standard AUVs are also operated without human intervention, they are constrained to survey operations, commonly flying at a safe altitude with respect to the ocean bottom whilst logging data whereas I-AUVs must be operated in the close proximity of the seabed or artificial structures.

The next sections include a short review of previous projects and a more detailed description of TRIDENT as well as the main objectives and the planned tasks to reach them.

2. RELATED PROJECTS

Pioneering studies concerning I-AUV, published in the early 1990s, addressed the coordinated control of the vehicle-manipulator system relying on numerical simulations of the coupled dynamics of both vehicle and arm systems. The first attempts to achieve an AUV endowed with a manipulator are found in the development of ODIN, from the University of Hawaii, OTTER, developed at MBARI and VORTEX from Ifremer. While ODIN and OTTER are AUVs controlled in 6 DOF and endowed with a very simple 1 DOF arm, the VORTEX is a 5 DOF ROV operated as an AUV which carries a 7 DOF PA10 arm. Although these vehicles represented a step forward in I-AUV technology they were mainly used as research test beds to demonstrate concepts such as the advanced hydrodynamics modelling of an underwater arm or the coupled AUV-manipulator simulation and control, always working in water tank conditions.

During the mid 90s, the AMADEUS EU project, described in Lane et al. (1997), achieved a step forward in the field of dexterous underwater manipulation, including within its objectives the realization of a set-up composed by 2 7-DOF ANSALDO manipulators to be used in cooperative mode (Casalino et al. (2001)).

After this period, researchers proposed new concepts to avoid the complexity of the coupled motion of the vehicle-manipulator system in order to achieve true field operation in open sea conditions. In 2001, Cybernetix tested its hybrid AUV/ROV concept with the SWIMMER project, presented in Evans et al. (2001). In this case an autonomous shuttle (AUV) carrying a ROV, is launched from a support vessel to autonomously navigate and dock into an underwater docking station in an offshore infrastructure. The docking station provides a connection to the AUV and from it to the ROV allowing a standard ROV operation to be carried out without the need of a heavy umbilical. After SWIMMER, two more projects were launched: ALIVE, see Evans et al. (2003), and SAUVIM.

ALIVE is a 4 DOF intervention AUV with a 7 DOF manipulator which is capable of autonomous navigation towards a position nearby an underwater intervention panel, detection of the panel and, finally, approaching and docking to the panel with two hydraulic grabs. Once the AUV is attached to the panel, the manipulation is a simple task. The ALIVE project was complemented with the European Research and Training networks FREESUB and FREESUBNET devoted to the fundamental research needed to further develop I-AUVs.

On the other hand, SAUVIM is an AUV carrying a 7 DOF electrical driven arm, ANSALDO, the same used in AMADEUS project, which is intended to recover objects from the seafloor using dexterous manipulation. The SAUVIM concept relies on keeping a strong difference of mass between the AUV and the manipulator, so that the control of the vehicle-manipulator system can be considered as an uncoupled control problem (see Marani et al. (2009).

It is clear from this literature survey that further research in I-AUV technology is needed to achieve full autonomous underwater intervention capabilities. Moreover, the I-AUVs developed so far, which have proven field capabilities, are heavy vehicles and are intended for very deep-water interventions. It seems clear that a point of interest for science and industry is the design and development of a very-light I-AUV (<300 kg) constrained to shallow water interventions (up to 500 m). Thus, the construction of a new I-AUV able to perform intervention activities that will be experimentally validated through a real scenario by using a real prototype, in a complete autonomous way would be a crucial technological contribution.

Currently, some EU FP7 projects such as GREX, UAN and COG3AUVs are working on multiple cooperative marine robots. Concerning manipulation issues, some FP7 representative EU projects would be GRASP and DEXMART, exploring new dexterous manipulation strategies by using one or two dexterous hands respectively but without any direct implication in the underwater robotics context. TRIDENT proposal aims to benefit from the experience and lessons learned in all the abovementioned projects, opening the door to multipurpose generic intervention operations in unknown, unstructured and underwater environments.

3. TRIDENT METHODOLOGY AND OBJECTIVES

The TRIDENT project proposes a new methodology to provide multipurpose dexterous manipulation capabilities for intervention operations in unknown, unstructured and underwater environments. The project is based on two main concepts: 1) the use of a team of heterogeneous marine robots with complementary skills, an ASC and an I-AUV, to achieve light intervention capabilities without the need for expensive support ships and 2) the use of a dexterous hand mounted on a redundant robot arm to achieve multipurpose manipulation capabilities.

