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Intervention AUVs: The Next Challenge ⋆

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Abstract: While commercially available AUVs are routinely used in survey missions, a new set of applications exists which clearly demand intervention capabilities. The maintenance of: permanent observatories underwater; submerged oil wells; cabled sensor networks; pipes; and the deployment and recovery of benthic stations are but a few of them. These tasks are addressed nowadays using manned submersibles or work-class ROVs, equipped with teleoperated arms under human supervision. Although researchers have recently opened the door to future I-AUVs, a long path is still necessary to pave the way to underwater intervention applications performed in an autonomous way. This paper reviews the evolution timeline in autonomous underwater intervention systems. Milestone projects in the state of the art are reviewed, highlighting their principal contributions to the field. To the best of the authors knowledge only three vehicles have demonstrated some autonomous intervention capabilities so far: ALIVE, SAUVIM and GIRONA 500 I-AUV. Next, GIRONA 500 I-AUV is presented and its software architecture discussed. Recent results in different scenarios are reported: 1) Valve turning and connector plugging/unplugging while docked to a sub-sea panel, 2) Free floating valve turning using learning by demonstration, and 3) Free floating multipurpose multisensory based object recovery. The paper ends discussing the lessons learned so far and presenting the authors view of the future.

Keywords: Autonomous Vehicles, Robotic Manipulators, Marine Systems

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1. INTRODUCTION

Nowadays a relevant number of field operations with unmanned underwater vehicles (UUVs) in applications like marine rescue, marine science and the offshore industries, to mention some but a few, need intervention capabilities in order to perform the desired task. In such scenarios, most of the intervention operations are being 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 operation with direct view to the object being manipulated. Their drawbacks are the reduced time for operation (typically a few hours), the human presence in a dangerous and hostile environment, and a very high cost associated with the need of an expensive oceanographic vessel to be operated. 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 ROVs 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 of opportunity reducing considerably the cost.

This paper surveys the principal achievements of the research community during the last 20 years of research and development in the field of autonomous underwater vehicles for intervention. First, relevant application domains for such technology are presented. Next, in Section 3 the most important projects undertaken in this area are reviewed pointing out their main contributions. In Section 4, the GIRONA 500 I-AUV recently developed is presented and its software architecture is reported in Section 5. A summary of the most relevant experimental results achieved so far with this I-AUV are reported next. Finally, the main lessons learned are reported and a long term view of the future is outlined before concluding.

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2. INTERVENTION APPLICATIONS

2.1 Oil and Gas Industry

The oil & gas Industry is one of the principal users of underwater robotics technology. It uses work-class intervention ROVs to routinely inspect and repair the submerged infrastructures. AUVs have recently entered in this market, being already used to undertake geophysical surveys prior to pipe installation and, later on, for their inspection. The use of hovering type AUVs for the inspection of 3D infrastructures like submerged oil wells, chains, risers, etc... has started to be considered, although still in a research stage, since they represent major challenges for nowadays field capabilities. Few simple intervention tasks have also started to be considered by the research community. For instance, proof of concept demonstrations for tasks like acoustic-based homing to a sub-sea panel, real-time vision-based localization relative to it, docking and opening a valve or plugging a hot stab have already been demonstrated in simplified mock-up environments.

2.2 Search and Recovery

I-AUVs have a great potential in fast recovery of black-boxes since they can be easily mobilized using commercial airplanes world wide. Moreover, they can be launched from inexpensive ships of opportunity (not requiring DP) which are much easy to find available than the expensive intervention/oceanographic vessels needed to deploy work-class intervention ROVs. With the intervention area localized and constrained with the help of acoustic methods (ACSA-ALCEN (2013)), these light I-AUVs could be deployed very fast, and taking profit of their high degree of automation, the recovery could be more easily achieved at a reduced cost.

2.3 Deep water Archeology

During a significant part of the human history (one million years), the continental shelf was wider than nowadays. The sea level was about 130 m lower, and these coastal and lowland landscapes were attractive for human settlement. About 16000 to 6000 years ago, after the last Ice Age, the sea level increased until current levels and these territories were drowned hiding important clues of our historical heritages. Shipwrecks, and in particular deep-sea wrecks (which may not be easily pillaged), are also a very important source of historical information. Underwater archaeologists are primarily interested in documenting submerged sites. High resolution 2D/3D seafloor mapping techniques are of high interest for them. Few precedents of deep underwater excavations exist and mostly using high cost *adhoc* hardware or expensive ROV operations. However, most of the archaeological institutions have no access to these equipment. They have only access to small boats not equipped for deep sea interventions. Therefore, small and light HROVs first, and I-AUVs later on, have a great potential to assist archaeologists beyond 50 m depth.

2.4 Science

Permanent observatories are artificial infrastructures located on the seabed. These observatories need periodic maintenance that includes tasks like downloading vast amounts of data (for isolated non-cabled observatories), connecting/disconnecting a cable, replacing batteries, instrumentation de-fouling, as well as placing and recovering sensor packages. I-AUVs have a direct application here, since they have the potential to be operated from inexpensive ships of opportunity drastically reducing the associated costs.

3. STATE OF THE ART

During the last 20 years, AUVs have become a standard tool for mapping the seafloor using optical (Eustice et al. (2006)) and acoustic (Paduan et al. (2009)) sensor modalities, with applications to dam inspection (Ridao et al. (2010)), marine geology (Escartín et al. (2008)) and underwater archaeology (Bingham et al. (2010)) to mention some but a few. After years of research, few autonomous platforms are already available in the market, most of them able to perform side scan sonar and bathymetric multi-beam surveys. Other functionalities, mostly related to optical mapping like 2D photo-mosaics, are not yet available through off-the-shelf applications although they have been extensively demonstrated in field application by several research institutions (Richmond and Rock (2007); Sigh et al. (2004); Ferrer et al. (2007)). 3D optical maps are nowadays one of the major fronts of research with some implementations already available based on monocular structure from motion (Pizarro et al. (2009); Nicosevici et al. (2009)), stereo (Johnson-Roberson et al. (2010)) and laser scanners (Inglis et al. (2012)).

However, a large number of applications exist which go beyond the survey capabilities. The maintenance of permanent observatories, submerged oil wells, cabled sensor networks, pipes, and the deployment and recovery of benthic stations, or the search and recovery of black-boxes are just some of them. Nowadays, these tasks require the use of work-class ROVs deployed from DP vessels making them very expensive. To face these new applications, the research to increase the autonomy of underwater intervention systems started early in the 90s with the pioneering works of OTTER (Wang et al. (1995)), ODIN (Choi et al. (1994)), UNION (Rigaud et al. (1998), Fig.2) and AMADEUS (Lane et al. (1997), Fig.1), but it was not until the 1st decade of the 21th century that field demonstrations arrived. Very successful approaches where based on hybrid ROV/AUV concepts like the one proposed by the SWIMMER project (Evans et al. (2001), Fig.3) where an AUV shuttle transporting a ROV, autonomously homes and docks into a seabed docking station. Next, the ROV, which is connected through the docking device to a remote operation station, is tele-operated during the intervention. The system avoids the need for a DP-capable ship with the consequent savings. Recently, another hybrid concept appeared, the HROVs (Hybrid ROV) (Fletcher et al. (2008)). These vehicles are essentially AUVs, reconfigurable as ROVs when tethered through an optical fiber umbilical. Thanks to its ultra light umbilical, HROVs may also be operated from ships of opportunity without DP. When plugged, HROVs behave as conventional ROVs avoiding some of the difficulties related to the cable. Moreover, they have the capability of detaching the cable before surfacing autonomously. The most advanced demonstration up to date has shown a wireless tele-operated intervention using a led light communications system from the HROV to an underwater gateway connected to an umbilical (Farr et al. (2010), Fig.9). Nevertheless, both systems keep the human within the control loop. The first fully autonomous intervention at sea, was demonstrated by the ALIVE project (Evans et al. (2003), Fig.4), where a hovering-capable AUV was able to home to a sub-sea intervention panel using an imaging sonar, and then, docking into it with hydraulic grasps using visual feedback. Once attached to the panel, a very simple manipulation strategy (fixed base manipulation) was used to open/close a valve. First object manipulation from a floating vehicle (I- AUV) was achieved in 2009 within SAUVIM project (Marani et al. (2009), Fig.5), demonstrating the capability of searching for an object whose position was roughly known *a priori*. The object was endowed with artificial landmarks and the robot autonomously located it and hooked it with a recovery device while hovering. Finally, the first multipurpose object search and recovery strategy was demonstrated in the TRIDENT project in 2012 (Fig.6). First, the object was located using a down-looking camera and photo-mosaicing techniques. Next, it was demonstrated how to autonomously "hook" the object in a water tank (Prats et al. (2011)). The experiment was repeated in a harbour environment using a 4 DOF arm (Prats et al. (2012a)), and later with a 7DOF arm endowed with a 3 fingered hand (Sanz et al. (2012), Fig.21).

