TRIDENT: Recent Improvements about Autonomous Underwater Intervention Missions

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Abstract: The need for intervention in underwater environments is significantly increasing in the last years. Possible applications include maintenance intervention in permanent observatories and offshore scenarios, and search & recovery for collecting objects of interest for different application domains like biology, fishery, or marine rescue just to name a few. Nowadays, these kind of tasks are usually solved with "work class" ROVs (i.e. Remote Operated Vehicles) that are launched from support vessels, and remotely operated by expert pilots through an umbilical communications cable and complex control interfaces. These solutions present several drawbacks. Firstly, ROVs are normally large and heavy vehicles that need significant logistics for its transportation and handling. Secondly, the complex user interfaces and control methods require skilled pilots for their use. These two facts significantly increase the cost of the applications. Moreover, the need of an umbilical cable introduces additional problems of control, or range limitation. The fatigue and high stress that users of remotely operated systems normally suffer supposes another serious drawback. All the pointed questions justify the need of more autonomous, cheap and easy-to-use solutions for underwater intervention missions, and this is the aim of the current FP7-TRIDENT project. So, in this paper an overview concerning the main research ongoing under this project will be presented and discussed.

Keywords: Autonomous marine vehicles, dexterous manipulation, multi-robot cooperation.

1. INTRODUCTION

A few years ago, the first pioneering projects concerning underwater intervention were launched. In particular, during the mid-90s, the AMADEUS EU project achieved a step forward in the field of dexterous underwater manipulation, including within its objectives the setting-up of a system composed by two 7-DOF, ANSALDO manipulators to be used in cooperative mode (Casalino et al. (2001)).

Progressing in this context, TRIDENT, described in Sanz et al. (2010), is a research project funded by the European Commission, that started on March 2010, and will end three years later. The consortium is made up of eight partners: Universities Jaume-I (UJI), Girona (UdG), Balearic Islands (UIB), Bologna (UNIBO), Genova (UNIGE), Heriot-Watt (HWU) and Lisbon (IST); and the company Graal Tech (GT). The long term objective of the project is the design and implementation of a new methodology enabling multipurpose underwater intervention missions with a very high autonomy level. Under this project, a new AUV for Intervention (I-AUV) has been developed. This I-AUV has two main parts: the vehicle, named *Girona-500*, and the attached hand-arm system, made up by a redundant manipulator and a three-fingered dexterous hand, currently manufactured and pending of final integration. See the concept in Fig. 1, where the I-AUV first maps the area of interest and after, a user identifies a target and specifies the intervention, so the I-AUV descends again and performs the recovery action.

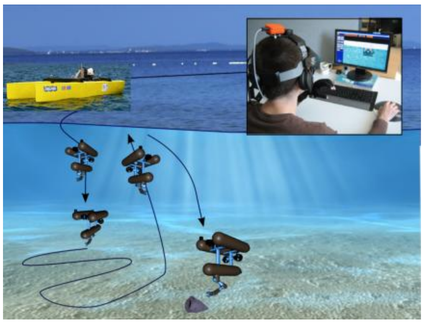

Fig. 1. The TRIDENT concept.

The aim of this paper is to give an overview concerning the research status of TRIDENT.

2. THE ONGOING RESEARCH

The work plan of this project has been divided in seven research work packages, and in the following a review will be made to clarify the current status achieved. To better understand the current situation about TRIDENT, see in Table 1, the five Milestones designed for research progress measurement and its current status of achievement.

Table 1. Milestones of TRIDENT

M1	Cooperative navigation	reached
M2	Fixed base manipulation	reached
M3	Integrated mechatronics	one month left
M4	Seaflor mapping	end project
M5	Free-floating manipulation	end project

2.1 Navigation and Mapping

Navigation and mapping are the basic functionalities required for the survey step (phase I) of the multipurpose multi-sensory based strategy proposed in TRIDENT.

