Forward-Looking Sonar Mosaicing: A new approach for underwater inspection in low visibility conditions

Natàlia HURTÓS, Pere RIDAO

Key words: forward-looking sonar, mosaicing, mapping

SUMMARY

Vehicle operations in underwater environments are frequently compromised by poor visibility conditions. The perception range of optical devices is heavily constrained in turbid waters, thus often complicating navigation and mapping tasks in environments such as harbors, bays, or rivers. A new generation of high-frequency forward-looking sonars (FLS) that provide acoustic imagery at near-video frame rates has recently emerged as a promising alternative for working under these challenging conditions.

We have proposed an end-to-end mosaicing framework tailored to the characteristics of forward-looking sonar imagery in order to build consistent overviews of underwater areas regardless of water visibility. Our solution targets versatility: it enables the generation of acoustic mosaics that involve roto-translational motions and comprise different vehicle tracklines; it is suitable for a wide range of scenarios, from feature-rich areas to environments with scarcity of features; it can be applicable on data collected with minimally instrumented vehicles; and it allows both offline and real-time operation. Moreover, the resulting mosaics provide a significant improvement of the signal-to-noise ratio and resolution with respect to the individual sonar images.

The presented system stands up as a valuable tool for short-range high-resolution acoustic mapping (up to centimeter level, depending on the employed sonar) but also opens new avenues for more challenging applications. The capability of being localized within a real-time generated acoustic map of the seafloor holds great potential for providing visual support to ROV pilots under low visibility conditions, AUV search and reacquisition tasks without the need of resurfacing or, in general, to any application that can benefit of context awareness regardless of the visibility conditions. The proposed framework has been validated with several experiments in the context of relevant field applications such as harbor monitoring or mapping of underwater archaeological sites.

1. HIGH RESOLUTION FORWARD-LOOKING SONAR TECHNOLOGY

2D FLSs, sometimes also referred to as acoustic cameras, are a category of sonars that provide high-definition acoustic imagery at a fast refresh rate. Although the specifications regarding operating frequency, acoustic beamwidth, frame rate, and the internal beamforming technology depend on the specific sonar model and manufacturer, the principle of operation is the same for all. The sonar insonifies the scene with an acoustic wave, spanning its FOV in the azimuth (θ) and elevation (φ) directions, and then the intensity of the acoustic return is sampled by an array of transducers as a function of range and bearing (Figure 1a). Because of the sonar construction, it is not possible to disambiguate the elevation angle of the acoustic return originating at a particular range and bearing. In other words, the reflected echo could have originated anywhere along the corresponding elevation arc. Therefore, the 3D information is lost in the projection into a 2D image. Following the nature of the transducer readings, the images are arranged and represented in polar coordinates. Therefore the dimensions of a raw frame correspond to the number of beams in the angular direction and the number of range samples in the range axes. This representation is then converted to the final 2D image in Cartesian coordinates for an easier interpretation. By directly delivering 2D acoustic images, they provide a closer rendition of what the eye naturally sees and thus minimize the required level of processing and interpretation compared to other types of sonar devices (see Figure 1b).

