TRIDENT

An European Project Targeted to Increase the Autonomy Levels for Underwater Intervention Missions

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***Abstract*— TRIDENT is the official acronym used for a funded European project entitled: "Marine Robots and Dexterous Manipulation for Enabling Autonomous Underwater Multipurpose Intervention Missions". This project has demonstrated a new approach for multipurpose underwater intervention tasks with diverse potential applications ranging from underwater archaeology and oceanography to the offshore industries. The methods and technologies defined and tested under TRIDENT go beyond present-day methods typically based on manned or purpose-built systems. The project was launched on 1st of March 2010 and has been running for a total of 36 months, achieving the "excellent" grade in its final review process by the European Commission (May 2013, UJI, Spain). In this paper the last achievements will be discussed, highlighting the main research efforts continuously supported by the consortium till reach its final objectives. In summary, TRIDENT represents a new benchmark for the scientific community, solving the underwater "search & recovery" problem, in shallow water conditions, with the highest level of autonomy ever seen before.**

Keywords—underwater intervention; cooperative robots; free-floating manipulation; sea floor mosaicking

I. INTRODUCTION

During the last 20 years, Autonomous Underwater Vehicles (AUVs) have become a standard tool for mapping the seafloor using optical and acoustic sensor modalities, with applications to dam inspection, marine geology and underwater archaeology 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.

Furthermore, 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 (Remote Operated Vehicles) deployed from DP vessels making them very expensive. To face these new applications, research to increase the autonomy of underwater intervention systems, started early in the 90's with the pioneering works of OTTER [1], ODIN [2], UNION [3] and AMADEUS [4], but it was not until the 1st decade of the 21th century that field demonstrations arrived. In particular, the first fully autonomous intervention at sea, was demonstrated by the ALIVE project [5], where a hovering capable AUV was able to home to a subsea intervention panel using 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 [6]. It was demonstrated 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 (see details in Sec IV). First, the object was searched using a down-looking camera and photo-mosaicing techniques. Next, it was demonstrated how to autonomously "hook" the object in a water tank [7]. The experiment was repeated in a harbour environment using a 4 DOF arm [8] and later with a 7DOF arm endowed with a 3 fingered hand [9].

The rest of the paper is structured as follows: Section II presents the TIDENT approach; Section III describes the research work plan implemented; Section IV highlights the milestones of TRIDENT, including the final experimental validation trials in shallow waters; and finally, some concluding remarks are presented in Section V.

II. THE TRIDENT APPROACH

TRIDENT proposes a new methodology for multipurpose underwater intervention tasks where a team of two cooperative heterogeneous robots with complementary skills, an Autonomous Surface Craft (ASC) and an Intervention Autonomous Underwater Vehicle (I-AUV) endowed with a dexterous manipulator, are used to perform underwater manipulation tasks.

The proposed methodology has two stages (see Fig 1). During the first stage, the I-AUV is deployed from the ASC to execute a pre-plotted survey, where it gathers optical/acoustic data from the seafloor whilst the ASC provides geo-referenced navigation data as well as communication with the end user. During this stage of the mission the I-AUV carries out accurate path following and terrain tracking, to maximize bottom coverage and data quality. The motion of the ASC is coordinated with that of the I-AUV to achieve precise USBL (Ultra Short Base Line) positioning and reliable acoustic communications. After the survey, the I-AUV docks with the ASC and sends the data to a ground station where a map is created and a target object is identified by the end user. In the second stage, the ASC navigates towards a waypoint near the intervention area where the I-AUV is launched to search for the object. When the object (i.e. the target of the intervention) has been found, the I-AUV switches to free floating navigation mode. The manipulation of the object takes place through a dexterous hand attached to a redundant robot arm and assisted by suitable perception technology. Particular emphasis has been made on the research of a vehicles' intelligent control architecture to provide the embedded knowledge representation framework and the high-level reasoning agents required to enable a high degree of autonomy and on-board decision making of the platform. The new methodology allows the operator to specify an intervention task, among a set of predefined ones, to be made on a specific target, selected by the end user from the map previously created. Hence, the intervention task is seen as a semi-automatic process, where a human selects the target and after it is automatically recognized and manipulated by the robot in a completely autonomous way.

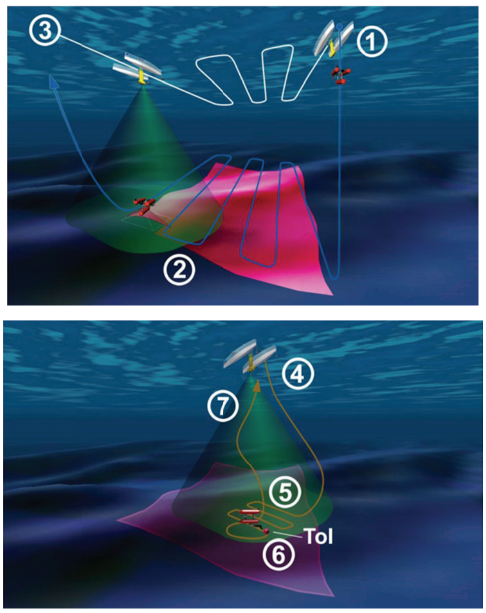

Fig. 1. The TRIDENT strategy. (**Top**) The initial stage focused in the survey task: (1) I-AUV deployed; (2) Coordinated Survey; (3) I-AUV surfaced. (**Bottom**) The final stage in charge of the intervention mission: (4) ASC dynamic position; (5) I-AUV looking for Target of Interest (ToI); (6) Grasping; (7) I-AUV docks to the ASC.

