From Survey to Intervention

The challenges of 3D Mapping for Multipurpose Intervention

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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 a totally autonomous way. One of the limiting factors precluding more complex intervention tasks is the understanding and characterization of the intervention environment. Such environment can be semi or totally unstructured, and only partially known a priori. Within the context of the research activities currently pursued at the University of Girona, we advocate that successful I-AUV missions require a challenging balance between accurate surveying, environmental understanding and agile intervention capabilities.

Introduction.

During the last 20 years, AUVs have become a standard tool for mapping the seafloor using optical [Eustice06] and acoustic [Paduan09] sensor modalities, with applications in dam inspection [Ridao10], marine geology [Escartin08] and underwater archaeology [Bingham10] to mention 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 as off-the-shelf applications, although they have been extensively demonstrated by several research institutions [Richmond07, Singh04]. 3D optical maps are nowadays one of the major fronts of research with several implementation already available based on monocular structure from motion [Pizarro09], stereo [Johnson-Roberson10] and laser scanners [Inglis12].

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Our work in this area spans applications domains as diverse as marine geophysics, ecology and archeology, and ranges from large 2D optical maps, to detailed 3D reconstructions of particular areas of interest. We have conducted 2D mapping of active volcanic sites in the Mid Atlantic Ridge region, using high-resolution still images from the ARGOII and the VICTOR6000 platforms. These large optical maps cover areas of more than 0.7 square km, and have directly supported studies on temporal evolution of deep-sea hydrothermal vents [Escartin08, Barreyre12]. A very large number of plot size mosaics (of several hundred sq. meters each) have been created from optical imagery alone, in support to reef ecology studies. These include health assessment [Lirman07, Elibol11], natural and human impacts [Lirman10] and long-term change [Gintert12]. Detailed 3D textured models have been created from close range video, to characterize fast changing vent structures [Garcia11a] and dynamics of coral reef colonies [Nicosevici09, Delaunoy09].

However a large number of applications exist which go beyond the survey capabilities. The maintenance of: permanent observatories underwater; submerged oil wells; cabled sensor networks; pipes; and the deployment and recovery of benthic stations, or the search and recovery of black-boxes are but a few examples. Nowadays these tasks require the use of work-class ROVs deployed from DP vessels making them very expensive. To face these new applications, research in underwater intervention systems started early in the 90's with the pioneering works of the sea OTTER [Wang 95], ODIN [Choi94], UNION [Rigaud98] and AMADEUS [Lane97], but it was not until the 1st decade of the 21th century that field demonstrations arrived, starting with the ALIVE [Evans03], SWIMMER [Evans01] and SAUVIM [Yuh98] projects.

Our work on autonomous underwater intervention, started with the RAUVI Spanish funded project, with the design and development of the GIRONA500 AUV [Ribas12] which was equipped with an ECA 4 DOF electrical arm [Fernandez13]. Later, in the TRIDENT European project [Sanz12], a 7DOF electrical arm equipped with a 3-fingered hand was mounted on the GIRONA500 AUV and used for multi-sensory multipurpose-based intervention. This project demonstrated the use of the AUV to build a photomosaic of the seafloor for object search. Later, the robot, now in I-AUV configuration, was sent back to the site, to autonomously grasp the object of interest [Prats11]. Very recently, our team took part in a field operation where our AUV was used to map an ancient shipwreck (fig.1) at 96 m depth. In this case, a 2.5 mm pixel photomosaic was built and rendered over the bathymetry map of the site. The multimodal 2.5D view of the area, together with 3D reconstructions of selected objects, were later used by the archaeologists to plan an object recovery task to be done with an ROV.

3D mapping for intervention, using AUVs in partially and potentially unknown unstructured areas is a challenging problem. In this paper, we first present a brief technical description of our work in opto/acoustic mapping and autonomous intervention vehicles. Next, with highly the main challenges to be faced to perform 3D surveys dealing to 3D maps of the environment enabling intervention, and finally, in the last section we draw a speculative view of the future of autonomous interventions systems.