Nevertheless, according to (Gilmour (2012)) "Long-term AUV vision" the technology for light intervention systems is still immature, but very promising. I-AUVs are currently in level 3 out of 9 (9 meaning routinely used) of the development cycle necessary to adopt this technology in the oil and gas industry, being expected to achieve up to level 7 by the end of 2018. I-AUVs will be necessary for efficient development of deep-water fields in particular those where there are long sub-sea tie-backs with no surface facilities. They will be even more critical in future under ice activities with limited vertical access. Other application domains, like permanent scientific underwater observatories, share most of the same needs and problems (Drogou07 (2007)): inspecting and surveying with video, performing manipulation tasks, docking to infrastructures and devices, sub-systems carrying and depositing, and handling surface-wire guided deployments/recoveries of devices. Plugging connectors, changing batteries, placing and recovering instruments are common activities, which would benefit from these autonomous manipulation skills.

In the next subsections the more representative projects involving autonomous intervention are reviewed in a chronological order, remarking their main contribution as well as the principal results achieved.

3.1 Relevant Research Projects

AMADEUS 1993-99 Phase I represents the first attempt to develop a dexterous gripper suitable for underwater applications. The three fingered gripper was hydraulically actuated and coordinately controlled by mimicking, within each finger, the motions of an artificial elephant trunk. Phase II was devoted to the coordinated control of two underwater 7 DOF electro-mechanical arms. Each arm weighs 65 kg, measures 140 cm, and is filled with oil enabling it to reach a depth of 500 m. To the best of the authors knowledge, AMADEUS represents the first demonstration underwater of an elctrical 7DOF arm with similar capabilities of those provided by of the shelf industrial manipulators. The project demonstrated the coordinated motion of the two end-effectors while manipulating a rigid object inside a water tank.

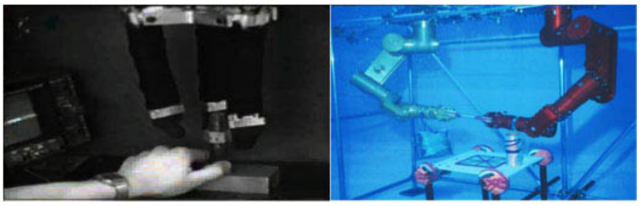

Fig. 1. AMADEUS concept

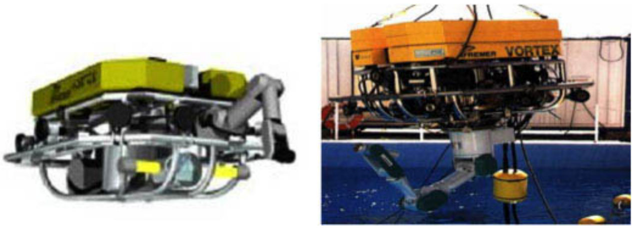

Fig. 2. UNION concept

UNION 1996-99 This was a pioneering project with the aim to develop methods for increasing the autonomy and intelligence of ROVs. The project focused mainly on the development of coordinated control and sensing strategies for combined manipulator (PA10) and vehicle (VORTEX) systems. The joint dynamics of the vehicle-manipulator system were studied and a robust non-linear control was proposed. To the best of the author's knowledge, UNION represents the first mechatronic assembly of a complete vehicle-manipulator system for automated manipulation. Nevertheless, authors have failed to find published experimental manipulation results with the complete vehicle-manipulator.

SWIMMER 1999-01 SWIMMER 1999-01 is a hybrid AUV/ROV intervention system conceived for the permanent Inspection, Maintenance, and Reparation operations over deep water oil production facilities. A ROV umbilical is integrated between the surface facility and the sub-sea site. The SWIMMER system is composed of an AUV shuttle which transports an intervention ROV to the sub-sea. SWIMMER is able to autonomously transit to the seafloor and dock to a sub-sea cradle-based docking station. The cradle is cabled to the teleoperation site. Once docked, the transported ROV is deployed and connected to the shuttle and through it to the docking station by means of an excursion umbilical. The intervention is carried out in a conventional teleoperated way. SWIMMER contribution consist on getting rid of the TMS and the expensive intervention vessel.

ALIVE 2001-04 ALIVE is a milestone project in autonomous underwater intervention. The ALIVE 3.5 Ton vehicle is equipped with two hydraulic grasps for docking and a 7 DOF manipulation arm. It has been reported as

Fig. 3. SWIMMER concept

Fig. 4. ALIVE concept

Fig. 5. SAUVIM concept

the first AUV able to autonomously carry out a manipulation action consisting in opening/closing a valve in a sub-sea panel. ALIVE intervention concept is based on docking to a sub-sea panel to perform fixed-base manipulation. There is no interaction between the arm and the vehicle, and hence, the manipulation, becomes a conventional single arm manipulation but underwater. During the final demo of the project ALIVE proved its capability to autonomously navigate, dock and open a valve on an underwater panel similar to those of the oil industry.

SAUVIM 1997-09 SAUVIM is also a milestone project. It was funded by the Office of Naval research and carried out at the Autonomous System Laboratory of the University of Hawaii. It was coexistent with ALIVE, but it proposed a very different approach to autonomous intervention. SAUVIM focused on the free floating manipulation concept. Having the AUV an approximate weight of 6 Tons and weighting the arm only 65 Kg, both system behave practically uncoupled. The perturbation of the AUV due to the motion of the arm is negligible, and hence they had uncoupled controllers. SAUVIM demonstrated accurate navigation and station keeping being the first project to show autonomous recovery of an *a priori* known object. It is worth noting that SAUVIM used the ANSALDO arm previously built in the context of the AMADEUS project.

RAUVI 2009-11 RAUVI is an Spanish funded project which was devoted to the design and implementation of a Reconfigurable AUV for Intervention Missions. The major outcome of RAUVI was the implementation of the GIRONA 500 I-AUV (Ribas et al. (2012)) which was equipped with the ECA/CSIP electrically driven arm with 4 DOFs (Fernandez et al. (2013)). The AUV was also equipped with a stereo pair and was used to demonstrate autonomous object recovery in a water tank environment (Prats et al. (2012c)). To the best of author's knowledge, after ALIVE and SAUVIM, RAUVI is the 3rd project which demonstrated experimentally autonomous intervention capabilities, being the lightest one (less than 200 Kg). RAUVI became the seed of a wider EU project named TRIDENT.