In particular, a new benchmark has been demonstrated solving the "search & recovery" problem for a black-box mock-up, following the aforementioned approach. A representation of this kind of validation scenario is depicted in Fig 2, where the concept of how navigation and mapping assist to the multipurpose intervention mission, that will be carried out in autonomous way is represented. The I-AUV first surveys the seafloor (using multi-beam sonar and video) assisted by the ASC on surface, which helps with the geo-referencing process. Next, the I-AUV is recovered and, a bathymetry and an ortho-photomosaic are built for enabling target identification, and the intervention specification task associated, by the user. After that the system is launched again and, after the correct positioning over the target, the intervention is performed (i.e. autonomous grasping) without any assistance. As a proof of concept, two real life environments have been the main experimental validation scenarios in TRIDENT, both in shallow waters (see details in Section IV).

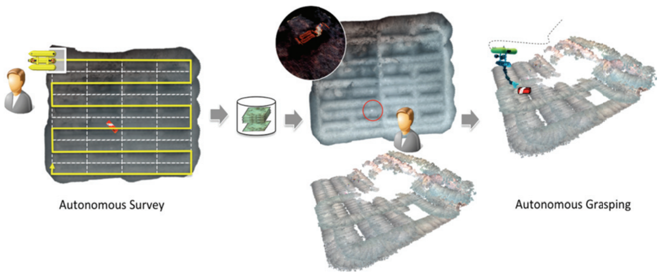

Fig. 2. The proof of concept based on the "search & recovery" problem.

III. THE WORK PLAN

The role of TRIDENT partners and their expertise have been supporting the necessary research that, structuring in Work Packages (WP's), have been necessary for integrating all the components to succeed with the project. In the following the description of the main results is described from the point of view of the seven scientific WP's executed during the whole project.

A. WP1: Navigation and Mapping

WP1 was responsible for endowing the team of robots with two fundamental capabilities: 1) building multimodal maps of the environment and 2) geo-referencing the robot position within the application scenario. In these WP different navigation techniques to allow for the localization of the individual robots involved in the team was explored.

Cooperative Navigation: This WP addresses the topic of cooperative navigation solutions developed within the framework of the EU project TRIDENT. Several different alternatives were 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 was 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 were 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 were proposed for estimation of linear motion quantities. For angular motion quantities, novel algorithms were 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 followed, keeping the stability and performance properties of solutions derived for single vehicles. Simulation results evidence excellent and promising results for all proposed solutions.

Mapping: This WP has dealt with the design and development of new techniques for the construction of 2D ortho-photomosaics, sonar-based SLAM, as well as the combination of their outcomes to produce multimodal maps. The research work related with the construction of photomosaics has focused on several aspects of the process which improve the results beyond the state of the art. Some examples are strategies for optimally solving the image topologies in front of unordered sets, dealing with different aspects related with image quality, such as attenuating sun flickering or non-uniform illumination, or reducing the effects of parallax by building ortho-photomosaics from the planar projection of 3D models of the environment. With respect to the use of sonar sensors, stochastic state estimators have been used to build accurate and consistent representations of the environment.

One of the main problems when working with sonar is the need of accumulating measurements over time to build 2D scans, in the case of mechanically scanned mono-beam sonars, or 2.5D elevation patches, in the case of multibeam profilers. This process has been integrated within the proposed SLAM frameworks by building patches of sensor information while merging navigation estimates to compensate for vehicle motion. Then, those patches are used as an input for a novel probabilistic scan matching process to introduce constraints in the trajectory estimates and improve coherence in the maps. As the logic consequence of having accurate bathymetric maps and ortho-photomosaics available, the next step was to combine both sources to produce multimodal maps in the form visual mosaics with 2.5D relief. All the proposed techniques have been demonstrated with datasets obtained during the experiments carried out as part of the TRIDENT consortium trials, but also from real application scenarios such as the inspection of a shipwreck or a sunken caldera.

B. WP2: Single and Multiple Vehicles Control

This design, analysis, and validation of navigation and control strategies for single and multiple vehicles were carried out under the framework of the EU project TRIDENT, namely bottom-path following, leader following, homing and docking tasks.

The marine habitat naturally poses a huge challenge for systems development mainly due to its harsh environment in which marine robotic vehicles have to withstand high pressures and aggressive metal corrosion. Out of several systems like robotic arm manipulators, thrusters, rudders and fins, one key role is played by the navigation system on-board marine surface and underwater robotic vehicles, which allows for the vehicles to navigate relative to either a fixed coordinate frame or relative to another vehicle for cooperative navigation and homing/docking operations. The development of navigation systems that can accurately estimate the underwater vehicle position and attitude has increased significantly over the past years due to the rising interest in the marine environment by the scientific community and private companies. In fact, the design and implementation of navigation systems stands out as one of the most critical steps towards the successful operation of autonomous vehicles and is on the basis for the development of the control tasks central for the TRIDENT project.