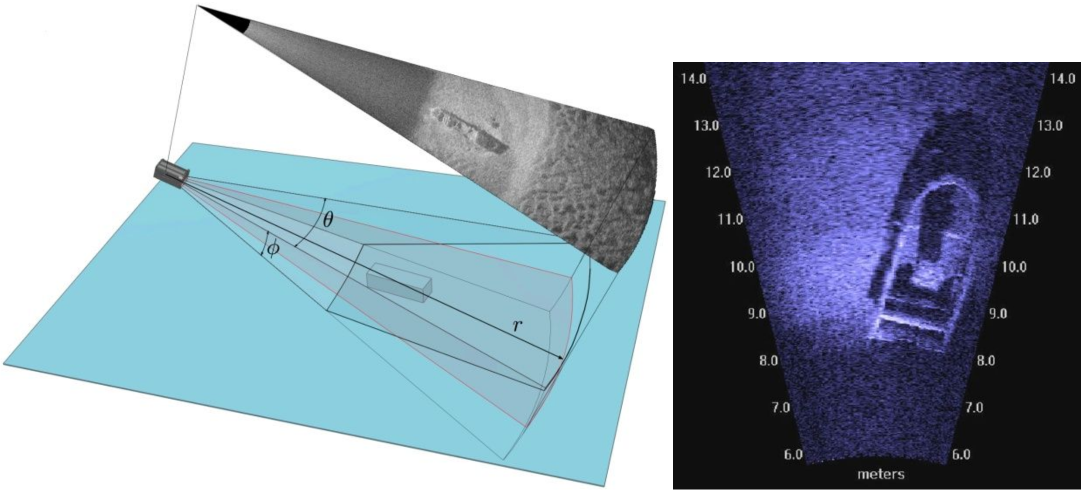


Figure 1: a) Geometry of a FLS. b) Example frame

2. MOSAICING OF FORWARD-LOOKING SONAR IMAGES

Mapping is a quintessential application for FLS devices and the analogy that can be established with popular photomosaicing approaches becomes straightforward: the effective FOV of FLS images can be increased offering extended overviews of underwater areas by registering individual frames. Moreover, by using acoustic images, this can be performed regardless of the visibility conditions, though at expenses of dealing with a more challenging type of data. The current lack of effective solutions to the problem has led us to develop a complete, versatile and efficient mosaicing pipeline tailored to the peculiarities of FLS images. The few existing FLS mosaicing approaches have shown limited results in terms of scale and complexity, as most of the reported mosaics are restricted to only a few frames gathered in a single straight trackline while imaging feature-rich scenarios. On the commercial side, there are several solutions that provide mosaics by using absolute positioning sensors to project the acoustic images over the navigation poses. However, they do not perform registration of FLS images and their results totally depend on the availability and accuracy of an absolute positioning system, thus not guaranteeing full consistency between the different images and not being a good option for underwater vehicles.

The developed mosaicing pipeline consists in three basic steps that are detailed in the next subsections and summarized in Figure 2.

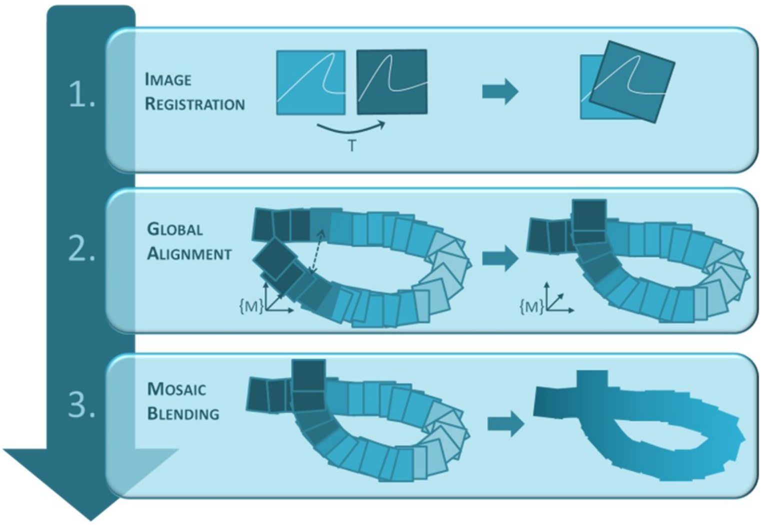


Figure 2: Steps of mosaicing pipeline.

2.1. Pairwise Sonar Image Registration

The first problem to address is the pairwise registration of sonar images which is a key step in the mosaicing pipeline. The characteristics of the FLS data, such as low and inhomogeneous resolution, low signal-to-noise ratio and intensity variations due to viewpoint changes, become a challenge for traditional feature-based registration techniques. For that reason we have proposed a Fourier-based methodology that, by involving all image content into the registration, offers robustness to noise and the different artifacts associated with the acoustic image formation. The approach relies on the phase correlation principle to estimate the image shifts and it is further adapted to cope with the multiple noise sources that can influence the registration, by providing specific masking, frequency filtering and rotation estimation procedures. When quantitatively compared, the proposed registration method shows superior performance to state-of-the-art feature-based approaches, while offering at the same time the possibility to be implemented efficiently [1].