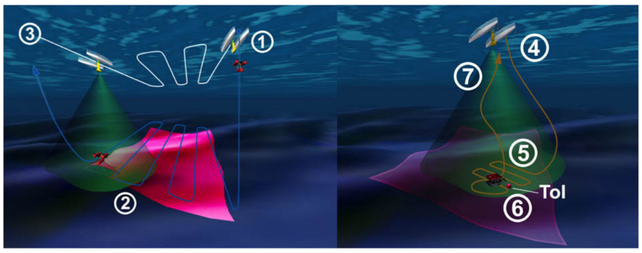

Fig. 6. TRIDENT concept

TRIDENT 2010-12 This project proposed a new methodology for multipurpose underwater intervention tasks. A team of two cooperative heterogeneous robots with complementary skills, an ASC and an I-AUV endowed with a dexterous 7 DOF manipulator and a 3-fingered hand, is used to perform underwater manipulation tasks. TRIDENT concept is based on two phases: survey and intervention. During survey, the tandem vehicles map the seafloor. Next, the I-AUV is recovered and a seafloor map is built. Next, the user selects an object and a desired intervention task and the I-AUV is launched again to navigate to the target. The vehicle searches the target and perform a multisensory-based intervention in free-floating manipulation. TRIDENT concept has been demonstrated in a harbour environment in an uncoupled way: 1) The capability of both vehicles working in tandem during mapping and 2) the capability of the I-AUV to intervene over the target. As an evolution of RAUVI, TRIDENT has become, together with ALIVE and SAUVIM, a milestone project in autonomous underwater manipulation, providing for the first time field results in multipurpose object recovery.

TRITON 2012-14 Is a Spanish funded project which aims to demonstrate intervention capabilities in a permanent submerged observatory. The intervention tasks to be demonstrated include docking to a custom sub-sea panel, fixed-based manipulation for both valve turning and hot stab connection, and free floating manipulation for camera dome de-fouling. The final demonstration will be carried out in the OBSEA (Aguzzi et al. (2011)) expandable seafloor observatory cabled to the shoreline in the Catalan coast. The final experiments plan to demonstrate high bandwidth data communication between the I- AUV and the observatory and from it to the world wide web through the observatory web page.

PANDORA 2012-14 The main goal of PANDORA is to make autonomous robots persistently autonomous, reducing the frequency of assistance requests. The key of this objective is the ability to recognise failure and respond to it, at all levels of abstraction and time constant. The

Fig. 7. TRITON concept

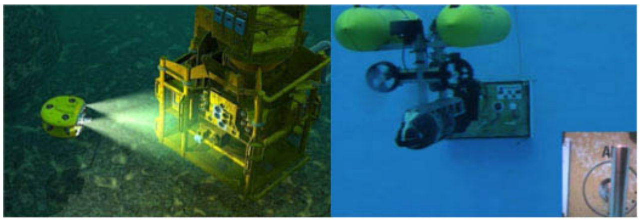

Fig. 8. PANDORA concept

project develops three themes: (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 center its validation tasks on AUVs acting in an oilfield scenario in which the robots perform inspection, cleaning and valve turning.

Hybrid AUV inspection, monitoring, and intervention of seafloor and sub-seafloor pipelines This very recent project (Kaiser (2013)) proposes the cooperation of a surface vehicle and an underwater one. In this case a wave glider is used at surface for vehicle tracking and communications gateway. A HROV, working in AUV mode, is used to perform autonomous survey close to the seafloor, for instance looking leakages in buried pipes. If an anomaly is detected, the underwater vehicle performs a detailed survey of the area while waiting for the assistence of a surface support vessel. By lowering an optical communications package, the surveyed data is downloaded and the vehicle is switched to ROV mode to perform a light intervention while a work-class is brought to the site for heavier work. Although this is a very recent project, wireless intervention through the teleoperation of NEREUS HROV through a high bandwidth opto/acoustic modem has been already demonstrated recently (Farr et al. (2010)).

4. GIRONA 500 I-AUV

The GIRONA 500 (Ribas et al. (2012)) is a compact-size I-AUV designed and developed in the university of Girona for a maximum operating depth of 500 m. The vehicle is built around an aluminum frame which supports three torpedo-shaped hulls as well as other elements like the thrusters. The overall dimensions of the vehicle are 1 m in height, 1 m in width, 1.5 m in length and a weight (on its basic configuration) of about 140 Kg. The two upper hulls, which contain the flotation foam and the electronics housing, are positively buoyant, while the lower one contains the more heavy elements such as the batteries and the payload. This particular arrangement of the components provides the vehicle with passive stability in pitch and roll, making it suitable for tasks requiring a stable platform such as video surveying or intervention.

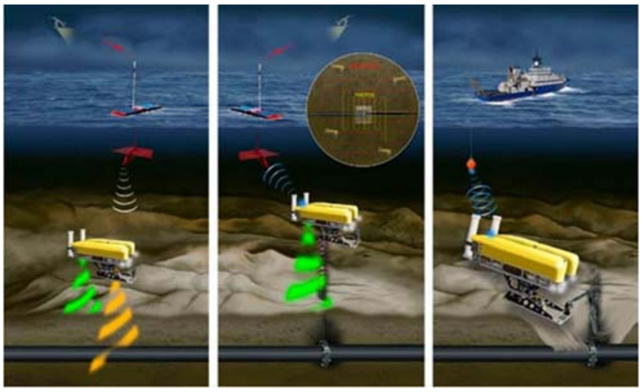

Fig. 9. Hybrid AUV inspection, monitoring, and intervention of seafloor and sub-seafloor pipelines concept.

The most remarkable characteristic of the GIRONA 500 I-AUV is its capacity to reconfigure for different tasks. On its basic configuration, the vehicle is equipped with typical navigation sensors (DVL, AHRS, pressure gauge and USBL) and a basic survey equipment (profiler sonar, side scan sonar, video camera and sound velocity sensor). In addition to these sensors, almost half the volume of the lower hull is reserved for mission-specific payload, which makes possible to modify its sensing and actuation capabilities as required. A similar philosophy has been applied to the propulsion system which can be set to operate with a different number of thrusters, ranging from 3 to 8, to actuate the necessary degrees of freedom and provide, if required, some degree of redundancy.

In the context of autonomous intervention, three different payloads have been developed. The first one (Fig.10-b) was developed in the context of the RAUVI spanish project and was composed of a light duty 4 DOF electrical manipulator, a video system and their corresponding control electronics. The main goal of the project was to perform a two-step autonomous underwater intervention mission consisting of an initial video survey phase in which a particular object was localized, and then retrieve this object using a hook attached to the robotic arm. This same configuration has been later used in the TRITON Spanish project to demonstrate more challenging tasks, such as the manipulation of valves and connectors, while docked at an intervention panel using a simple gripper as end-effector. The second payload (Fig.10-a) was developed as part of the TRIDENT FP7 project. The main difference with the previous one is the higher level of dexterity of the system achieved with a 7 DOF manipulator and a three-fingered hand. This made possible to demonstrate grasping capabilities for recovery tasks, while opening the door to the manipulation of objects with more complex shapes. Finally, the last payload (Fig.10-c) was built for the PANDORA FP7 project. A new small size 4 DOF arm was integrated into the GIRONA 500 I-AUV to demonstrate the autonomous free-floating operation of valves on an intervention panel. For that purpose, a fixed tool was installed as end-effector to actuate the valves, with the