3.1 Methodology

A new methodology for multipurpose underwater intervention tasks is proposed that goes beyond present-day methods, typically based on manned and/or purpose–built systems. TRIDENT methodology has two stages. During the first stage the ASC is launched to carry the I-AUV towards the area where the survey is to be performed. Then, the I-AUV is deployed and both vehicles start a coordinated path following and terrain following manoeuvre to cover the area selected for exploration. During the survey, the ASC/I-AUV team gathers navigation data from Doppler Velocity Logs, Fibre Optic Gyros and DGPS-USBL units so that the environment related measurements (seafloor images and multibeam bathymetry profiles) may be geo-referenced. At the end of this phase the I-AUV surfaces and contacts the end user to set-up an acoustic/optical map of the surveyed area. Using this map, the end user selects the target object for the mission as well as a suitable intervention task (grasping, hooking, etc…). The object is then characterized in order to allow for its automatic identification when it further appears in the field of view of the I-AUV. The different steps of this stage can be seen in Fig 1 where the numbers correspond to deployment (1), survey (2) and emergence (3) steps.

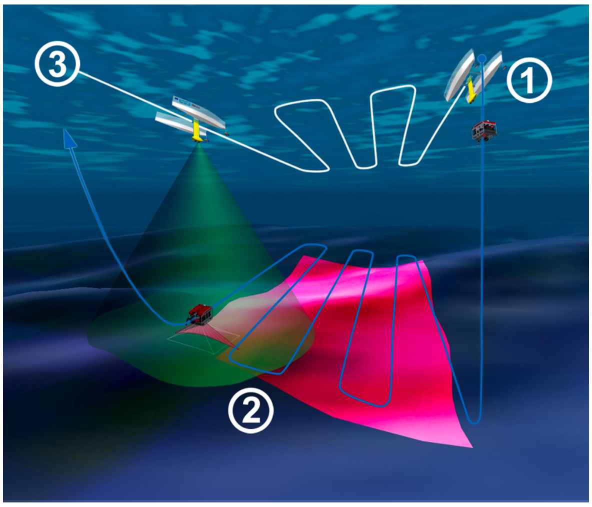

Fig. 1. Steps for survey stage of TRIDENT project. Deployment (1), survey (2) and emergence (3).

Once the target has been selected, the ASC/I-AUV team navigates towards a waypoint located near the target position. Then, the ASC performs dynamic positioning manoeuvres while keeping the I-AUV inside the USBL cone of coverage. Then, the I-AUV performs a search pattern looking for the Target of Interest (ToI). When the object appears in the robot's field of view, it is identified by the computer vision subsystem and the I-AUV switches to free floating mode using its redundant robotic arm as well as the dexterous hand to carry out the complex manipulation. Finally, with the help of the robotic arm, the I-AUV docks to the ASC before recovery. The steps for the intervention stage have been sketched in Fig 2.

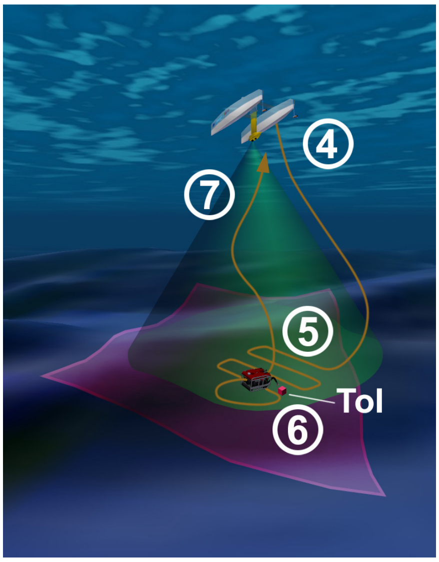

Fig. 2. Steps for intervention stage of TRIDENT project. (4) ASC dynamic positioning (4), target localization (5), manipulation (6) and I-AUV recovery (7).

3.2 Objectives and Milestones

To achieve the generic intervention scenario presented above, it is necessary to address, among others, the following scientific and technological objectives:

O1: Design and development of cooperative navigation techniques to achieve robust, high accuracy navigation (localization) of all the vehicles involved in the robotic team.

O2: Design and development of innovative mapping algorithms to robustly build consistent multimodal maps of the seafloor using complementary sources of information: Short range high accuracy data from visual imaging devices and long range low accuracy data from sonar.

O3: Design and development of new guidance and control algorithms for the team vehicles alone but also to cooperatively guide and control both vehicles in formation.

O4: Design and development of the embedded knowledge representation framework and high-level reasoning agents, enabling autonomy and on-board decision making for the various vehicles in the robot team.