2.2 Global Alignment

Next, we address the global alignment of the mosaic in order to enforce consistency between consecutive and non-consecutive image pairs. We lay out the problem as a graph optimization over the image poses, integrating spatial constraints from pairwise registrations as well as from navigation data when available. We provide a front-end to determine the constraints that should be included in the graph according to an initial estimation of the trajectory and a selection of potential overlapping candidate pairs. The workflow followed to build the graph is provided for both offline mosaicing and the online approach [2], where constraints are added incrementally and under stringent restrictions to warrant real-time operation. In addition, we propose an uncertainty measure derived from the registration method to weigh appropriately the contribution of the registration constraints in the optimization.

2.3 Mosaic Blending

Finally, we have explored the blending of the acoustic images into a smooth and informative mosaic while improving the signal-to-noise ratio and resolution of the final composition with respect to the individual frames [3]. Furthermore, we have identify the different photometric irregularities that can arise from the sonar imaging configuration and we provide a set of strategies to minimize their impact both at frame and mosaic level.

3. USE CASE APPLICATIONS

We have validated our FLS mosaicing pipeline through a series of experiments, showing successful results in relevant field applications such as ship-hull inspection, harbor mapping and archaeological exploration. As evidence of the framework's versatility we'll present hereafter results of datasets involving data from different sonar models, gathered through different setups and imaging diverse environments in terms of morphology and scale.

3.1. Harbor monitoring

The surveillance of port facilities is a key application routinely performed for security and husbandry purposes in a low visibility environment. From the inspection of ship hulls to the periodical monitoring of the harbour's seafloor there are many cases where the generation of an image mosaic could avoid the inspections by divers, which are a hazardous and time consuming task.

Figure 3 presents an example of a mosaic of a ship hull elaborated with the presented pipeline using DIDSON data [4], courtesy of Bluefin Robotics. The experiment was conducted on the King Triton vessel in Boston Harbor using the Hovering Autonomous Underwater Vehicle (HAUV) [5]. The vehicle navigated across the bottom of the hull, maintaining a constant distance to it and covering an area of about 15m x 6 m. Ground truth is not available, but we can see that the rendered mosaic presents a consistent overall appearance and allows the identification of the various features on the hull.

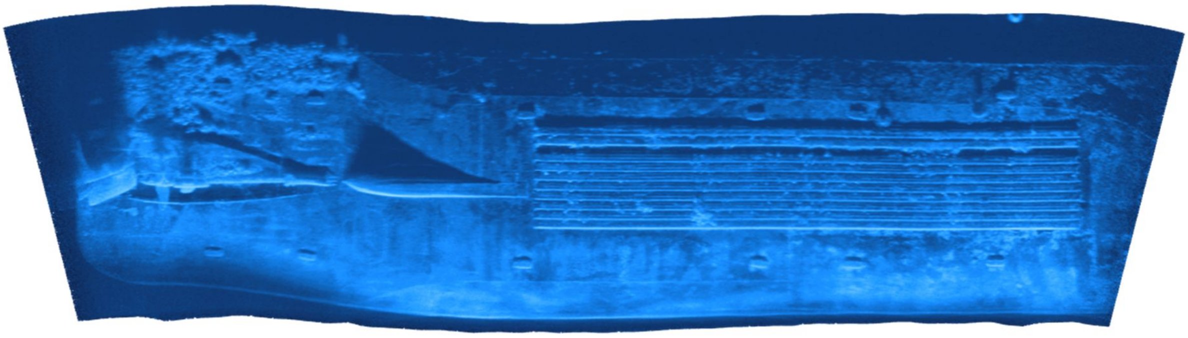


Figure 3: Ship hull inspection mosaic.