Regarding the navigation solutions developed under the project several different alternatives are provided, depending on the sensor suite that equips the vehicles and the overall cooperative structure. A constructive and progressive approach towards the final goal of developing cooperative navigation systems for a formation of two vehicles is taken, with different sensor suites, always keeping global asymptotic stability as a priority, in contrast with existing solutions in the literature that resort to the Extended Kalman Filter and that do not offer GAS guarantees. As such, the problems of estimation of linear and angular motion quantities were considered separately and solid navigation algorithms are first derived for single vehicles. In particular, sensors that give absolute and relative positions, range measurements, and sensor-based solutions that take into account the direct readings of an Ultra-Short Baseline acoustic positioning system are proposed for estimation of linear motion quantities. For angular motion quantities, novel algorithms are proposed that overcome well known drawbacks of existing solutions in the literature such as singularities, unwinding phenomena, or topological limitations for achieving global asymptotic stability. The extension to two vehicles working in tandem follows, keeping the stability and performance properties of solutions derived for single vehicles. Simulation results evidence excellent and promising results for all proposed solutions. Alternatively, the scenario where the ASC is equipped with an USBL in the direct configuration, and feeds the absolute position fixes to the AUV through an acoustic modem has also been considered. EKF (Ridao et al. (2011) or ESEIF Ribas et al., (2012) vector augmentation strategies have been proposed to deal with the communication delays while providing a smooth estimation of the last trajectory piece.

With respect to the mapping, two main sensing modalities are used, namely sonar and vision, providing two types of maps, bathymetries and ortho-photomosaics. Bathymetries provide a 2.5D elevation map of the seafloor giving a global perspective of the surveyed area. They are also useful to choose promising areas for high accuracy optical survey as well as to plan paths among possible intervention sites for phase II (intervention).

The development process for the sonar-based SLAM included: 1) work on the application of probabilistic ICP for EKF pose-based 2D SLAM in structured and non structured environments, 2) Gathering experimental bathymetry data-sets from a manned boat for preliminary testing of scan matching methods with bathymetry data and 3) extending the solution to 2.5D mapping using a multi-beam profiler sonar to capture surface patches which are then registered using a 3D extension of the probabilistic ICP technique. Current efforts are dedicated to the capture of a geo-referenced data-set with G500 including multi-beam profiles and seafloor images time synchronized with USBL navigation data for ground truth.

The work on photo-mosaicing included the development of image ordering methods for supporting the incremental estimation of structure from motion, the planning of image matching and alignment for efficient mosaicing of large image sets, the mitigation of refracted sunlight on video sequences and the use of high quality blending techniques to improve the quality of the produced mosaic. Different data-sets have been collected including a water tank scenario [Prats12], a harbor scenario, and a real marine scenario, the first two of them with a direct application to the intervention. The last one has been also used for testing Visual SLAM methods taking profit of sub-mapping algorithms.

2.2 Single and Multiple Vehicles Control

The development of the vehicle controllers is currently progressing toward its final objective (implementing floating manipulation via reactive cooperation between arm and vehicle) along the following development lines.

Bottom-path following. The problem of bottom-path following, point a), has been posed as that of maintaining the intervention autonomous underwater vehicle (I-AUV) at a predefined distance from the sea floor using not only the current vertical distance but possibly also incorporating the terrain characteristics ahead of the vehicle as provided by echo sounders or sonar profilers. Preliminary studies indicate that the problem may be solved as a discrete-time path following control problem where a conveniently defined error state space model of the plant is augmented with bathymetric (i.e., depth) preview data. A suitable control design strategy will rely on piecewise affine parameter-dependent model representation that describes the I-AUV linearized error dynamics for a predefined set of operating regions. For each region, a state feedback control problem for affine parameter-dependent systems is posed and solved using linear matrix inequalities (LMIs).