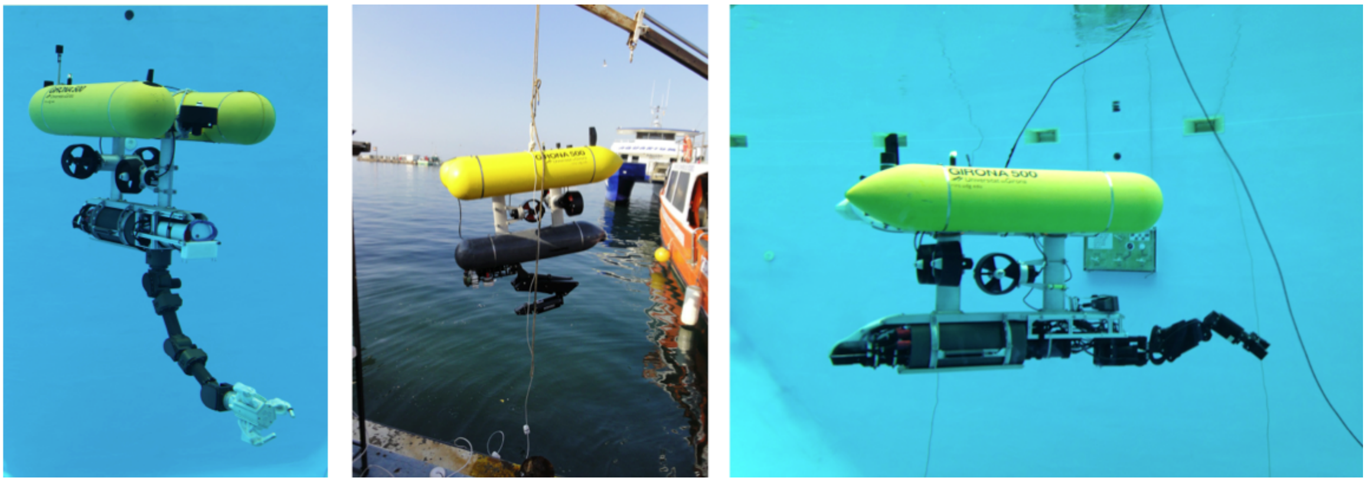

Fig. 10. GIRONA 500 I-AUV in: a) TRIDENT configuration with the GRAALTECH 7DOF arm and the 3 fingered hand developed by university of Bolonia; b) RAUVI/TRITON configuration with the ECA/CSIP Light Weight 4 DOF arm; c) PANDORA configuration with the ECA/CSIP Micro 4 DOF arm.

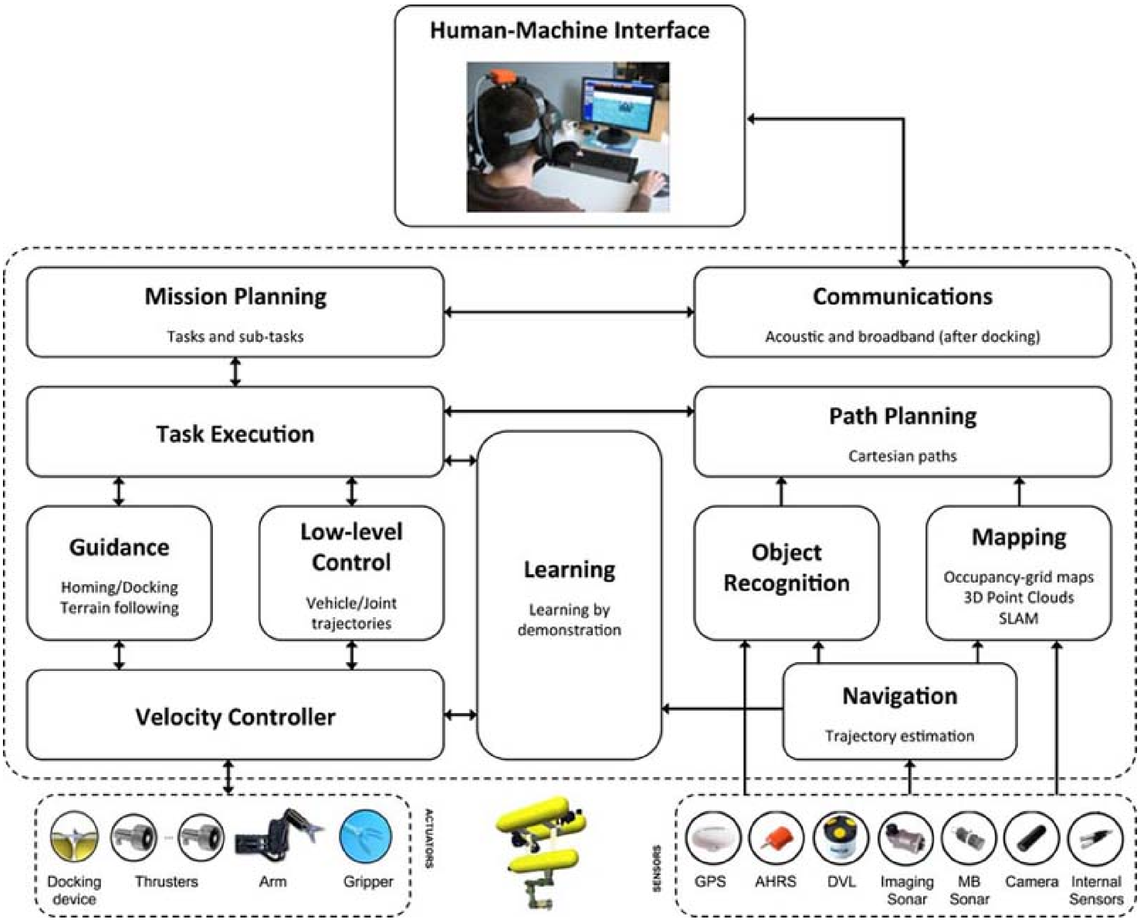

Fig. 11. GIRONA 500's System Architecture

arm mounted on the front part of the vehicle to provide a more convenient workspace.

5. COLA2: GIRONA 500'S SYSTEM ARCHITECTURE

GIRONA 500's system architecture, termed COLA2 (Component Oriented Layer-based Architecture for Autonomy), allows to control the AUV during survey and intervention missions. A block diagram describing the architecture is shown in Fig. 11. The architecture consists of a vehicle interface module with device drivers for sensors and actuators in connection with a perceive-plan-act (PPA) module. The PPA module constructs a representation of the world using sensor measurements including images, point clouds and ranges. An estimate of the robot's trajectory is maintained by the Navigation component, and this estimate is used by the Object Recognition and Mapping components. The Object Recognition component uses *a priori* knowledge to seek for matchings between sensor measurements and object models. The Mapping component maintains a multi-modal 3D representation of the world and uses it to provide feedback to the Navigation component via SLAM.

The Mission Planning component monitors the execution of a mission plan consisting of a sequence of tasks received from the user via the Human-Machine Interface and Communications components. The Task Execution component executes each task during a mission making use of the Path Planning component for generating collision-free Cartesian paths and of the Learning component to perform manipulation tasks. The tasks are executed by sending position setpoints to the Guidance and Low-level Control components, which generate velocity requests. Finally, the Velocity Controller component finally transforms the desired velocity requests to setpoints that are sent to the actuators.

6. EXPERIMENTS

During the last years the authors of this paper have found very useful the definition of realistic mission scenarios to drive our research and development. Forcing ourselves to demonstrate the technology in realistic scenarios or mock-ups, roots our work to real problems that must be solved to make autonomous intervention a reality. In order to allow for a smooth transition from simulation to experimental validation, the proposed scenarios are implemented at least at three levels of complexity: 1) Graphical simulation, 2) Water tank testing and 3) Sea trials. In all cases, the condition of the experimental setup are clearly defined and easy to reproduce by third parties in order to promote reproducible research. In this section, the experimental scenarios being used in our recent projects are described and the already available results highlighted.

6.1 Sub-sea Panel Docking and Fixed-Base Manipulation

This is the simplest and easiest scenario but also the closer to nowadays field applications.

Problem statement Given a sub-sea panel equipped with a funnel-based docking mechanism, and a visual feature-rich textured panel to allow for real-time vision based localization, the I-AUV starts at a random position with the panel in the field of view (it is assumed to have reached the panel vicinity by acoustic means) and docks autonomously to the panel. Next, it has to be able to complete an autonomous valve turning and connector plugging/unplugging actions. The valve and the connection have been placed inside the manipulator working space. A custom made connector based on a hot stab has been designed with passive accommodation. To allow for a easy reproduction by third parties, the docking station (Fig.15) is made with cheap aluminum profiles, a digital image has been printed and laid on the panels, and the components (funnels, valve and connector) have been printed in 3D.