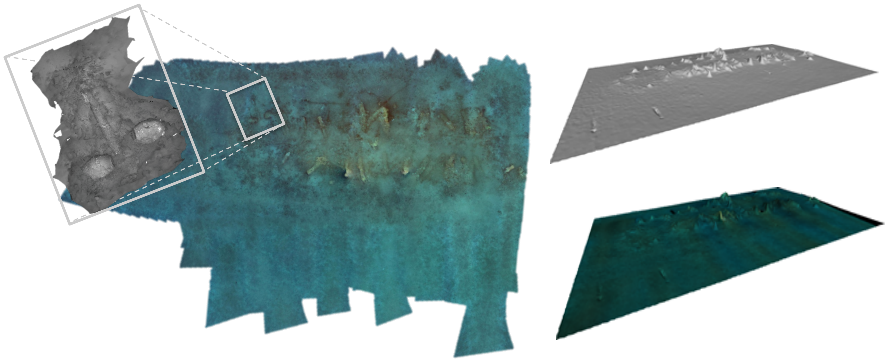

Fig.1 Photomosaic of an XVII century shipwreck. A 3D reconstruction of a canon and 2 amphorae is detailed. At the right, the sonar bathymetry, and the multimodal map resulting from rendering the photomosaic over the bathymetry are shown.

1. Technical Description

Our **experience in optical navigation and mapping** spans several research topics within the field of underwater computer vision, including 2D and 3D mapping, image enhancement and image blending. We have developed efficient methods to create *large 2D photo-mosaics* while addressing the complexity of dealing with tens of thousands of survey images and inaccurate navigation data [Ferrer07]. We have demonstrated the usefulness of mosaics as navigation maps by introducing and validating the concept of mosaic-based visual servoing for underwater robots [Gracias2003]. Our approaches use robust feature matching combined with graph optimization and information theory tools [Elibol11a], to make the loop-closing process significantly more efficient even for the cases of entirely unordered image sets with no navigation information [Elibol12]. Developments in *3D mapping* focused on structure from motion techniques [Nicosevici09] where the 3D model is generated and updated whenever new sensor data becomes available, and on incremental visual vocabularies for loop closure detection [Nicosevici12]. This modeling was further extended to support the detection of changes in the benthos at centimeter scale over areas of square meters [Delaunoy09]. The creation of detailed 3D surfaces (meshing) from noisy image data is being tackled by extending the state of the art methods to use higher-order patches and robust patch fitting [Campos11]. *Image enhancement* techniques have been developed to counteract the reduced visibility of the underwater medium, such as turbidity [Garcia11], inconsistent illumination [Shihavuddin12] and dehazing. Finally, *image blending* techniques have been developed to create seamless texture maps from multiple images, using distance depending illumination correction, graph-cut optimization and gradient blending [Prados12].

Our **experience in sonar navigation and mapping,** started developing SLAM solutions for 2D navigation and mapping in a partially structure environment like a marina, using a mechanical scanning imaging sonar to detect the wall lines and its uncertainty, and using conditional independent local maps within and EKF SLAM framework [Ribas08]. The work was extended, first, to a probabilistic scan matching EKF pose-based SLAM to deal with feature-less environments, which are more common in natural environments [Mallios10]. Next, the method was extended to perform 2.5D bathymetry based SLAM using a multi-beam sonar profiler [Zandara12]. Recently, our team has demonstrated the feasibility of motion estimation through image-sonar registration by means of spectral registration methods. Moreover, using state of the art techniques the non-linear error functions associated with the image-to-image registration may be globally optimized to provide a consistent 2D photomosaic [Hurtós12].