Leader following. Preliminary studies indicate that the problem of leader following, point b), can be addressed as a particular case of a cooperative path-following problem of two autonomous vehicles with discrete-time periodic communications. The objective will be to steer the autonomous surface craft along a virtual path that remains on the most accurate cone of the acoustic equipment coverage. Preliminary studies indicate that Lyapunov-based techniques may be employed and the adjustment of the speed of the surface vehicle will play a key role in achieving tracking performance of the acoustic cone.

Vision based docking controller. The docking problem has been set as a tracking problem based on image measurements of a set of landmarks placed underneath the autonomous surface craft, in addition to depth readings. Preliminary studies point towards the development of a stabilization law that results from a nested saturation control design with the objective of keeping the landmarks visible in the image sensor while the underwater vehicle is approaching the surface craft.

Regarding the solution of the resulting control problem we are particularly interested in devising strategies for motion control of the I-AUV, taking into account both the dynamics and the underactuated nature of the vehicle which from the control point of view will be compensated by the camera movements.

2.3 Vehicles Intelligent Control Architecture

The main challenge when tackling a self-governing solution for a team of marine vehicles is to develop a system that can perform complex tasks reliably and with minimal operator intervention. A critical issue to achieve this is to design and build a system with the ability to deal with internal faults, changes in the environment as well as their impact on sensor outputs used for the planning phase. Therefore, this new generation of marine vehicle platforms require a certain degree of autonomy (including coordination among vehicles and underwater manipulation facilities), and a collaborative operation mode in order to minimize the operator intervention. They also have the requirement of providing on-the-fly re-planning of activities when needed.

TRIDENT proposes an Intelligent Control Architecture (ICA) to enable multiple marine vehicles to carry out autonomous multipurpose underwater intervention missions. Thus, an Autonomous Surface Craft (ASC) and an Intervention Autonomous Underwater Vehicle (IAUV) are required to work cooperatively. They are capable of cooperating towards the execution of complex activities since they have different but complementary capabilities. The ICA proposed moves away from fixed mission plans and very elementary diagnostics scheme currently used in the community to a more robust architecture to deal with the above missions. It is able to handle unexpected faults within vehicles as well, e.g. at the sensor and sensor processing levels based on either hardware failure or environmental changes. The architectural foundation to achieve the ICA lays on the flexibility of Service-Oriented Computing (SOC). Each vehicle module provides basic services which advertise their capabilities to the system. The service also publishes regular updates on its current status. In addition, a knowledge-based database captures the domain specific skills of the human expert (how to perform a specific task) as well as the dynamic information concerning the environment and platform capabilities. This makes possible to include small atomic plans to test and validate the performance of specific services. The knowledge captured enables high-level reasoning agents to monitor, refine or adapt mission plans based on the current situation.

The resulting architectural solution is a service-oriented agent-based approach which is suitable for integrating the vehicle modules (from project partners) as well as the capabilities of each marine vehicle in a collaborative manner (see Fig. 2). In the top of the figure, the system deals with hierarchical mission goals that are achieved by the execution of agent plans (sequence of command messages that invoke agents' activities). The planning of activities is carried out by matching agents' capabilities with required activities. The agents can discover each other's and monitor them in near real time.

In the bottom of Fig. 2, the activities can be seen as service processes (execution of services). They can have a basic or composite structure. The basic ones are indivisible and the composite ones can be decomposed in other activities. This composition of activities or service processes is called orchestration of services. It plays an important role in the system architecture since it can define different encapsulation levels to execute services. On the other hand, choreography of services deals with the messages exchanges among services that are executed in parallel (collaborative nature). Orchestration and choreography are terms that come from the SOC.