In terms of the control problems addressed, an integrated bottom-following preview controller is proposed for Autonomous Underwater Vehicles (AUVs) that resorts to well established control design methods such as H2 state feedback, gain scheduling, and the D-methodology. The proposed solution yields good results in simulation, while keeping an acceptable computational load. With respect to the leader following problem, a novel strategy is proposed that builds on Lyapunov and model-based control techniques, together with concepts from graph theory, in order to characterize the stability properties of the proposed decentralized control structure, which is formed by an interconnection of two subsystems: path-following and cooperation control. With the control structure adopted, path-following (in space) and inter-vehicle cooperation (in time) become essentially decoupled and results obtained in simulation evidence good performance.

The homing solution developed corresponds to a new sensor-based integrated guidance and control law, able to drive an underactuated autonomous underwater vehicle toward a fixed target, in 3-D, using the information provided by an ultra-short baseline (USBL) positioning system. The guidance and control law is first derived at a kinematic level, expressed on the space of the time differences of arrival (TDOAs), as directly measured by the USBL sensor, and assuming the plane wave approximation. Afterwards, the control law is extended for the dynamics of an underactuated AUV resorting to backstepping techniques. The proposed Lyapunov-based control law yields almost global asymptotic stability (AGAS) in the absence of external disturbances and is further extended, keeping the same properties, to the case where known ocean currents affect the motion of the vehicle.

Docking is addressed and solved resorting to a novel integrated guidance and control strategy divided in two steps: i) in the first, at higher speed, the AUV vehicle dynamics is assumed to be underactuated and an appropriate control law is derived to steer the vehicle toward the final docking path, achieving convergence to zero of the appropriate error variables for almost all initial conditions; ii) in the second stage, at low speed, the vehicle is assumed to be fully actuated, and a robust control law is designed that achieves convergence to zero of the appropriate error variables for all initial conditions.

All the solutions developed were successfully tested and validated at sea during the life of the project.

C. WP3: Vehicles Intelligent Control Architecture

Work package 3 focused on developing an intelligent control architecture (ICA) for the Trident project. It was also responsible for the overall software integration of the systems involved in Trident.

Control Architecture. The control architecture focused on the high level control of a number of distributed agents across the two platforms involved in Trident; an autonomous underwater vehicle (AUV) and an autonomous surface vehicle (ASV). The proposed architecture moves away from fixed mission plans and very elementary diagnostics scheme currently utilized to a more robust architecture to deal with the above missions. It needs to handle unexpected faults within vehicle, 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. It is based on the notion of a hierarchy of services. Low level services provide low-level functionalities and are combined hierarchically to provide higher level services. The combination includes logical links between services as well as scheduling and orchestration of services. Each vehicle module provides basic services, which advertise their capabilities to the system. The service also publishes regular updates of 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 it 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 proposed is a service-oriented agent-based approach which is suitable for integrating the vehicle modules as well as the capabilities of each marine vehicle in a collaborative manner. The agents are embedded in the marine vehicles. They are specialized in different disciplines, and provide different capabilities available as platform services (e.g. navigation, mapping, vision, manipulation, grasping, etc.) to the overall system. A planner is integrated to the system at the top level to schedule high level tasks and provide tolerance to faults.

The ICA was implemented in the ROS middleware. Elemental tests of the ICA infrastructure, in particular, the advertisement and discovery mechanisms for services as well as the resource management were successfully carried out. The autonomous nature of the ICA paves the way for a reduction in the expensive deployment and operation of ROVs, and brings within reach complex multi-vehicle collaborative missions that were previously too costly or logistically infeasible. The ICA was demonstrated on real platforms performing the first phase of the Trident mission, namely collaborative survey, homing and docking. The ICA was also validated in simulation for the second part of the Trident mission focusing on autonomous manipulation. Its fault tolerance capabilities were also tested and demonstrated.

System Integration and simulation. The ICA is the backbone for the development of agents and provides a de-facto integration approach. One of the successes of Trident was the ease of integration of the various software components. This success hinged on three critical decisions and developments early in the project: (1) the decision to adopt ROS (Robotics Operating System) as the standard for all developments and interfacing in the project, (2) the development of a set of standard messages and interfaces for the project and (3) the development of a simulation environment, compatible with ROS and integrating kinematic models for the vehicles used in the project. These 3 components together enable the project team to perform extensive simulation of the software in semi-realistic conditions whilst running the exact same software that would run on the vehicles. In practice, this meant that moving from simulation to real demonstrations took a few days and focused on adapting the algorithms to the environmental conditions and differences between sensor simulation and real sensing rather than core system integration.

D. WP4: Visual/Acoustic Image Processing

The main responsibility of WP4 is providing the other modules of the system with the relevant information of the environment as well as the detection and localization of the target so the vehicle can approach it and manipulate. Acoustics is traditionally the main source of information to endow underwater vehicles with information of its operation surroundings, due to its large propagation distance in that media. Anyhow, at short distance, optical systems can provide higher spatial and temporal resolution information than acoustics, at a lower price, consumption and space. Because the intervention job to be carried out in the TRIDENT project is bounded by the length of the manipulator, an important part of the mission occurs at a very short distance of the sea bottom and of the target. Besides, to execute the manipulation process, the detection and localization of the target and the vehicle are required to be very precise and robust. Thus, much attention has been paid to acoustics and optical methods and systems.