Arm initialization and visual servoing Prior to the experiment, when the I-AUV is started, the arm must be initialized in order to know its zero position in the join space. To this aim each join is moved to its mechanical limit where its zero is fixed. Later on, the hall effect sensors located in the electrical motors are used to track the join angles. Nevertheless, the uncertainty in the kinematics model and the non linearities in the linear-to-circular transmission used to move the rotative joins by means of electrical driven pistons, are responsible for the inaccuracy of the Cartesian position of the end-effector, in particular at the boundaries of the working space. To solve this issue, a visual servoing approach has been followed. An ARToolKit Marker (see Kato and Billinghurst (1999)) has been placed in the jaw grip. Placing the arm in a known position, and locating the marker with the camera, allows to estimate the camera to robot base transformation (${}^{b}M_{c}$). Later, each time the marker is detected within the camera, its pose is measured and using the arm inverse kinematics, the manipulator position in the configuration space is updated. This approach mitigates the arm inaccuracies ensuring consistency between the arm and the valve/connector poses.

Panel detection Detection of the underwater panel is performed using vision by comparing the images from the camera against an *a priori* known template of the panel. By detecting and matching unique features in the camera image and template, it is possible to detect the presence of the panel, as well as accurately estimate its position/orientation when a sufficient number of features are matched.

In this work, we choose the oriented FAST and rotated BRIEF(ORB) (Rublee et al. (2011)) feature extractor for its suitability to real-time applications. The ORB feature extractor relies on features from accelerated segment test (FAST) corner detection (Rosten and Drummond (2006)) to detect features, or keypoints, in the image. These are obvious features to detect in man-made structures and may be detected very quickly. Moreover, there is a descriptor vector of the keypoints based on binary robust independent elementary features (BRIEF) (Calonder et al. (2010)). This allows us to rapidly obtain the difference between descriptors and allows real-time matching of keypoints at higher image frame-rates when compared to the other commonly used feature extractors such as scale invariant feature transform (SIFT) (Lowe (2004)) and speeded-up robust features (SURF) (Bay et al. (2008)).

Figure 12 illustrates the matching between the panel template and an image received from the camera. A minimum number of keypoints must be matched between the template and the camera image to satisfy the panel detection requirement. A low number of matched keypoints indicates that the panel is not in the camera field of view. The correspondences between the template and camera image can be used to compute the transformation (or homography) of the template image to the detected panel in the camera image. This allows us to compute the image-coordinates of the corners of the panel in the camera image. Using the known geometry of the panel and the camera matrix, we are able to determine the pose of the panel in the camera coordinate system (Palomeras et al. (2013)).

Docking The vehicle starts in the vicinity of the panel with a visual contact already established. The above

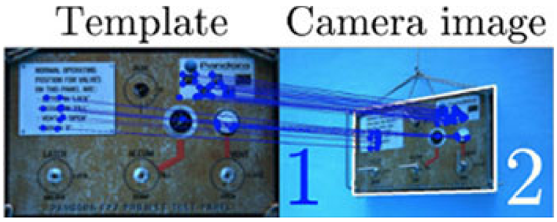

Fig. 12. Vision-based localization with respect the panel.

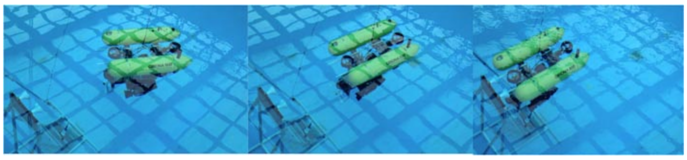

Fig. 13. Docking Sequence.

mentioned vision-based localization algorithm is used to compute the panel position with respect to the robot. Next, and single landmark SLAM problem (Palomeras et al. (2013)) is instantiated so the robot and panel position become known in the world frame. With the panel mapped, vehicle localization improves significantly due to visual feedback provided by the visual detector every time that the intervention panel is identified. The state machine governing the robot motion generates a waypoint just in front of the mapped panel position at a distance in which the intervention panel should be inside the vehicle's field of view. This waypoint will be used later as a recovery position if next step fails. From this position the vehicle starts facing the intervention panel moving holonomically in 4 DOFs until the vehicle docking devices and the panel docking cones are aligned and separated approximately 0.25 m. If during this process the visual detector is unable to detect the intervention panel the facing step is aborted and the vehicle returns to the previously defined recovery waypoint. However, if as expected, the panel has been detected during the facing step, last step starts pushing the vehicle forward by sending directly a force in the X-axis, while keeping the same depth and angle that it has in this moment. Last step produces the mechanical coupling of both systems. Since no latching mechanism is used, to keep the I-AUV docked to the intervention panel it is necessary to keep pushing it with a desired force (i.e. 40N with our vehicle) until the intervention operation is concluded. Few snapshots of the docking sequence are shown in Fig.13.

Valve and Connector Detection For the valve/connector detection and operation a stereo camera has been placed in the bottom hull of the GIRONA 500 I-AUV, pointing to the region where the objects to be manipulated are supposed to be when the vehicle is already docked (see Fig.14 a). Regarding the target detection, two methods have been implemented that can run individual or simultaneously to increase its robustness (see Fig. 14 b). First, a method that uses the histogram of hue and saturation in the HSV color space reported in (Prats et al. (2012c)), has been adapted to detect three red marks on the valve. Once the stereo correspondence of the marks is established, they are fitted to the 3D model of the valve using an optimal rigid transformation. Thus, a reference frame is attached to the target and published, allowing its manipulation. Alternatively, a landmark detection method that does not require stereoscopy has been also developed. In that case two tags, one placed close to the connector base and the other on the gripper, are used. The detection of the tags allows a continuous visual feedback and offers the 3D transformation needed for the end-effector to properly grip the connector handle. Both methods are based on the premise that the valve and the connector, as well as the supporting structure, are rigid and its geometry known. New methods allowing certain uncertainty are under study for a more robust vision-based manipulation approach.

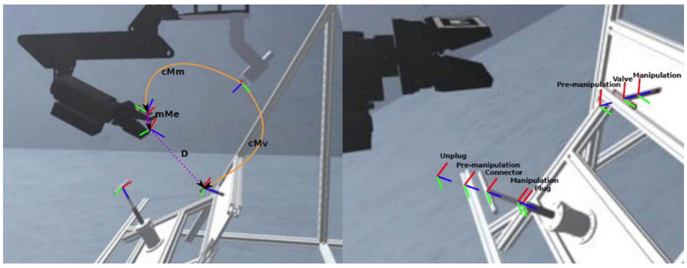

Fig. 14. a) System frames and transformations; b) Waypoints of the interventions.

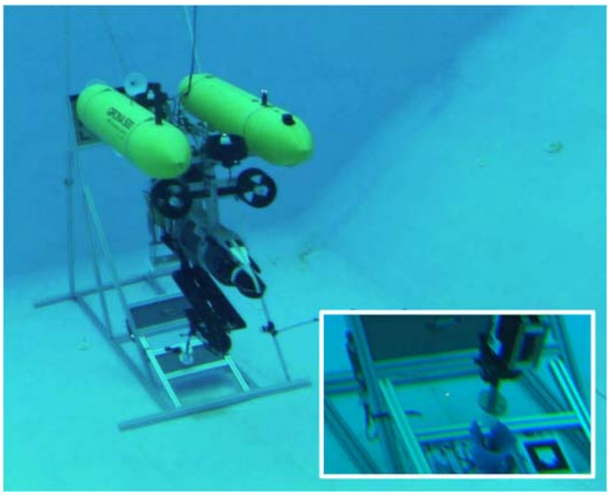

Fig. 15. GIRONA 500 I-AUV in the TRITON configuration connecting a hot stab.

Valve Turning and Connector Plugging/Unplugging After docking, the intervention begins. Two operations are performer: open/close a valve and plug/unplug a hot-stab connector. The main steps followed for the intervention are summarized hereinafter. Given an object to manipulate (valve or hot stab) and given its camera relative pose ($^{c}M_{o}$) provided by the above mentioned vision algorithm, the object's pose with respect to the arm-base can be easily computed as $^{b}M_{o} =^{b} M_{c} \cdot^{c} M_{o}$. Next, three waypoint frames are defined (see Fig.14 b) named: 1)Pre-manipulation, 2) Object and 3) Manipulation. To reach each waypoint (frame), the system computes the Cartesian distance from the end-effector to the waypoint, and drives the arm in the Cartesian space. Since the arm only has 4 DOF, the orientation of the waypoint is not taken into account. First the arm is driven to the pre-manipulation pose, and then to the manipulation pose, where the intervention is performed.