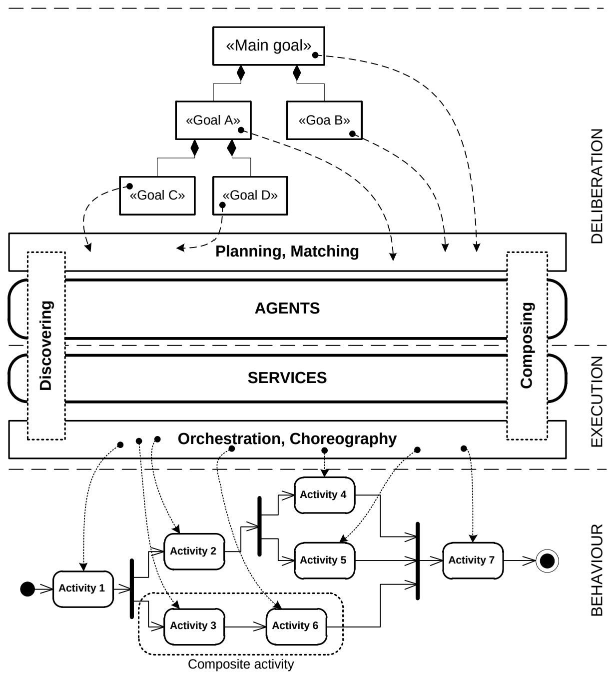

Fig. 2. Service-oriented agent-based architecture.

The ICA implementation is based on the Robot Operating System (ROS) middleware. Services or capabilities from different project partners (navigation, mapping, vision, communication, manipulation, guidance, etc.) are managed as messages, services, and actions in ROS. The approach is been tested in computer simulations, and the first tests of partial functionalities in real marine vehicles have already begun.

2.4 Optical/Acoustical Image Processing

The imaging infrastructure design and implementation and some of the main image processing modules developed for the intervention mission will be the main contributions to describe concerning this WP.

After a thorough revision of imaging systems described in the literature and technical documents, and taking into account the payload and energy sources available in the *Girona-500*, a solution based on two stereo rigs and a processing unit, has been adopted. The cameras are placed in independent waterproof cases and separated from the computer system, so the geometry of the vision system can be configured in a very flexible way, depending on the mission to carry out. Fig. 3 shows one of the cameras in its case (upper right corner) and its placement at the bow of the vehicle lower hull during a sea trail.

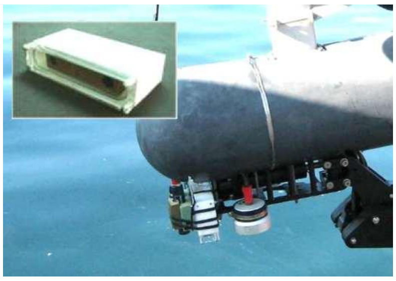

Fig. 3. One of the cameras mounted on the bow of the lower cylinder of the *Girona-500* vehicle.

Concerning the software, the vision module follows a ROS compliant architecture, according to the Trident system specifications. Thus, each service of this module is compartmentalized and implemented as nodes. The camera node is independent because it needs to reside on hardware close to or on the camera. The image node is independent because it needs to reside on the hardware used for storage. Other computationally expensive modules related to the odometer and target detection functionalities, are kept independent to allow its migration to other hardware if needed.

The first version of the odometer is a monocular two-dimensional system that achieves the mission requirements when the seabed is reasonably flat. Two methods to process three-dimensional information are under development, integrating structural information both from consecutive images and from binocular cameras.

The target localization process can be divided into four consecutive phases, from the vision point of view:

- Model Generation. Given an image and a mark for the target (e.g. an outline) the system has to generate an abstract model of the target for usage in the following phases.
- Detection. Determine if the target is inside the current camera image and where.
- Pose Estimation. After the rough position of the target is determined, its exact position and orientation has to be estimated to determine the best way of approaching for the planned intervention.
- Tracking. Due to vehicle and water movement the pose of the target in the camera image changes over time. When the target and its pose are defined, it has to be tracked to cope with this motion.

Up to now the above mentioned steps are solved using the hue and saturation channels from the HSV colour-space as colour descriptors (Prats et al., 2012). Even the simplicity of the described method, it has been demonstrated its efficiency during the field experiments made in Roses last October 2011.