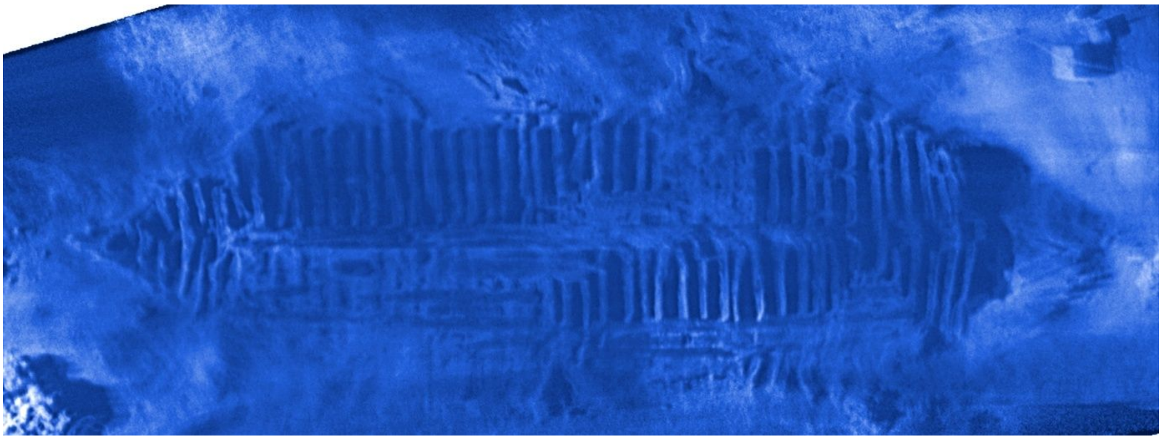
Another related example is shown in Figure 4. This is the resulting mosaic of a harbour survey performed during the ANT'11 sea trial organized by the Centre for Maritime Research and Experimentation (CMRE), former NATO Undersea Research Centre, in collaboration with the University of Girona. The experiment was conducted using a Blueview P900-130 [6] FLS mounted on CMRE's Autonomous Surface Vessel (ASV). The employed setup allows us having precise differential GPS data and heading from 2 antennas which we use as ground truth. The dataset is composed of 4416 sonar frames gathered along a 2.1 km trajectory comprising both translational and rotational motions in order to survey the whole marina environment. This dataset is useful to assess the proposed methodology under a more natural environment containing typical sea floor features (e.g. vegetation, rocks) which are sparse and less prominent than those found in man-made scenarios. The resulting mosaic presents an overall view of the surveyed area with a continuous and uniform appearance. A result of this type is of special interest not only to observe the harbor features and their spatial arrangement but also because it enables us to perceive features that otherwise would be difficult to distinguish given the low resolution and SNR of this particular sonar. Moreover, since in this case position ground truth is available, we can see that the trajectory obtained after the graph optimization closely matches the GPS track, indicating that the registration constraints lead to a valid solution. Detailed quantitative analysis and plots are not reported here but the interested reader can refer to [1].

Figure 4: Mosaic of a harbour environment

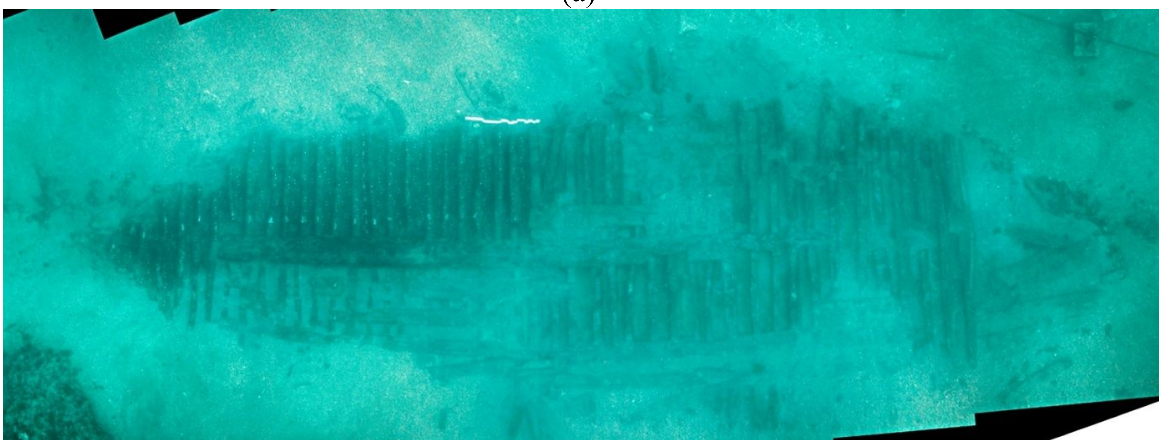
3.2. Archaeological exploration

In an effort to demonstrate the real-time capability of the mosaicing pipeline we present an experiment in the context of archaeological explorations. The results reported in this section are based on the data gathered at the Cap de Vol shipwreck located at Port de la Selva (Costa Brava-Spain) with the Girona500 AUV [7]. An ARIS Explorer 3000 sonar [8] and stereo camera system were installed in the payload area for this particular mission. The Girona500 was teleoperated over the shipwreck area at approximately 0.2 m/s, whilst maintaining a fixed