6.2 Learning for Free Floating Based Manipulation on a sub-sea Panel

This is a more challenging environment where the I-AUV is hovering in front of the panel, compensating the environment perturbations. This setup, however, has the advantage of combining the motion of the AUV and the arm to compensate for the limitations of the manipulator workspace.

Problem statement Given a sub-sea panel equipped with a visual feature-rich textured panel to allow for real-time vision-based localization, and equipped with T-shaped valves, the I-AUV has to start at a random position with the panel in the field of view (it is assumed to have reached the panel vicinity by acoustic means) and has to be able to simultaneously control the AUV and the arm in order to perform an autonomous valve turning task in free floating configuration.

Learning to Turn a Valve The strategy followed in this case consists in transferring the knowledge of a ROV pilot to the I-AUV control system using Learning by Demonstration (LbD). In this case, the ROV pilot teleoperates the I-AUV in the water tank and gives different demonstrations. After the demonstration phase, using the LbD approach, a model of the task is learned and the AUV is able to later reproduce the task autonomously. The LbD technique that has been used in this work is the dynamic movement primitives (DMP) algorithm. The DMP is a framework where the skill is encapsulated in a superposition of basis motion fields. This method has a compact representation and it generates motion trajectories that are robust against perturbations. The proposed method is an extension of DMP (Ijspeert et al. (2001)) (Hoffmann et al. (2009)) proposed by Kormushev (Kormushev et al. (2011)).

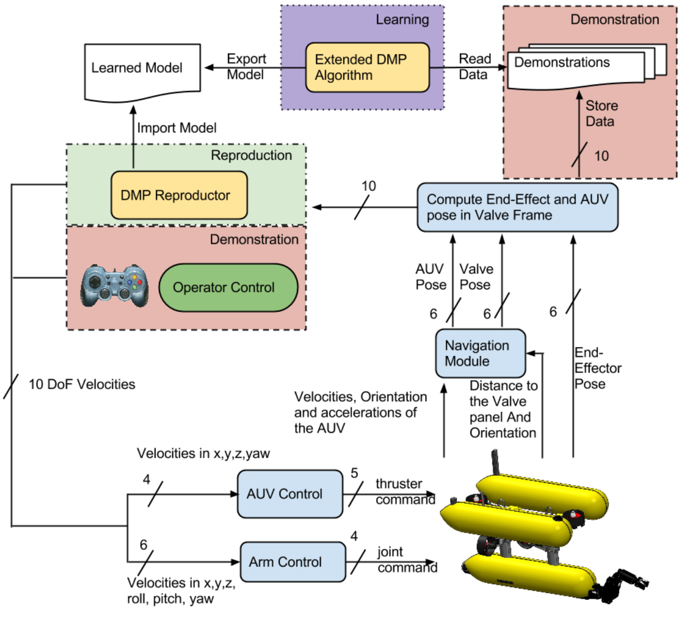

Fig. 16. Block diagram of the learning by demonstration method of autonomous valve turning.

Figure 16 shows the block diagram of the proposed method. During the demonstration, while the user manually performs the valve turning several times in different initial configurations, the DMP algorithm learns the end-effector pose $(x, y, z, \phi, \theta, \psi)$ and the AUV pose (x, y, z, ψ) simultaneously. Both poses are referenced to a frame located in the target valve. The output of the DMP algorithm is the learned model of the valve turning action. Later on, the autonomous grasping task is launched. Given the current I-AUV configuration (AUV and arm poses) and the already learned model, a new desired I-AUV configuration is abstracted from the model, and sent to the AUV and arm controllers. When the valve and the end-effector are aligned in the same position, a wrist motion command is issued and the valve is turned.

The sequence of images in Fig. 17 reflects the valve turning intervention task, showing the AUV and end-effector motions. Images 1 and 2 show the approaching trajectory perpendicular to the panel while the arm is outside the camera field of view. Images 3 and 4 show the AUV in station keeping, while the manipulator approaches the valve. In image 5, the AUV and the end-effector have been moved to grasp the valve. Finally, after executing the learned trajectory, the wrist motion command is launched turning the valve handle 90 degrees, as shown in image 6.

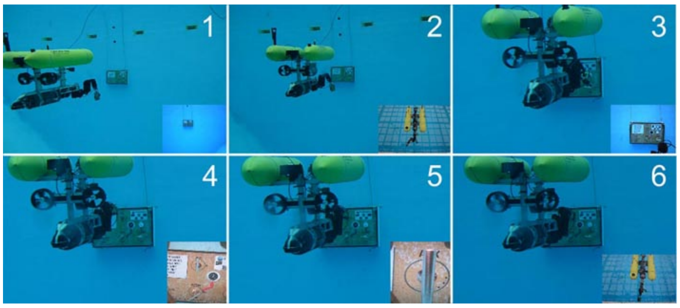

Fig. 17. Image sequence of the reproduction of a previously learned valve turning task.

6.3 Object recovery

TRIDENT project proposed a new benchmark for the *search & recovery* problem using a black-box mock-up. Figure 21 shows the envisioned scenario. First, the user programs a lawn-mower pattern trajectory for the I-AUV in order to survey the seafloor with 100% coverage. Next, the I-AUV is recovered and a high resolution seafloor photo-mosaic is built. Then the user identifies and selects the target and specifies the intervention task to be undertaken. After, the system is launched again. The robot dives towards the target which position is now known *a priori*. When the robot reaches the region of interest, it searches for it. Once the robot flies over the target and identifies it on-line with the bottom looking camera, it aligns itself with respect to the target, and autonomously performs the grasping operation. This benchmark has been demonstrated in different experimental conditions: 1) hooking the black-box using a 4 DOF arm in a water tank (Prats et al. (2011)), 2) hooking the black-box using a 4 DOF in a harbor scenario (Prats et al. (2012a)) and finally 3) grasping the black-box using a 7 DOF arm endowed with a 3 fingered hand in a harbor scenario (Sanz et al. (2012)).

Optical Survey In order to locate the object of interest that we are looking for (in this case, the mock-up black box), the robot is required to perform a survey of an underwater area. During this survey, the robot gathers imaging and navigation data among others. When the survey finalizes, having the set of images collected by the robot, the process continues by finding a set of point features on each image, which represent points that are surrounded by distinctive texture that should make them easily recognizable in other images. Next, the texture surrounding those points in the image is characterized using a feature descriptor. With the set of features/descriptors for each image, we search for correspondences between consecutive image pairs. To do so, we compare the descriptors of the features in each image. However, simply using the similarity between descriptors could lead to obtaining outliers, which are wrong associations between two image points that look similar but do not correspond to the same point in the sea floor. In order to avoid this, a robust model estimator is used (RANSAC), where the correspondences are considered valid if they follow the same motion model. A basic assumption behind this estimator is that we are looking at a rigid scene. With this step, we also recover the motion model in the form of a homography (3x3 matrix). Once we have the homographies between consecutive images, we can obtain a first approximation of the trajectory followed by the camera by concatenating them. As it happens with all localization methods that rely on many sequential motion estimates to infer the robot position, errors are rapidly accumulated, and the map gets distorted. However, we can use this first approximation to find new image pairs that could correspond to the same area, and thus, could be matched together. Candidate matches between non-consecutive images are found, and now this information is merged together. In order to do it, we perform a non-linear optimization that takes into account the reprojection error (differences between the location of the detected feature, and the estimated position after projecting using the homographies). Moreover, this optimization procedure allows including navigation data provided by other sensors of the robot. Since this navigation data is georeferenced, the resulting mosaic will also be georeferenced.

Having a georeferenced mosaic, we will be able to manually inspect the mosaic, locate the object of interest that we are looking for, and program the robot to go back to this position to perform the intervention task. Figure 20 shows the 2D photomosaic of the field experiment performed in the Soller Harbor in Mallorca (Spain). It is also shows a 3D map built by compounding the disparity maps captured by the stereo with the robot poses along the trajectory. The black box is marked in both cases.