2.5 Underwater Floating Manipulation with Agility Performances

The goal of WP 5 is that of designing the functional and algorithmic real-time control architecture (and relevant real-time control software) which is in charge of "coordinating the vehicle and arm motions in a concurrent way, to the aim of improving the overall performances via the system agility which follows by reducing at most the need of separate sequential motions; while also guaranteeing the fulfilment of all enabling and safety system conditions".

In order to clarify the idea, we can consider the floating Manipulator when grasping an object, once this last has been captured within the visual cone of the endowing stereo camera. In this situation we can easily note how the control problem is not only that of having the gripper precisely reaching and matching the object; since meanwhile also all a set of inequality conditions must be also satisfied. An example is provided by the following figures where, together with the indicated current two "grasping error vectors" of Fig. 4 (a), jointly representing the gripper pose with respect to the object, to be eventually zeroed); also some other vector quantities are reported in the successive Fig. 4 (b...d); where the module of each one of them measures the level of fulfilment of a corresponding inequality condition to be also achieved, and then maintained, concurrently with the grasping motion. For instance, in Fig. (b), the so called camera-centring error-vector represents the misalignment between the camera axis and the object visual line, whose module must remain below a given threshold for maintaining the camera adequately centered on the object during grasping.

However the camera should meanwhile stay not so close to the object; thus requiring the camera-height vertical error vector with a module greater than a certain minimal value. Moreover the vehicle should also stay approximately horizontal, for reducing its thruster's power consumption; thus requiring the horizontal-attitude misalignment vector to be it also with a module below a given threshold. Naturally enough, also other inequality constraints, actually not evoked by the figures, must nevertheless be accounted; like for instance those regarding the arm joint-limits constraints, its manipulability-measure, possibly its so called arm-angle and arm-postural-shape, etc., which might be they also driven, and then maintained, within specific ranges, still while grasping. In the adopted TRIDENT terminology, all inequality constraints to be achieved and maintained are denoted as set-objectives; while those requiring the zeroing of a vector are denoted as precision-objectives. By associating a suitable smooth penalty functions to each set or precision objective (with its scalar argument denoting the module of the associated error vector; and with the penalty functions for set-objectives obviously with a finite null supports within their admissible ranges) the overall control problem of eventually having all the set-objectives achieved, together with the precision ones, has been solved via the development of a procedure based on a priority task control philosophy; where higher priorities (in a sense "higher concerns") have been assigned to the progressive reductions of the set-objective penalty functions, than to those relevant to precision ones. Provided the various set and precision objectives admit a so called "non conflicting zone" (i.e. a non-void compact set of system configurations where all set-objectives can be achieved; which in turm must contain the non-void subset of those syetem confgurations also satisfying the precision objectives) then the devised procedure for assigning the system velocity vector (i.e. the arm joint velocity vector, plus the vehicle linear and angular velocity ones), which follows from the adopted control philosophy, guarantees the eventual entering of the system configuration within such non conflicting zone; and then the prosecution toward the eventual achievement of the precision objectives, as well. Some important features of the developed procedure can be summarized as follows:

- Once all set objectives have been achieved (i.e. the system has ntered the non-conflicting zone) then the residual motions for also achieving the precision ones cannot perturb the any of the set-objective achievements (i.e. the system cannot exit the non-conflicting zone).

- Its algorithmic core-structure allows the management of both set and precision objectives in a totally uniform manner (i.e. without making any computational distinction between the two) while also resulting considerably simpler than the one early developed in Siciliano et al. (1991) for precision-only objectives.

- It parallels the one very recently proposed by Kanoun et al. (2011), whose proposed procedure also includes set-objectives, other than precision ones. Also with respect to this last, the control procedure developed within TRIDENT howvere results considerably simpler, just in force of the previous point; since (oppositely to waht proposed by Kanoun et al. (2011)) no systems of linear inequalities need to be cumbersomely solved.