altitude (3 m) and heading to ensure more consistent shadows within the dataset. Several tracklines were performed to guarantee the coverage of the site as well as the possibility to establish loop closures between parallel tracks. In total, 2720 sonar frames were recorded during the experiment which lasted approximately 22 minutes, covering an area of 17×8 m.
We have applied the proposed mosaicing pipeline in an online fashion over the described dataset. Thus, to achieve real-time performance we must ensure that we can process the incoming number of frames per second, that is, registering each frame with a number of candidate frames gathered in their vicinity. The key point is adapting the number of attempted registrations per frame (the more the better as there will be more constraints) so as to take advantage of all the available processing power but still being able to keep the computations in real-time. By processing the dataset under these real-time parameters (refer to [2] for details) we have obtained the mosaic of Figure 5a where the wooden structures of the shipwreck can be clearly seen.



(a)



(b)

Figure 1: 5) Acoustic mosaic of the "Cap de Vol" archaeological wreck. b) Optical mosaic of the same wreck.

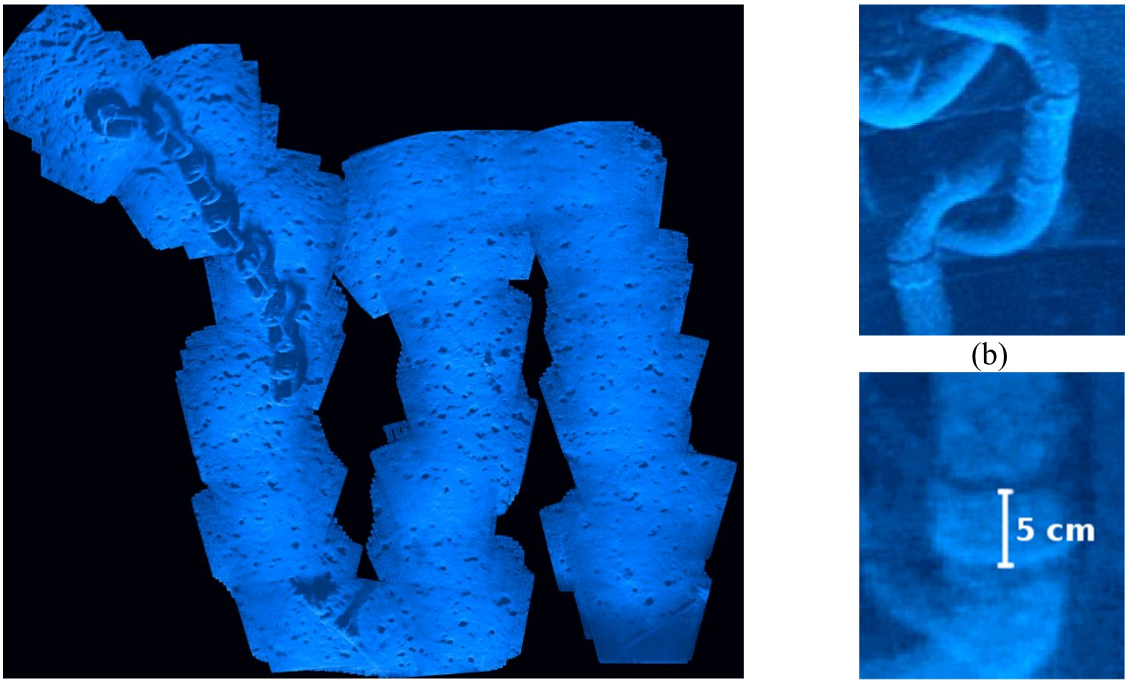
The rendering, also conducted in real time, is performed only by averaging the overlapping intensities at each mosaic pixel while the mosaic size is automatically expanded with the addition of new frames. Given that the day of the experiment water visibility was good, an optical mosaic of the same area is provided in Figure 5b for comparison purposes.