Vision. Due to the nature of light propagation undersea and due to the special characteristics of typical underwater scenes, imaging infrastructures and image processing techniques addressing these issues and devised for land scenes may not be effective enough for dealing with oceanic environments. Consequently, 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.

Taking into account all the conditions abovementioned and the specific characteristics of the mission to be executed, a new underwater vision system was implemented. After the hardware and software of that system has been developed, and tested in lab and sea conditions, it has been successfully integrated as part of the TRIDENT system and used in all the experimental project validation.

The TRIDENT vision system has been conceived to provide 3D visual perception in a very flexible way to a generic AUV. It is made up of two stereo rigs and a computer system linked through a Firewire bus. Each camera and the computer system are placed in separate sealed cases. In that way, the system geometry can be easily adapted to the specific mission to carry out or to the structure of the host vehicle. The adaptability of the vision system has been tested along the project with different vehicles and configurations. Concerning the main functionalities offered by the vision system, there could be distinguished the Stereo odometry, the Target identification and the 3D reconstruction.

Stereo odometry: Visual odometry focus on fast frame-to-frame motion estimates without keeping a large history for loop closing. The emphasis lies on accurate measurements at high frequencies. Systems that use just one camera need translational movement for 3D motion estimation and all measurements have to be scaled by an unknown factor to be on a metric scale. Using a calibrated stereo camera overcomes both of the aforementioned problems as 3D coordinates of matched points in a single left/right image pair can be computed by triangulation. Different visual odometry algorithms, initially developed for land or aerial applications, have been adapted and compared in TRIDENT, and some of them are still under study. The best performance has been obtained with libviso2 and fovis. Both algorithms have similar processing pipelines containing feature detection, filtering, matching, and motion estimation. After intensive online and offline testing using the TRIDENT infrastructure, we conclude that these algorithms can be used in an underwater environment if the visibility conditions and the appearance of the sea floor result in images with sufficient texture. Like all incremental motion estimation methods, visual odometry suffers from drift and has to be combined with other sensors to get precise long-term position estimates. Despite the mentioned drawbacks we have shown that a visual odometer using a downward looking stereo camera can be a valuable sensor for underwater vehicles giving good estimates for linear movement and rotation about the vehicle's vertical axis.

Target identification and localization: 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 object model. During the detection stage, interest points and descriptors were extracted from the current view. Using stereovision, the 3D coordinates of these interest points were computed. Correspondences from the training to the current view were established by matching the feature descriptors. Minimizing the re-projection error of the matched 3D points projected on the training image, the pose of the camera while taking the training image was computed. This pose and the 2D grasp points together with the point cloud generated from the current stereo view were then used to calculate 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 online during autonomous grasping.

3D reconstruction: The 3D point cloud generated from stereovision can be used to reconstruct a scene. To be able to do this, the exact pose of the camera in map coordinates while taking the images for the point cloud generation has to be known online or recovered offline. Drift-free pose estimation algorithms need to do loop closing, which was beyond the scope of this project. We therefore used positioning data from the robot's navigation system or directly from the stereo odometry to concatenate the point clouds.

Acoustics. Acoustic information processing centred its attention in different aspects related to localization and mapping and to target detection. A short description of some of the processors developed follows. These algorithms have been tested on real datasets obtained from other projects and facilities different from TRIDENT.

Target detection: The accurate detection of possible objects of interest on the seabed for examination by video sensors is very important in TRIDENT. Their possible inspection by acoustic means is also of interest when visibility is poor. For that reason, possible approaches to the detection and classification of objects in side-scan imagery and their possible extension to forward looking sonar have been studied. The majority of existing techniques concentrate on the analysis of the acoustic shadow casted by the objects. With the development of ultra-high-resolution systems, new techniques inherited from the computer vision community can now be applied, taking into account the acoustic echo and shadow. The method developed starts by computing Haar features on the acoustic image, then outliers are eliminated thanks to an efficient variant of AdaBoost and finally a simple classifier model, referred to as the cascade, rejects most background images in the very early stages and focus the main computation only on object like patches. An input patch is classified as a target only if it passes the tests in all stages. Cascade detectors have demonstrated impressive detection speed and high detection rates. This technique can be readily applied to forward-looking sonar. However, in this case, the fact of seeing the target multiple times is an advantage because enables tracking techniques to be used.

E. WP5: Floating Manipulation

WP5 had the responsibility of designing, realizing and then implementing and testing, on the TRIDENT floating manipulator, the entire functional, algorithmic and real-time SW architecture, allowing to control the system, when performing autonomous floating grasping and manipulation activities, by suitably real-time distributing and coordinating the motions of the arm and the supporting vehicle (and in the final phase of grasping, also the gripper).

The motions had to be smooth, concurrent, as well as synergic among them at each time instant, in such a way to consequently achieve system agility, via the complete elimination of any sequential motion scheduling of the two subsystem (namely, the vehicle move first, then stops, then the arm follows, and so on) that would greatly affect the system operability (need to reschedule the motion sequences in correspondence of each exception) since generally requiring non negligible operational times.

Meanwhile such synergic motions had to guarantee the achievement, and then the maintenance during time of all a set of inequality conditions related with both the overall system safety its best operational conditions, as well as its internal subsystems motion priorities (i.e. heavier parts, as it is for the vehicle, have to generally smoothly move as much as possible less than lighter ones; while however always respecting the currently required levels synergies) other than achieving the ultimate goal of grasping and manipulating objects.