We should however note how the above outlined procedure, just in the form it has been presented, actually assigns priorities to the different objectives only, and not to the motions of the mechanical subsystems composing the overall one (i.e., in the TRIDENT case, the arm and the vehicle). If no adequate measures are taken, the net result of this is that of imposing the motion to the whole structure, even for tasks where the sole motion of the lighter arm would actually be sufficient. This drawback can howver be avoided by simply reformulating the same procedure within the framework of a dynamic programming technique to be applied along the composing subsystem chain; which automatically allows the vehicle moving for helping the arm only when needed (apart possibly moving for achieving its own specific objectives); while also introducing, as a by-product, two other important advantages; namely:

- The automatic compensation of possible disturbance superimposed to the vehicle velocity (i.e. sea current), provided the vehicle velocity can be measured (via for instance the on-board DVL and Gyros)

- The automatic management of the multirate case; as it actually is within the TRIDENT system, where the arm and the vehicle are controlled at the different sampling rates of 100 Hz and 10 Hz, respectively.

Since such properties are actually the natural outcome of the application of dynamic programming along the chain, they are not so easily identifiable within any other "whole system approach" to its control.

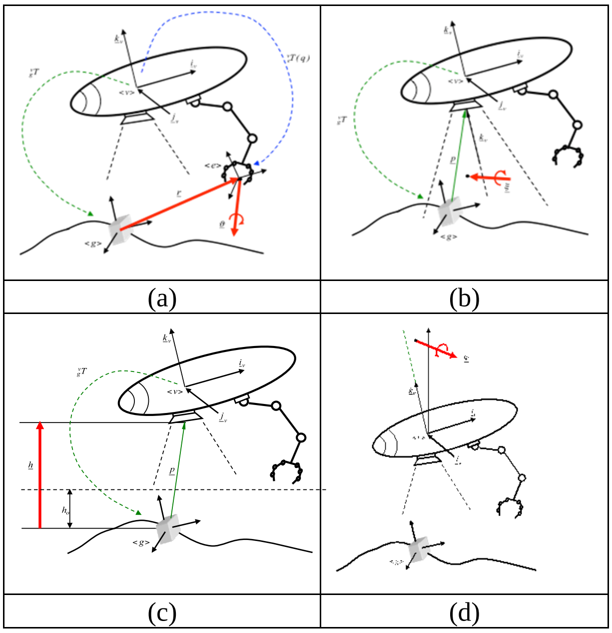

Fig. 4. Floating manipulation grasping an object.

2.6 Hand+Arm Mechatronics System and Control

The main objectives of this WP6 have been the definition of the main specifications for the manipulation (arm/hand) system, its design and implementation. Concerning the specifications for the manipulation systems, and based on the analysis of the TRIDENT reference mission, a 7 DOF arm and a three-fingered hand with tactile sensors included, have been recently implemented, see Fig. 5.

An important aspect for the design of the hand-arm system has been the selection of the actuation system. To this aim two alternative solutions, namely electric and hydraulic, were considered. Finally, the electric solution was adopted, enabling a more precise control system and also lighter configuration than the corresponding hydraulic one.

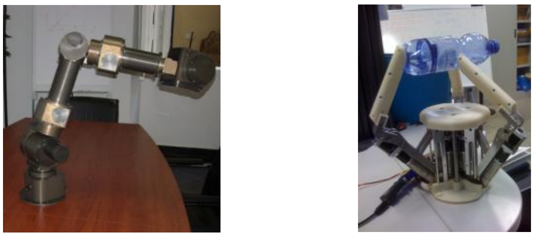

Fig. 5. (Left) the 7 DOF arm. (Right) the three-fingered dexterous hand.

The next step now is the integration of the hand and the arm, from the mechanical, electrical and control points of view, and finally, with the vehicle previously developed (i.e. *Girona-500*).