Our team has experience in the design and development of **Autonomous Underwater Vehicles for high accuracy opto/acoustic mapping and intervention**. To the best of our knowledge, only 3 robots worldwide have demonstrated autonomous intervention capabilities to date, namely: ALIVE, SAUVIM and GIRONA500. Being the lightest one (< 200Kg), our vehicle has proved to be flexible enough to accommodate in its payload area up to 3 different electric robotic arms ranging from 4 to 7 DOF. Our current method to intervention is based on two steps. **1. Survey:** Given an a priori bathymetric map, coverage planning techniques may be used to obtain a survey trajectory to conduct a high-resolution survey of selected areas of interest [Galceran12]. Next, the survey is done; the optical map is built being used to select the target. **2. Intervention:** The elevation map is used to plan a path to the target [Hernandez11]; Next, the AUV is deployed and driven to the target; After, it executed visual-servoing station keeping [Prats12] and performs an autonomous grasping [Prats11]. Now, our past experience in robot learning [Carreras05, El-Fakdi10] is being applied to autonomous manipulation tasks common of subsea intervention panels, with promising results.

2. Key Challenges

The major challenge that will drive our research during the next years is the **design and development of the hardware/software systems necessary to conduct 3D surveys for 3D map building at different resolutions and sizes, with different sensor modalities and having intervention applications in mind.** This challenge requires significant advances at the different mission phases of an I-AUV operation:

- **Pre-Mission**: Advanced coverage planning algorithms should take into account already available prior maps, the imaging-sensor and AUV-motion constrains, as well as criterions for the optimization of the navigation, mapping and inter-vehicle communications, to produce “optimal” survey trajectories.
- **During-Mission:** Long-term navigation in an unconfined environment still is the major challenge. Online coverage planning algorithms will be necessary to refine in real-time the offline planned-paths, in order to survey 3D benthic structures not visible at the resolution of prior maps. Active strategies will be necessaries for motion-planning to achieve better: navigation; mapping; and trajectories to arrive to a target way-point, with the minimum uncertainty. Navigation and safe guidance, at close distances to 3D benthic structures to perform intervention, is

also challenging, since bottom-lock is likely to be lost. Advancing in mapping from different sensor types (monocular SFM, stereo, laser-camera, imaging sonar, profilers sonar), and their fusion into a single consistent map is also a great challenge. Finally, it is necessary to endow vehicles with online capabilities to extract semantics (scene understanding) from the 3D maps to enable manipulation planning, and failure/risk assessment.

- **Post-Mission:** How to combine data coming from different sensor modalities into a single and consistent model of the environment is one of the main challenges. Advancing towards the co-registration of several 2D/3D maps, potentially from surveys in different periods of time is also necessary. Finally, new methods will be needed to extract and classify relevant information from within the vast stream of data recorded by the vehicles, for human interpretation.

3. Underwater Intervention: A Speculative View of the Future

UUVs have been traditionally categorized into ROVs and AUVs. The last decade has witness 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 become fuzzier. There will be gliders, able to do seafloor surveys in AUV mode, 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. Getting rid of the fiber tether, using a laser communications system was recently demonstrated at short distance. Next years, the advances in underwater wireless communications technology, are expected to increase this distance, as well as the communication bandwidth, enabling online reconfiguration from AUV to ROV and vice versa. HROVs will behave as intervention ROVs or as I-AUVs depending on the operator's 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, f.i. 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[1] 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 realized 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 enabling multiple vehicle mapping without recovery.

[1] beyond the coverage area of acoustic transponder networks

When equipped with arms (I-AUVs) cooperation will go beyond navigation and mapping to face challenges like **cooperative manipulation** (f.i. 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 field, etc.). They will need the skill to build 3D occupancy maps of the environment (free/occupied/unexplored) online 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 (1m). At 1m distance, the 3D relief becomes significant, easily violating the maximum slope-threshold of the DVL to allow for 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.
Advanced 3D imaging methods (stereo, laser scanners) will allow gathering 3D point clouds of the site of interest. Next, prior models of the expected objects (amphorae, black box, underwater intervention panels…) will be used for object recognition to enable **semantic mapping,** providing a more elaborated world model for manipulation planning. Semantic maps pave the way to **scene understanding**, where the **feasibility of accomplishing a task** may be evaluated on the fly, as well as the **risk for the robot** (example: retrieving a black box that is unexpectedly in the middle of broken cables). Finally, these vehicles will bring back vast amounts of data making it impossible the human interpretation of the raw optical and acoustic imagery. Methods will have to be developed to highlight the relevant data for the application at hand to allow for a correct human interpretation.

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