O5: Design and development of advanced acoustic/optical image processing algorithms to allow for feature detection and tracking with application to object recognition, target detection and tracking as well as relative vehicle-target localization.

O6: Design and development of a redundant robotic arm endowed with a dexterous hand as an enabling technology for multipurpose manipulation underwater.

O7: Design and development of innovative strategies for the coordinated control of the joint AUV-Manipulator system as an enabling technology to achieve free-floating manipulation capabilities for light weight vehicles.

O8: Design and development of the mechatronics as well as the perception/action capabilities needed to cope with the autonomous docking of the I-AUV to the ASC.

O9: Design and development of multisensory control architecture, including a knowledge-based approach, to guarantee the suitable manipulation actions for enabling a multipurpose intervention system able to operate in unexpected conditions under uncertainty.

In order to guarantee the measurable progress of the project a set of five milestones have been designed:

M1: Cooperative Navigation

M2: Object recovery from a fixed base manipulator

M3: Integrated AUV/ARM/HAND Prototype

M4: Seafloor Mapping through Coordinated Motion of the ASC/AUV team

M5: Object recovery from a free floating AUV/ARM/HAND system.

These milestones are linked to the objectives previously defined as it is summarized in Fig 3.

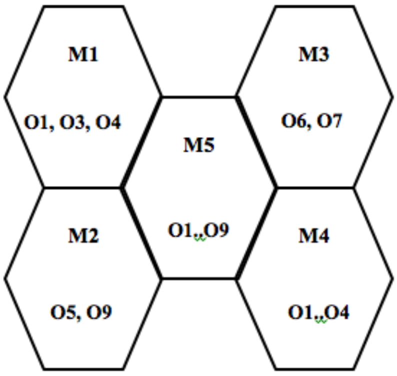

Fig. 3. Relationship among objectives and milestones

3.3 Metrics for assessing performances

Usually, the concepts underlying the levels of autonomy are managed only from a qualitative point of view. This approach is not sufficient for a project like TRIDENT. In this project, the use of metrics will be a must. These metrics will be based on the current research in autonomous systems in the US and at the Defense Technology Centre in Autonomous Systems in the UK who are leaders in this area. Broadly speaking, the levels of autonomy will be assessed by evaluating the quantitative amount and conceptual level of interactions between the autonomous platforms and the operators during the various stages of the mission (planning, supervision, control).

Moreover, the use of benchmarks allows measuring the progress towards the project objectives. For this reason, the project will widely use benchmarks whenever available and will also propose new benchmarks in areas where they not yet well established:

- Navigation and mapping: An accurate evaluation of the navigation results in underwater environment is a very hard task due to the lack of accurate absolute positioning through DGPS, an approach which is possible in outdoor land robotics but not underwater. Nevertheless, an important step towards benchmarking consists of developing well-documented datasets resulting from field experiments to provide other researchers testing their own algorithms with exactly the same data input. Although the SLAM community has broadly used this approach, few documented datasets are available for the underwater domain. In this respect, the project will contribute to making widely available through specialised web pages, the datasets used to test the proposed algorithms.

- Underwater Dexterous Manipulation: The project will benefit form previous experience working on benchmarking definition in the grasping/manipulation context gained by two partners (UJI and UNIBO) in former projects. Due to the reduced number of contributions in underwater manipulation, there is not a clear benchmark currently defined and accepted by the scientific community. TRIDENT plans to use recent manipulation results from the SAUVIM project, which are among the most advanced results in the area, as the base to define a benchmark for underwater manipulation.

4. WORK PLAN

The TRIDENT Work plan is structured in nine work packages (WP). The title and the leader of each WP are shown in table 1. In WP 1 to 7, briefly described in the next subsections, relevant scientific/technological problems are addressed. Two additional non-scientific packages are concerned with knowledge dissemination (WP8) and project management (WP9), respectively.

Table 1. Work packages titles and leaders

WP	Title	Leader *
1	Navigation and Mapping	UdG
2	Single and Multiple Vehicles Control	IST
3	Vehicles Intelligent Control Architecture	HWU
4	Optical/Acoustical Image Processing	UIB
5	Floating Manipulation	UNIGE
6	Hand+Arm Mechatr. System and Control	UNIBO
7	Multisensory based Manipulation Archit.	UJI
8	Dissemination, Education and Training	UdG
9	Project Coordination and Management	UJI

* See authors' affiliation for definition of the acronyms

4.1 WP1: Navigation and Mapping

WP1 is responsible for endowing the team of robots with two fundamental capabilities: building multimodal maps of the environment and geo-referencing the robot position within the application scenario. Different navigation techniques to allow the localization of individual robots involved in the team will be explored. The proposed techniques will include the use of stochastic state estimators, terrain-based navigation and simultaneous localization and mapping techniques.