2.7 Multisensory based Manipulation Architecture

WP7 is responsible for ensuring that suitable manipulation actions are performed during the final intervention mission. As has been aforementioned, one of the main objectives of TRIDENT is the improvement of the intervention capacities beyond the state-of-the-art. Currently, the robotic manipulation systems are very specialized and it is difficult to implement a system that is able to simultaneously open a valve, manage a tool, press a button, or simply grasp an object. In particular, a new methodology for multipurpose manipulation was successfully proved recently by Prats et al., (2010), and one of the main goals of our work package is to adapt it to the underwater robotics scenario using multiple sensors. The second main objective is to integrate all these methods into knowledge based manipulation architecture and define and implement a clear interface that links the manipulation software with the high-level architecture of TRIDENT. For this, perception and action modules must be suitably organized into a layered knowledge-based architecture providing a manipulation service to the high-level layer.

In order to validate our sensor-based methods, several experiments have been performed in different conditions. First of all, the experiment concerning “Object recovery from a fixed base manipulator” was carried out with successful results. Then, other experiments were performed, involving grasping and hooking actions in water tank conditions. In a first approach, the robotic arm was assembled into a fixed structure. In a second attempt, the manipulator was attached to the Girona-500 I-AUV, and object recovery with a non-fixed base was demonstrated. The obtained results are beyond the expectations, and further experiments demonstrate the suitable progress of WP7 towards the TRIDENT objectives.

Currently, a total of four different sensors are being considered, some of them already tested in water tank conditions, the rest tested in the ground and being adapted for underwater. Vision and laser scanning approaches have been developed and applied for pose estimation, 3D reconstruction, grasp planning and visual servoing. Real experiments in water tank conditions have been carried out with satisfactory results using these sensors. On the other hand, force and tactile sensors have been integrated into manipulation controllers and tested with a manipulator in ground. The underwater counterparts of these sensors will be available in the next months.

3. DISCUSSION

An overview of an ongoing project named TRIDENT, highlighting the main research aspects currently in progress, has been presented. By now, all the Milestones, Deliverables and goals have been achieved in due time, approaching so with optimism to the second annual review during the next spring of this year.

ACKNOWLEDGEMENTS

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REFERENCES

Casalino, G. et al., (2001). Dexterous Underwater Objet Manipulation via Multirobot Cooperating Systems. In Proceedings of the IEEE International Conference on Robotics and Automation, Seoul, Korea, 3220-322.

Kanoun, F., et al., (2011). Kinematic control of redundant manipulators: generalizing the task priority framework to inequality tasks, IEEE trans. on Robotics, 27(4), pp.785-792.

Marani, G., et al., (2009). Underwater autonomous manipulation for intervention missions AUVs. Ocean Engineering, 36, 15–23.

Prats, M., et al., (2010). A framework for compliant physical interaction: the grasp meets the task. Journal of Autonomous Robots (special issue on autonomous mobile manipulation), 28(1), pp. 89-111.

Prats, M., et al., (2012). Reconfigurable AUV for intervention missions: a case study on underwater object recovery. Intelligent Service Robotics, 5(1), pp. 19-31.

Ribas, D., et al., (2012). Delayed State Information Filter for Aided-USBL AUV Navigation. Accepted for publication in the 2012 IEEE International Conference on Robotics and Automation.

Ridao, P., et al., (2011). USBL/DVL Navigation through Delayed Position Fixes IEEE International Conference on Robotics and Automation, pp. 2344-2349.

Sanz, P. J., et al., (2010). TRIDENT: A Framework for Autonomous Underwater Intervention Missions with Dexterous Manipulation Capabilities, in the 7th Symposium on Intelligent Autonomous Vehicles, Lecce (Italy).

Siciliano, B., et al., (1991) A general framework for managing multiple tasks in highly redundant robotic systems, in International Conference on Advanced Robotics, pp. 1211–1216.