To these aims, the functional architecture has been organized into two hierarchical layers: the upper Kinematic Layer, in charge of closed loop real time providing the most suitable velocity reference signals (to the vehicle and the arm joints) driving the overall system toward the achievement of all the objectives; an then the lower Dynamic Layer instead devoted to close loop real-time track such velocity references by providing the corresponding suitable joint torques to the arm, as well as the thrusts to the vehicle propellers.

In order to drive the overall system toward the achievement of all the objectives, the Kinematic Layer has been developed on the basis of the well-known task-priority-based methodology, which has been suitably extended, actually in a very uniform manner, in order to also account for the presence of the inequality objectives to be they also achieved.

Moreover, the so extended task-priority-based methodology has been also organized in such a to be possibly integrated within a dynamic programming procedure that, once made running, at each time instant, along the overall system sub-chains (namely, the arm and the vehicle just listed in such order) inherently allows for both optimal compensations of possible vehicle velocity disturbance (i.e. sea currents and/or propellers deficiencies in producing the required vehicle velocity, etc.) even within non stationary conditions; as well it also inherently allows for directly managing multi-rate control situations (as it is for the TRIDENT system, where the arm is controlled at 100 Hz, while the vehicle at 10 Hz), without any additional control design effort.

Moreover, the right motion priorities among the subsystems (again, the arm and the supporting floating vehicle) result they also guaranteed as an inherent property of the dynamic programming part of the overall adopted methodology.

Further, the overall methodology, since has been developed in very general terms, then resulted in a unifying and uniform very general framework, also valid for more complex connected chains than a single arm floating manipulators, like for instance possible extensions to multi-arm floating systems.

Additionally, but absolutely not least, the algorithmic translation of the developed methodology for the Kinematic Layer resulted it also very simple: actually constituted by a number (equal to the number of concurrent tasks to be executed) of repetitions of the same, standard and structurally invariant, finite and short sequence of a matrix/vector linear operations, to be performed at each sampling time. A fact this last that consequently makes its implementation actually very simple and also very fast in terms of required computational times.

Finally the resulting algorithmic structure also results invariant with respect to changes, even on fly, on the currently assigned task priorities, and even on the number and/or types of requested tasks to be concurrently accomplished; where in case the relevant transitions (i.e from one overall task situation to another) are always guaranteed smoothly occurring with adjustable transient times.

Also as a consequence of this last observation, the developed algorithmic structure then resulted into an invariant kernel for the Kinematic Control Layer, always ready to adequately support any objective and/or control requirement variation that, even at run time, might be required by higher command and control layers.

As it instead regard the underlying Dynamic Layer, a suitable dynamic model for the overall system has been formerly developed, by suitably composing the separate dynamic models for the vehicle and the arm respectively. The resulting overall dynamic model; namely the so-called Higher-Order-Decoupled (HOD) Fossen model (since extending to floating manipulators the well-known Fossen model only valid for floating vehicles without any arm), can be built by very easily combining the two separate model terms (for the vehicle and for the arm) in a standard manner; thus without any substantial additional modelling effort when considering the interconnection of the two.

Apart the above, however noteworthy advantage, the other very important one, gained when referring to the HOD Fossen model, is that it clearly indicates how, also at dynamic level, it becomes possible to develop, also at dynamic level, a control law based on a Dynamic Programming procedure it also made running (like at kinematic level) along the arm and vehicle sub-chains (still in such order); thus directly achieving advantages strictly similar to those that were obtained at kinematic level; namely, the still inherent direct management of multi-rates, without any additional control design effort; and the inherent possibility of optimally compensating for possible, at this level of force/torque type, disturbance acting they also on the vehicle, even of non-stationary type (like for instance force/torque produced by abrupt sea current changes, propeller deficiencies in producing the commanded resulting overall thrust and torque, etc.).

The resulting algorithmic structure results it also reasonably simple to be implemented; since only a fixed finite number of linear operations involving matrices and vectors are at the end required, within the core part of the resulting dynamic control law; where the most parts of such matrices and vectors can in turn be deduced by combining the constant ones associated to a), the ones which are constant within the separate Fossen model for the vehicle, when considered alone; and b), those at each time instant provided by the separate sole arm model, once numerically evaluated via the well know, linear and very efficient, finite step numerical Newton-Euler procedure. As a matter of fact, by organizing the algorithmic structure of the dynamic control law as just outlined, the only non-linear varying terms which still remain to be evaluated, via an ad-hoc isolated procedure, are those relevant to the hydrodynamic effects to which the vehicle is subjected; which however can be generally neglected within the range of moderate vehicle velocities (as just are those required during grasping and manipulation operations).

Further, the so devised algorithmic control structure for the Dynamic layer, can obviously it also accept the use of approximate dynamic models (till the extreme case of very rough ones, where vehicle and arm are controlled by separate, totally non interacting controllers); obviously provided that, in dependence of the ranges of approximations; as well as the ranges of the commanded reference velocities, sufficiently high gains have to be used at the error nodes for masking the model approximations and however forcing the desired closed loop behavior; while however avoiding to fall into instabilities.