State of the art navigation systems for AUVs commonly include a subset of navigation sensors (DVL, MRU, depth cell, INS and/or FOG) integrated together by some sort of sensor fusion technique providing dead-reckoning navigation. In the envisioned project scenario the ASC is self-localized by means of a DGPS and a MRU and uses an onboard USBL transceiver in a direct configuration (transceiver mounted on the ship) to geo-reference the AUV and feed its position back to it in order to bind the drift of its onboard DVL-MRU based navigation system. USBL and in particular acoustic modems are known to work better when both systems, the AUV and the ASC, are vertically aligned. For this reason strong cross-links will be established with WP2 to ensure the cooperative path following capability between the ASC and the AUV.

4.2 WP2: Single and Multiple Vehicles Control

A systematic and efficient acoustic survey of the seabed requires an I-AUV able to perform a bottom-following / path-following integrated maneuver. In this adaptive survey strategy the I-AUV follows a pre-assigned surveying pattern in the horizontal plane, to guarantee proper acoustic coverage of the seabed, and a bottom-following maneuver in the vertical plane to ensure that the onboard acoustic surveying equipment will operate at a pre-specified distance from the seabed. The bottom-following control strategy to be developed here will take into account the seabed characteristics ahead of the vehicle, measured by the surveying equipment. The envisaged methodology to solve this integrated bottom-path-following control problem amounts to posing it as a discrete time path following control problem where a conveniently defined error state space model of the plant is dynamically augmented with the bathymetric preview data acquired by the look ahead sensors. This will allow the control system to see the seabed profile ahead of the vehicle as an external disturbance to be rejected by the resulting closed loop system.

Cooperation among the vehicles is essential in order to guarantee that the I-AUV is able of properly geo-reference the data produced by the on board seabed surveying sensors and to keep contact with the end use. In most cases, cooperation is achieved through the exchange of information among vehicles, implying that control mechanisms must be designed taking into account practical constraints such as limited bandwidth and intermittent communication failures. In this mission scenario the I-AUV will be acting as an accurate mobile sensor suite to acquire scientific data, while the ASC plays the role of a fast communication relay between the I-AUV and the end user, providing simultaneously accurate USBL positioning of the I-AUV with respect to the ASC.

4.3 WP3: Vehicles Intelligent Control Architecture

WP3 is responsible for providing the embedded knowledge representation framework and the high-level reasoning agents required to enable autonomy and on-board decision making of the platform.

The current state of the art for information processing and transfer in underwater vehicles is embryonic at best and mono-domain (no interaction between domains such as diagnostics and mission planning) leaving the autonomous platforms with only the capability of performing data gathering in predefined and static missions. In these missions, embedded agents work in isolation and are incapable of adapting or react to the changes sensed or processed by other agents. This work package will provide a generic and extendable semantic knowledge base framework for standardization of information storage across all agents. This architecture will provide local (agent) and global (system) situation awareness, temporal and spatial context and platform behavior, increasing the platform's operability by means of hierarchical distributed representation of the knowledge extracted from the expert and inferred from the processed sensor data. The WP will also include the implementation and integration of the high level reasoning tools required to infer new knowledge, preserve knowledge consistency and the planning agents for providing embedded adaptive solutions to the problem of procedural and declarative mission planning. Additionally, this work package also provides the planning and reasoning agents required for the high-level deliberative control of the platform.

4.4 WP4: Optical/Acoustical Image Processing

Processing the incoming optical and acoustical images and providing the other modules of the system with the relevant information of the environment is the main responsibility of WP4. Consequently, two fundamental issues arise: providing an adequate imaging infrastructure for intervention missions and developing the image processing modules acquiring the required information.

First task for WP4 is the selection of an imaging infrastructure, taking into account the relevant characteristics of the I-AUV (i.e. its structure, power availability, or its maneuvering capability, to name but a few). Geometric and radiometric calibration will follow in order to study the resulting behavior at both levels and tune the sensor to ensure the best image quality given the operational conditions of the vehicle. Specialized image processors for the different tasks must be defined, taking into account not only its specific task target, but also very frequent underwater conditions such as light attenuation and scattering, strong lighting non-uniformities and cast shadows, suspended particles or abundance of marine life on top or surrounding the target of interest.

Remaining issues derive from the very nature of intervention missions, in which the related target must be first, characterized using the data available in the multimodal maps of the working area, and then localized prior to the intervention. Both functionalities will be accomplished by the use of suitable image features followed by the application of adequate tracking and matching algorithms. On the other hand, given the complementarities of operational ranges and spatiotemporal resolutions of visual and acoustical sensors, fusion strategies will be explored, to obtain better and more robust information.