Target Detection and Tracking Because the target identification and localization process is used as feedback to the Free Floating Controller, the detection (or tracking) frequency must be high enough to enable the controller to react on externally imposed vehicle movements. We therefore require the detector to work at a minimum frequency of 5 Hz. Different approaches were developed based on the scene conditions and the type of sensors available. First versions were based on colour and shape of the target; later ones were based on image features and allowed to fully recover 3D information of the vehicle-to-target relative position. In the version used for the TRIDENT final experiments, the user only had to mark the grasp points of the object in a single monocular training image. Interest point coordinates and their descriptors were extracted from the whole image and stored as an object model. During the detection stage, interest points and descriptors were extracted from the current view. Using stereo vision, the 3D coordinates of these interest points were computed. Correspondences from the training to the current view were established by matching the feature descriptors. The pose of the camera while taking the training image was computed minimizing the re-projection error of the matched 3D points projected on the training image. This pose and the 2D grasp points together with the point cloud generated from the current stereo view were used to compute the 3D grasp points. In this way, simple 2D interactions is sufficient for object detector training and grasp planning, as all 3D processing is done on-line during the autonomous grasping.

Fig. 18. 2D and 3D views of the surveyed area.

Intervention When the vehicle is sent back to the target position which is now known, it lands in the neighborhood of the black box. Then a local search must be performed

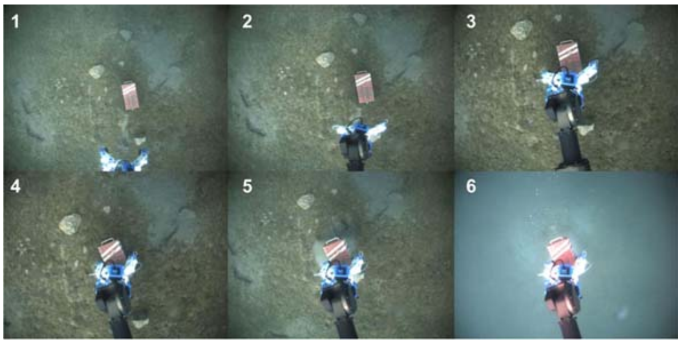

Fig. 19. Autonomous object grasping.

until the black box appears in the vision-based detection system. At this point, The target was detected and tracked by the above mentioned vision algorithm. The object pose was used to plan the grasp. The tracking system output is used to control the end-effector towards the target. The target pose, given in camera coordinates, is transformed into end-effector coordinates through the kinematic chain composed of the camera-arm base calibration and the arm forward kinematics. This allows to compute an error, in the Cartesian space, between the current pose of the end-effector and the desired one, which is then transformed into a velocity request sent to the free-floating controller. This low-level controller is in charge of the coordinated control of the vehicle/arm system (Casalino et al. (2012)). When the end-effector reached the box, it was properly grabbed by the multisensory dexterous 3-fingered hand, being brought to the surface.

7. LESSONS LEARNED

Although first articles about intervention systems date to the mid 90's, experimental results in realistic scenarios did not arrive until the first decade of the 21^{th} century. Moreover, still now, field results are scarce in this area of research. This is mainly due to the complexity of the mechatronics of the involved systems. Although it is possible nowadays to acquire a low cost AUV or ROV, endowed with an arm, it is not yet possible to acquire an I-AUV. It has to be designed and built. Prior to the GIRONA 500 I-AUV only heavy I-AUVs like SAUVIM (6 Ton) or ALIVE (3.5 Ton) existed. With our design, we demonstrated light intervention capabilities with one order of magnitude less in weight (<200 Kg). There have been two key factors which allowed us to succeed. First, the three hull design has proven to be a very stable platform, in particular when the arm is located in the bottom configuration to manipulate objects on the seafloor (Fig. 10-a and b). Second, the recent appearance of low-cost and low-weight electric-arms in the market, allowed the adaption of already existing mechatronics instead of going through the slow process of designing and building a complete new arm. The ECA/CSIP arm 5E with only 27 Kg in air (18.5 Kg in water) was chosen as the candidate arm for our small I-AUV. Nevertheless, instead of just acquiring an off-the-shelf system, we went through a customization process with the company engineers. The aim was to reduce as much weight as possible, trying to make the arm neutrally buoyant component by component. The result was the ECA/CSIP Light Weight 5E/arm (Fernandez et al. (2013)), with only 17.2 Kg (3.8 Kg in water), being currently commercialized by the company. Later on, the company built a second model, the ECA/CSIP 5E micro, even lighter with only 10Kg in air (2.2 Kg in water). The major constrain of these arms is the reduced number of available DOFs, which may be partially alleviated through the additional DOFs provided by the vehicle, achieving a redundant system with 8 DOFs (surge, sway, heave and yaw in the vehicle and base, shoulder, elbow and wrist in the arm). The second constrain of these arms is due to its simple mechatronics and poor instrumentation. In the TRIDENT project, GRAALTECH was responsible for the design and development of a new lightweight dexterous arm. With 7 DOF, the arm weights 28 kg (13 in water) and was endowed with a 3 fingered hand weighting 4.5 Kg (1Kg in water). At the cost of a higher weight and mobile mass, the use of harmonic drives and an advanced arm instrumentation, provides an accurate smooth motion in the order of magnitude of standard industrial robots, enabling dexterity. Moreover, the arm redundancy together with the vehicle-arm cooperative control (Casalino et al. (2012)) allowed the system to perform the object grasping described in section 6.3 even in the presence of the failure of one of the DOF of the arm.

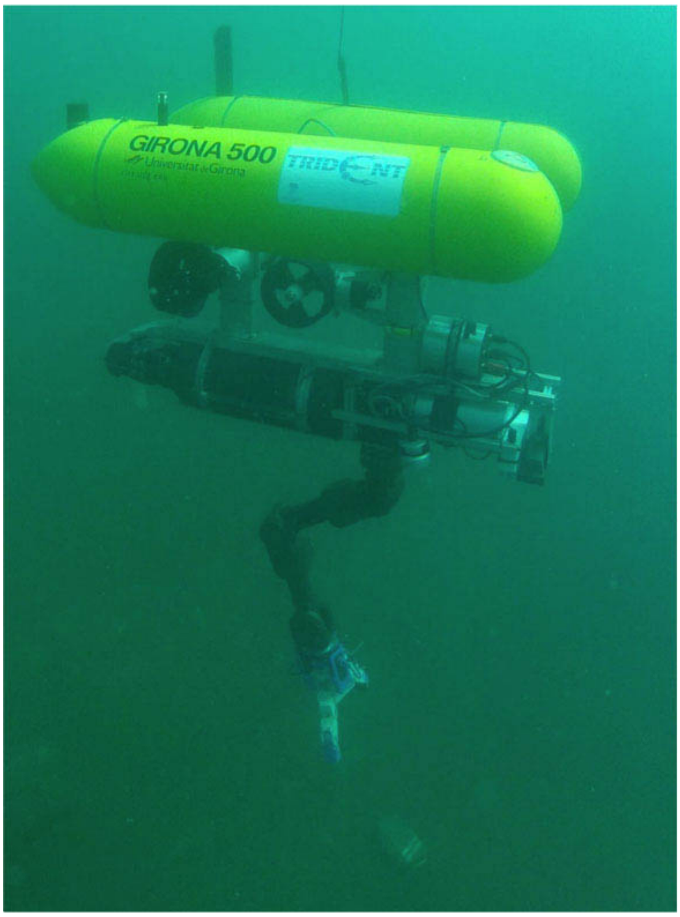

Fig. 20. GIRONA 500 I-AUV in the TRIDENT I-AUV configuration.