As it is well known, in case of large model uncertainties (as it has actually been for the project system) compromising moderate error gains at the dynamic loop can however be used, without falling into instabilities, provided the rate of variations of the reference velocities (i.e. their accelerations) are maintained sufficiently low (i.e. smooth varying reference velocities).

Within the economy of the TRIDENT project, since a sufficiently precise HOD Fossen model were not available, former extensive simulations adopting totally decoupled vehicle and arm controllers, then followed by extensive field trials for compromising requestable kinematic performances with allowed feedback gains at dynamic level have been actually performed before achieving the best judged final compromise; thus eventually proving the practical feasibility and efficient operability of the overall developed theory, methodology and algorithms for the coordinated control of the overall floating manipulator during the execution of autonomous grasping and manipulation activities.

Finally, the implementation of the above theoretical, methodological and algorithmic results for autonomous, coordinated floating manipulation has been performed via the development of real-time SW architecture which includes the overall kinematic layer and all its interfaces with: a) the arm lower level dynamic control, including its joint sensory system; b) the gripper controller including its fingers sensory system; c) the vehicle lower level dynamic controller (as it can be seen the two dynamic controllers for arm and vehicle have been therefore maintained separate non interacting at dynamic level); as well as with d), the overall vehicle sensory system (and in particular with the stereo vision system in charge of real-time providing the information about the relative position of the object to be grasped).

F. WP6: Hand+Arm Mechatronic System and Control

Within this WP, the main achievement is related to the design and the development of the hand (gripper), the arm and the control system for these devices. Also the integration of these subsystems within the I-AUV has been successfully carried out.

The I-AUV is conceived to autonomously operate in a non-structured environment, and in particular the gripper will physically interact with the object, and eventually also the environment, during grasping operations planned to recovery the object itself. Then, the gripper has been provided with a proper actuation and sensory equipment. Moreover, to simplify the integration with the arm and the vehicle, the hardware/software infrastructure for the low-level control of the system has been implemented to allow the simultaneous control of both the hand and the arm, sharing the same digital bus, supply lines, and computational platform.

To allow performing grasp on a large variety of objects, with different shape, dimensions and also different grasp configurations, such as parallel or envelop grasps, a three-fingered gripper concept has been adopted. After some problems detected with a first prototype, a second one, characterized by a different mechanical implementation, based on remotely located waterproof actuators that drive the fingers by means of a cable based transmission, has been finally constructed. This gripper has been equipped with waterproof force/torque sensors on each fingertip.

As a consequence of the unstructured environments in which the I-AUV will operate, different scenarios with different needs may occur. Therefore a robotic arm characterized by high re-configurability has been designed. A modular approach has been adopted, and in particular two different type joints have been implemented: the first is characterized by a single rotational dof along its principal axis ("Roll" joint); the second is a 2 dof joint enabling rotations along 2 orthogonal axis ("Pitch/Roll" joint). By joining the basic joints with cylindrical links of various length and shape a number of different kinematic structures can be obtained, as shown later in this document.

Both families of joints are equipped with embedded control systems, providing basic low-level motion control functionalities. The set of controllers are linked together through a common communication line, running along the whole structure. The embedded solution provides the advantage of reducing issues related with cables' routing. Indeed just two electric lines are required, one for data, the other for power (the same concept is used for the connection to the motors of the hand). In addition, the design allow the possibility of filling the joints with oil, with a twofold motivations: enabling the use of the manipulator at high depths (although out of the scopes of the TRIDENT missions), by compensating the environment pressure with an external oil pump; introducing an additional level of reliability for protecting the electronic components against possible water leakages at medium depths. For lower depths however the oil filling is not mandatory, as every joint is properly sealed with a lip ring. In order to allow the employment of a single external pressure compensator, the joints have on both their ending interface (other than an electric underwater connector) a hydraulic connector for making the oil flowing among all the joints through hydraulic hoses.

Both the two versions of the gripper has been mounted on the redundant arm and validated during laboratory and pool experiments. The integration of the arm/hand subsystem on the I-AUV has been completed and several experiments have been executed in pool. The control software for the arm/hand system has been finalized and experimentally evaluated on the underwater platform. The software has been developed in order to work within the RTAI (Real Time Application Interface) real-time operating system. From the software point of view, the main integration problem is the fact that both the hand and the arm controller share a single CAN bus line, which is connected to all the servos of the arm and the hand. This in turn implies that the two controllers must interface to a single, shared driver, which sends and receives CAN messages from the actual bus line.

To overcome this problem, two dedicated RT-tasks have been created: the "CAN Manager", which relays the messages from the tasks to the CAN bus, and the "CAN Dispatcher", which receives all the incoming messages from the servos and sends them to the two controllers.

To interface the arm and the hand controller with the vehicle software, a “bridge” task has been developed since the ROS calls cannot be directly used from a hard-real time process. This bridge has the specific goal of transferring the data from the real-time system to the ROS topics and vice versa. In addition to the “bridge” task, also a ROS “console” task has been implemented. This console allows any other partner to send commands to the arm or the hand controllers, for example to arm the robot and start the homing procedure.

The integration of all the mechatronics components, including the I-AUV, has been finally tested in shallow waters (see details in the next Section).

G. WP7: Multisensory Based Manipulation Architecture

WP7 is responsible for ensuring that suitable manipulation actions are performed during the final intervention stage, and this is exactly what has been demonstrated along TRIDENT’s life. All the algorithms and strategies developed for the multisensory guided manipulation tasks, under WP7, are easily reusable, and so are paving the way for the autonomous multipurpose intervention missions in underwater domains.