4.5 WP5: Floating Manipulation

WP5 is responsible for guaranteeing the maximum of dexterity during the execution of intervention tasks while not excluding specific work activities on submerged items, to be performed by part of the hand-arm system acting within the floating conditions exhibited by the supporting base, represented by the vehicle itself.

The movements of a manipulator attached to a light weight vehicle will affected the stabilty of the whole system. In similar situations, the existing interactions are often considered by the control designer as generic disturbances acting on separate systems, resulting on a sequential use of the vehicle and the hand-arm system (i.e. the vehicle moves while the arm is resting on it and, vice versa). In our totally light-weigh case, this might severely limit the level of dexterity that such more agile mechanical interconnections would actually allow. Thus, it will be therefore preferable considering the above mentioned interactions in terms of extra degrees of freedom added to the system by the vehicle. Consequently, the development of more sophisticated control laws and algorithms that can optimize the intervention performances will be needed.

Concerning the floating manipulation, despite station-keeping strategies are not excluded, it is worth commenting two main aspects: use of all the DOFs (vehicle and hand-arm system) for maximally improving the overall manipulation manoeuvring and performing grasping on-route, using the position/velocity of the vehicle as a moving constraint for the arm. In any case the success of such kind of manipulation, will heavily depend on the vehicle manoeuvrability. Provided that the overall control problem is formerly interpreted as a cooperative distributed control problem to be defined between the vehicle and the arm-hand system, the results clearly show how the overall structure can immediately exhibit a "self-organizing behaviour". Hence, the task execution can be guaranteed within the required performance if a moderate real-time data exchange is allowed between the two isolated controllers of the two composing agents. The integration of such sensory systems at the control coordination level will represent one of the main challenges of this WP besides those related to the adaptation to the marine environment of the existing control coordination mechanisms.

4.6 WP6: Hand+Arm Mechatronics System and Control

For the execution of underwater advanced grasp and manipulation, in WP6 it is planned to use a manipulation system composed of a redundant arm with 7 degrees of freedom and a dexterous robotic hand with at least three articulated fingers. Some expected challenges are the reduced dimension and weight of the arm/hand system, its mechanical/functional integration with the carrying platform, and the development of proper sensory equipment allowing dexterous functionalities and the use of this system in an integrated and fruitful manner with the carrying vehicle.

The final system will be composed of two new hardware subsystems: the arm and the hand. In order to reach its goals, WP6 will require a strict cooperation with WP2, 3, 5, and 7.

4.7 WP7: Multisensory based Manipulation Architecture

WP7 is responsible for ensuring that suitable manipulation actions are performed during the final intervention mission. In particular, objects to be grasped/hooked will be recognized primarily by means of the video system. This implies that a database of the most suitable grasp configurations for standard objects can be made, or that a proper procedure for selecting the optimal grasp configuration can be implemented in case of non-standard objects.

To succeed with this critical goal, several sensor inputs will be integrated inside the control loop guiding the dexterous hand to perform the previously specified intervention. An important assistance will be obtained from the knowledge-based approach previously developed by the UJI. A vision-tactile-force integration approach that has been recently proposed and validated will also be used. Moreover, different combinations, such as force-alone, vision-force or tactile-force, are also possible in case one or more sensors become unavailable. The challenge will be the adaptation of these techniques to the new underwater scenario.

Basically, the main differences found between robotic manipulation actions in air and underwater domains arise from both, perception and action. Thus, in a very hostile context like underwater, traditional sensor inputs like vision could be very poor and other kind of sensory information must be used for complementing the perception. On the other hand, the robot actions increase their complexity because the platform, the arm and the potential target are moving.

5. CONCLUSIONS

TRIDENT is a three years research project recently approved by the European Commission. Eight partners form the project consortium: Universities Jaume-I, Girona, Balearic Islands, Bologna, Genova, Heriot-Watt and Lisbon; and the company Graal Tech. The main objective of the project is the design and implementation of a methodology for multipurpose underwater intervention tasks. The project brings together research skills specific to the marine environment in navigation and mapping for underwater robotics, multi-sensory perception and a range of control techniques related to intelligent control architectures, vehicle-manipulator systems and dexterous manipulation.

The technologies to be developed would improve any underwater task requiring manipulation capabilities. Potential end-users would be companies and organizations responsible for risky or repetitive and time-consuming missions nowadays carried out by divers or ROV: offshore companies, marine rescue services or coastal and ocean observatories, among others.

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