Another key factor to achieve experimental results quickly, has been the systems integration. From the hardware point of view, a clear definition of the payload area and a rich signal interface, has allowed for an easy integration of the

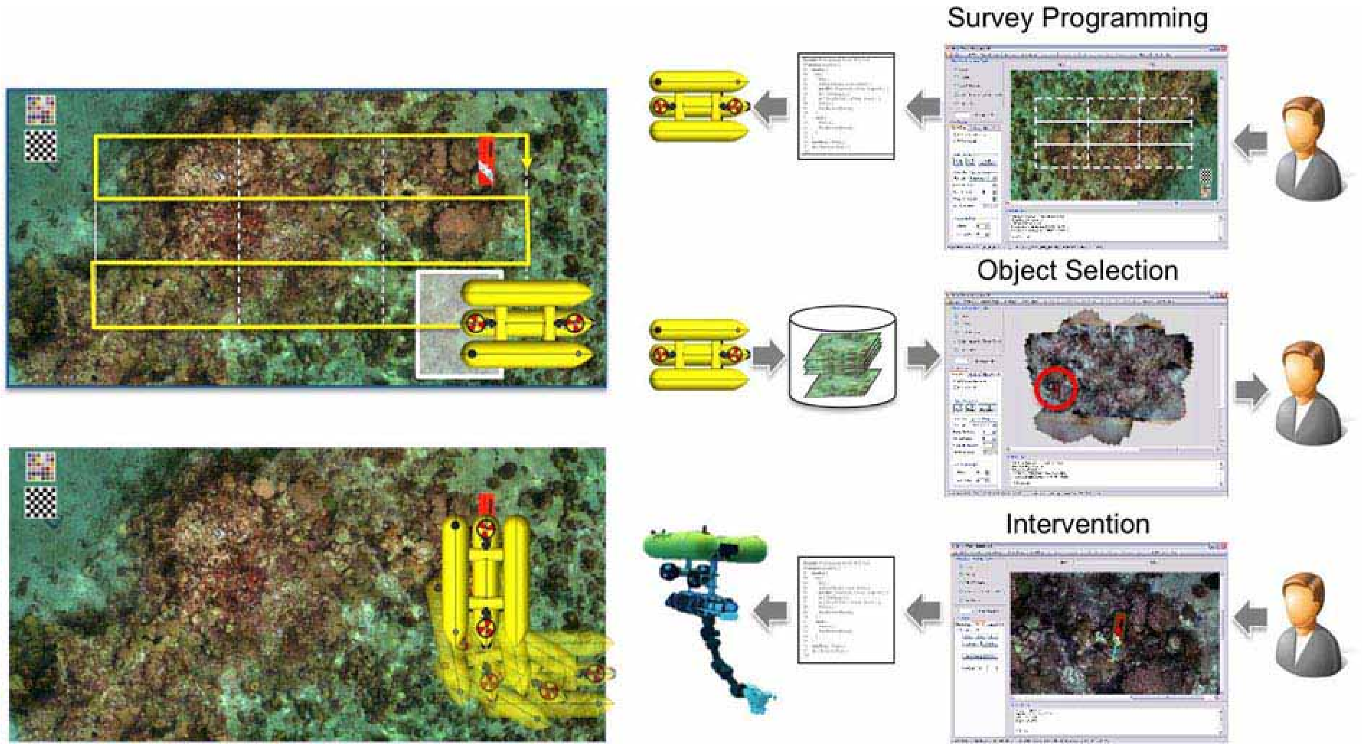

Fig. 21. Multipurpose Multisensory Based Intervention Concept.

three manipulators shown in Fig.10. To promote modularity and easy integration, often the payloads have included their own computer system connected to the vehicle computer through an Ethernet. From the software point of view, the adoption of the ROS middleware (Quigley M., Conley K. Gerkey B. P. Faust J. Foote T. Leibs J. Wheeler R. and Y., Ng A. (2009)) has proven to be of vital importance. It has allowed to design and implement the AUV navigation, guidance and control nodes, the computer vision nodes and the arm control nodes independently and later on integrate them in a very straight forward manner.

Another important aspect, which played an important role, was the adoption of a clear experimental methodology based on three sequential steps: 1) Hardware in the loop simulation (HIL); 2) water tank testing and 3) Sea trials. Using the UWSim (Prats et al. (2012b)) it was possible to develop the software components without actual access to the real mechatronics. In multiple partner projects, it allows to conduct the first software integration without the needs of mobilizing human resources, and hence, decreasing costs. Next, mechatronics from different partners (arm, vision system, etc...) were integrated to complete the I-AUV at CIRS (Centre d'Investigació Submarina) at UdG installations, where preliminary water tank test were carried out. This ensured mechatronics worked properly, so it did the software integration. Finally, when everything run flawlessly, sea trials, commonly in a harbor environment were carried out to test the system in a realistic environment, validating the proposed method.

8. A LONG TERM VIEW OF THE FUTURE

UUVs have been traditionally categorized into ROVs and AUVs. The last decade has witnessed the appearance of new categories like the gliders and the I-AUVs, but also the appearance of hybrid categories like the HROV. In the upcoming years, the boundaries among these categories will probably become fuzzier. There will be gliders able to do seafloor surveys as AUVs after reaching a site of interest. The advances in battery technology, will progressively substitute the work-class ROV by the HROV while keeping the human in the control-loop for intervention operations. Using optical communications, the possibility to get rid of the tether at short distances has been recently demonstrated. Next years, the advances in underwater wireless communications technology are expected to increase this distance, as well as the communication bandwidth, enabling on-line reconfiguration from AUV to ROV and vice versa. HROVs will behave as intervention ROVs or as I-AUVs depending on the operators role. Following the trend shown by AUVs during this decade, the size of the upcoming vehicles is expected to decrease, becoming smaller, cheaper and easier to deploy and operate. This will open the door to underwater operations involving multiple vehicles. Besides the obvious outcome of reducing the mission-time by dividing the work (e.g. the area to survey), new robot-to-robot interactions are likely to appear to counteract the limitations in vehicle autonomy and communication range. Long-term navigation in an unconfined region will still be the big challenge to solve. Multiple robots will cooperate to improve their navigation and mapping accuracy (cooperative navigation and mapping). While the first may potentially be achieved with state of the art acoustic modems, a break-through in wireless technology is necessary for the second. Nevertheless, recent advances in docking technology make AUV-to-AUV docking possible allowing, after a rendezvous, for vast communication of data and multiple vehicle mapping without recovery. Recent advances in visible light communication systems also have a great potential in this context since they may allow for broad band communications among vehicles at visual contact distance. When equipped with arms (I-AUVs), cooperation will go beyond navigation and mapping to face challenges like cooperative manipulation (e.g. cooperative transportation of bulky objects). Other tasks, like autonomous object assembly, are better solved with two arms on a single vehicle. With AUV-to-AUV docking in place, we can even think in transforming two single-arm I-AUVs into an advanced dual-arm system. This new breed of vehicles will have to be able to navigate in partially unstructured and unknown environments like permanent underwater stations (permanent observatories, submerged oil fields, etc.). They will need the skill to build on-line 3D occupancy maps of the environment (free/occupied/unexplored) to allow for real-time path planning. Robust guidance algorithms together with reactive obstacle avoidance will be necessary to safely follow the planned path, close to the submerged infrastructures. The robots will need to move very close to them to allow for a high-resolution imaging (< 5 m for inspection) and even closer for intervention (1 m). At 1 m distance, the 3D relief becomes significant, easily violating the maximum slope-threshold for a DVL to allow bottom tracking. Hence, real-time navigation at this distance is a challenge, which will require advanced navigation strategies, based on computer vision or cooperative navigation.

9. CONCLUSION

This paper has reported the main advances in autonomous underwater intervention over the last two decades. The most relevant projects in the area have been discussed, highlighting their principal contributions. Then, the GIRONA 500 light weight I-AUV being used in 4 different projects about underwater intervention has been described. Three different scenarios with experimental results have been presented: 1) Docking and fixed-base Manipulation, 2) Learning by demonstration for free-floating manipulation and 3) Multipurpose manipulation for object recovery. From this experience, the lessons learned have been discussed and a long term view of the future has been outlined.

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