<u>Object tracking and pose estimation for visual control</u>: For manipulating an object, it is necessary to localize it in the image, track it and compute its pose. Object recognition and initial detection is carried out in WP4. Therefore, this module receives input from WP4 and uses it for initializing a tracking and pose estimation algorithms. The tracking algorithm is template-based. More concretely, the Efficient Second-Order Minimization method (ESM) is used. Once the template has been matched in the image, the tracking algorithm consist of a minimization problem that continuously tries to decrease the error between the template gradient and that present at its estimated position in the image.

Switching between detection and tracking allows accelerating the vision-based control loop, since tracking is normally much faster than detection because of its local search. However, it is quite common to lose the tracked object, especially under fast relative motion of the camera and object, but also due to occlusions, strong illumination changes, etc. It is therefore desirable to combine detection and tracking so that the tracker can be re-initialized in case of failure. In our approach, tracking failures are detected by a large inter-frame displacement of the tracked template, or if the template normal being tracked in the image is not normal to the camera plane.

For manipulation purposes, the 3D pose of the object relative to the vehicle needs to be known. As the camera is calibrated and the size of the object can be known from the geo-referenced mosaic built during the survey phase, its 3D pose can easily be calculated.

The output of the tracking system is also used for controlling the arm 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 computing an error in the Cartesian space between the current pose of the end-effector, and the desired one, which is transformed into a control velocity reference sent as input to the free floating controller.

<u>3D Reconstruction and Grasp planning</u>: We have developed a laser-based approach for 3D reconstruction and grasping of unknown objects underwater, either with recovery purposes, or for other applications that require a firm grasp (e.g. fixing the vehicle to an underwater structure). In summary, with the combination of laser peak detection, target tracking, 3D reconstruction and grasp execution, this is a unique system in the underwater robotics literature. Further details can be found elsewhere [10].

<u>UWSim and HIL Simulation, Benchmarking and main functionalities</u>: A main contribution under WP7, with strong impact in TRIDENT succeed, has been the development of a new open source software tool for visualization and simulation of underwater robotic missions, UWSim [11]. The software visualizes an underwater virtual scenario that can be configured using standard modelling software. Controllable underwater vehicles, surface vessels and robotic manipulators, as well as simulated sensors, can be added to the scene and accessed externally through network interfaces. This allows to easily integrating the simulation and visualization tool with existing control architectures, thus allowing hardware-in-the-loop simulations (HIL) as well as benchmarking. The main functionalities are a configurable environment, multiple robots support, simulated sensors, contact physics, network interfaces (ROS integrated), grasping tools and a benchmarking module. UWSim has been extensively used in TRIDENT in order to perform HIL experiments, to reproduce real missions from the captured logs and for benchmarking.

Concerning benchmarks, a set of them was defined in order to evaluate the progress of the project, in the context of the autonomous intervention capabilities. With this aim, different scenarios were established for testing the performance, focused on the object recovery problem. The developed UWSim simulator is focused on the autonomous “search and recovery” intervention mission problem in the shallow waters domain, and it is not only suitable for software validation, but also for defining benchmarking mechanisms, so that control algorithms can be easily compared in common scenarios.

IV. ACHIEVED MAIN RESULTS

A. Roses harbor experiments (Oct 2011)

In the middle of the project, after a lot of trials in simulation and water tank conditions, the first real trial was performed in the Roses harbor (Oct 2011, Girona, Spain). It is noticeable that at this time the final mechatronics for the hand-arm system was still under construction, so an alternative system available in UJI was used to carry out the first experimental validation of TRIDENT in shallow water conditions. In Fig 3 the picture showing the recovery process of a black-box mockup, after localization and identification, can be observed.

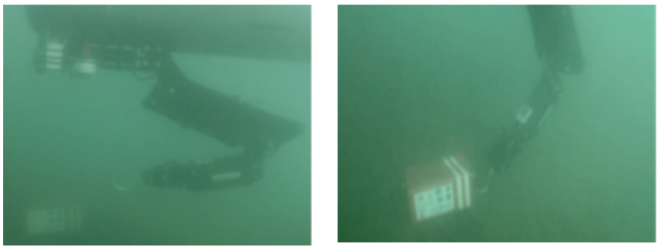

Fig. 3. The intervention in Roses harbor, by using a hooking device in place of the final dexterous hand under construction, and running station keeping control in place of "free floating" manipulation techniques under development.

B. Sóller harbor experiments (Oct 2012)

After succeed in the sea trial of Roses, and before the final TRIDENT validation experiments (Sóller, Oct 2012) some trials for integration and testing control were developed at CIRS (Univ. of Girona, Set 2012). Here the complete mechatronics was successfully tested, and all the SW components for controlling everything were validated. So, the black-box detection and recovery was successfully tested in the pool. Other previous experiments were carried out, like a visual free-floating intervention simulation under UWSim (see Fig 4). After this preliminary integration, the team did the integration again in Sóller to perform the field experiments.