3.3. Mooring chain detection and inspection

Following an underwater chain using an autonomous vehicle can be a first step towards more efficient solutions for cleaning and inspecting mooring chains. We have performed several experiments in the context of locating and mapping a mooring chain with a FLS device. This is an example of an application where the role of the FLS data is twofold: it is the input used to control the AUV and, at the same time, is used for mapping purposes.

Our experiment accounts for a detection phase, in which first the vehicle must automatically find the chain in the environment. This is done by using a detection algorithm that we have developed to robustly detect chain links on sonar imagery in real time [9]. As they are detected, the link positions are transformed to navigation waypoints that the vehicle must follow. The vehicle is guided through these waypoints using a high level controller that has been tailored to simultaneously traverse the chain while keeping track of upcoming links. Finally, with the FLS images gathered along the trajectory we can produce a mosaic of the chain and its surroundings.

Figure 6 shows results from experiments conducted in a harbour environment with Girona 500 AUV and the ARIS 3000 Explorer in order to validate the performance of the system in finding, following and mapping a chain. The framework proved able to locate the chain, in this case placed on the seafloor, within a large harbour environment. Moreover, thanks to the accurate detection of the different chain links, the vehicle was able to perform a trajectory closely following the link's centres. Furthermore, the resolution of the obtained acoustic mosaics allows to identify features up to centimetre level thus providing a useful map to detect chain parts that need further inspection (see Figure 6).



(a) (b) (c)

Figure 6: a) Mosaic from the search and tracking trajectory b) Detail of one chain link. c) Detail of a link's feature.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

We have addressed the 2D mapping of low-visibility underwater environments by providing a full framework to generate acoustic mosaics from FLS imagery. The motivation comes from the recent breakthrough in the market of new high resolution FLS devices that can deliver 2D acoustic imagery. The cost of these sensors is still quite high, but as their size and price decrease we believe they become an increasingly interesting option for both ROV and AUV mapping applications.

A particularly interesting application is to provide real-time mapping for ROV pilots. This would help them to ensure coverage of the area and immediate location of targets of interest in the environment, regardless of the water visibility conditions. Such application would require pushing the envelope of the pipeline's real-time processing, but is definitely a line to explore. Moreover, after acquiring experience on the imaging capabilities of FLSs, we gained insights of what can and cannot be easily observed with this sort of sonar devices. This opens the door to explore totally different application areas that could exploit the FLS imaging capabilities, even if they are not in the form of mosaicing. Some applications that are worth considering for the future are, for instance, flow detection and measurement (such as in hydrothermal vents or in underwater pipe leaks) or detection of fishing nets.

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BIOGRAPHICAL NOTES

Natàlia Hurtós is a postdoctoral researcher in the Underwater Vision and Robotics Laboratory (CIRS) of University of Girona (UdG), Spain. She holds a B.S. degree in Computer Science (2007), an European Master in Computer Vision and Robotics (VIBOT, 2009) and a PhD in Computer Engineering (2014). Since 2006 she has participated in several research projects (both national and European) and contributed to multiple field campaigns. Her research interests are mainly focused on autonomous underwater robots and mapping of underwater environments using different types of sonar data.

Pere Ridao received the Ms.C. degree in computer science in 1993 from the Technical University of Catalonia, Barcelona, Spain, and the Ph.D. degree in computer engineering in 2001 from the University of Girona, Spain. His research activity is mainly focused on underwater robotics in research topics such as intelligent control architectures, UUV modelling and identification, simulation, navigation, mission control and real-time systems. Currently, he is an associate professor with the Department of Computer Engineering of the University of Girona and the head of the Research Center in Underwater Robotics (CIRS) located in the Scientific and Technological Park of the University of Girona. He is involved in national projects and European research networks about underwater robotics and some technology transference projects about real-time and embedded systems. Dr. Ridao is member of the IFAC's Technical Committee on Marine Systems, member of the editorial board of Springer's Intelligent Service Robotics journal, secretary of the Spanish OES chapter and also a board member of the Spanish RAS chapter.

CONTACTS

Natàlia Hurtós Vilarnau
Girona Underwater Vision and Robotics, University of Girona
Edifici CIRS. C/Pic de Peguera, 13. Parc Científic i Tecnològic de la Universitat de Girona
17003 Girona
Spain
+34 972419651
nhurtos@eia.udg.edu
http://cirs.udg.edu, http://eia.udg.edu/~nhurtos