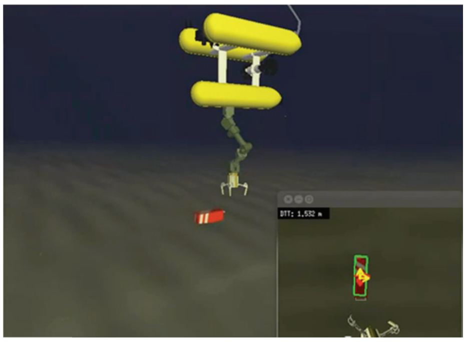

Fig. 4. Visual free-floating simulation intervention by using UWSim.

During 1-5 October 2012, the whole TRIDENT consortium met at Sóller Bay, Mallorca, to perform the project final experimental validation. During the whole week, the system was integrated and fully tested to carry out the TRIDENT final experiments in the sea. The two basic demonstrations were:

Survey and mosaicing of the intervention area: The first step for the Autonomous Intervention experiment that took place during the first week of October 2012 in Port de Sóller's harbour (Mallorca) was the surveying and mosaicking of the area where the target was supposed to be. The goal was to autonomously perform a survey trajectory under difficult harbor conditions (bad visibility, large rocks and steep slopes) with the purpose of building an image mosaic with sufficient quality to identify a target of interest, a mock-up black-box, for a subsequent intervention. The Girona500 AUV was equipped with several navigation sensors during the experiment: a Doppler Velocity Log (DVL) to measure the velocity, an Attitude and Heading Reference System (AHRS) to measure the angular position, a Sound Velocity Sensor (SVS) with an embedded pressure sensor which makes possible to estimate depth, and an echo sounder to provide more reliable altitude measurements than the DVL ones. In addition, the vehicle was also equipped with a down-looking HD stereo colour video camera to capture images for building the mosaic and characterize the target. The vehicle performed a grid trajectory of approximately 25x20m, with parallel swaths along the larger dimension of the harbour, flying at approximately 1.5m from the seabed. The trajectory plotted from the estimate of the vehicle navigation system and the resulting mosaic after composing all the images can be seen in Figure 5. The black box can be identified in the mosaic image and in the 3D point cloud map obtained combining the navigation estimated by the vehicle and the point cloud created from the stereo camera system.

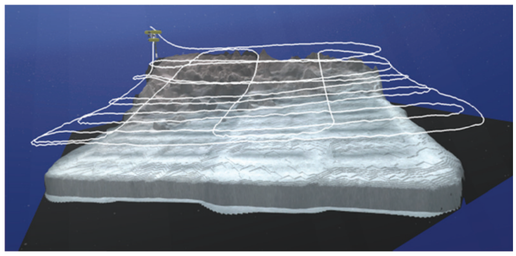

Fig. 5. Surveyed trajectory and 3D reconstructed mosaic in UWSim.

Detection, grasping and recovery: The autonomous intervention stage consisted on a black box detection, grasping and recovery from the seafloor, previously launched from a boat in a random point of the harbor area. At this time, the team had to solve some onboard computer and mechatronic problems, but thanks to the redundancy of the system, the situation was properly managed to guarantee the experiments success. After getting the seafloor mosaic, the robot did autonomous target detection. Once the black box was detected, the grasp was specified by the human operator using a specially designed user interface. Then, again with the aid of the vision system, the black box recovery stage was autonomously initiated by the system. The vision system of the robot is robust enough to allow working both in 2D and 3D (using in this case a stereo camera and a specially developed software modules). Once the box was properly grabbed by the multisensory dexterous 3-fingered hand, the vehicle brought it to the surface. The success of the experiment was observed by the TRIDENT team from the quay, thanks to the images provided by the onboard cameras of the AUV, and with the help of divers that recorded the experiment.

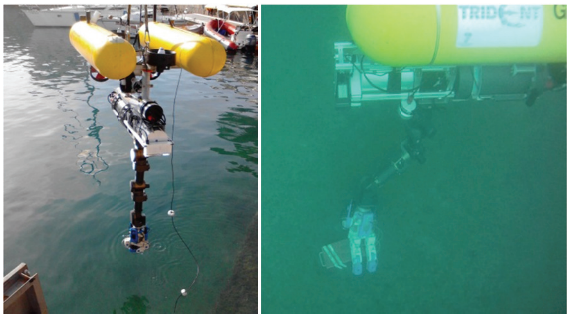

Fig. 6. Final intervention experiments in Sóller: (Left) I-AUV deployment. (Right) Successful intervention.

The experimental validation was concluded with having accomplished all the programmed objectives. The black-box was located, grasped and recovered (see Fig 6). Further information regarding the final experiments is available on-line through the official website of TRIDENT.

V. CONCLUDING REMARKS

In summary, thanks to the project and its experimental validation, a new benchmark has been established solving the “search & recovery” problem for a submerged black-box mock-up. Thus, the TRIDENT project brings together research skills specific to the marine environment in navigation and mapping for underwater robotics, multi-sensory perception and numerous techniques related to intelligent control architectures, vehicle-manipulator systems and dexterous manipulation.

The main beneficiaries of the know-how developed in this project should be companies or institutions working in underwater scenarios with specific tasks requiring intervention skills. Therefore, whichever underwater task requiring manipulation, like valve opening, button pushing, cable connecting, seabed sampling or object recovering, can now be solved in a more efficient, secure, robust and cheap way. Potential end-users are, but not limited to: offshore companies, maritime rescue organizations, coastal and ocean observatories, among others.

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