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# Forward looking sonar mosaicing for Mine Countermeasures[☆]

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ABSTRACT

Forward looking sonars (FLS) are nowadays popular for many different applications. In particular, they can be used for Automatic Target Recognition (ATR) in the context of Mine Countermeasures. Currently, ATR techniques are applied to raw data which generates many false positives and the need for human supervision. Mosaicing FLS data increases target contrast and thus reduces false positive rate. Moreover, it implies a considerable data size reduction which is important if one thinks of exchange of data in real time through an acoustic channel with very limited bandwidth. Results of applying a real-time mosaicing algorithm to FLS data generated during Mine Countermeasures missions are shown and discussed thoroughly in this article.

## 1. Introduction

Sonars have been used as a possible alternative to optical cameras due to the optical cameras' limitations. Sonars work under conditions which affect deeply optical cameras such as turbidity and lack of illumination. They become especially useful in underwater vehicles that lack artificial light or work too far from the bottom or in surface vehicles working in non-shallow waters, as the light attenuation in the water gives a very limited range to optical cameras.

Sonars can have several applications including but not limited to; obstacle avoidance (Karabchevsky, 2011; Petillot, Ruiz, & Lane, 2001), bathymetric mapping (Singh, Roman, Pizarro, Eustice, & Can, 2007), chain inspection (Hurtos et al., 2014b; Yong, 2011), motion estimation (Dolbec, 2007), 3*D* reconstruction of objects (Aykin & Negahdaripour, 2013) or ATR (Beaujean, Brisson, & Negahdaripour, 2011; Galceran, Djapic, Carreras, & Williams, 2012; Reed, Petillot, & Bell, 2004; Williams & Groen, 2011). Many of these applications are based on data collected with Side-Scan Sonars (SSS), Synthetic Aperture Sonar (SAS) or high resolution forward-looking sonars (FLS). Forward-looking sonars with lower resolution are also used because of their satisfactory range resolution and lower cost. Their dimensions and power requirements allow them to be mounted on Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs) and Autonomous Surface Vehicles (ASVs) of medium size.

One of the applications that a FLS allows is mosaicing. In the optical imaging domain, mosaicing is quite common and many examples can be found not only working in real-time (Ferreira, Veruggio, Caccia, & Bruzzone, 2012; Richmond & Rock, 2007) but also offline with higher quality both in 2*D* (Negahdaripour & Xu, 2002) and 3*D* applications (Pizarro, Eustice, & Singh, 2009). In the sonar imaging domain, there exist Commercial Off-the-Shelf (COTS) software products for post-processing and real-time mosaicing of numerous sidescan, subbottom and bathymetric sonars, such as SonarWiz5n (SonarWiz, 2013). However, in particular for FLS data, much less work has been published on mosaicing and specifically on real-time mosaicing.

Nonetheless, real-time mosaicing of FLS data can be extremely useful in applications such as Mine Countermeasures. In the context of an underwater mine detection, providing a mosaic in real-time is important to fulfill the ultimate goal of the full mission (target recognition). Typically, target recognition algorithms run on raw sonar data instead of mosaics. As it shall be seen, the Signal-to-Noise ratio (SNR) increases for mosaic data comparing it with the raw data. The mosaic can provide a better input image to the Target Detection algorithm and diminish the number of false positives, an important issue in ATR. While building a mosaic for sonar data, special care has to be taken due to the peculiarities of acoustic cameras. Nevertheless, in recent years, mosaicing algorithms for sonar data have been evolving and the current state of the art is promising.

Namely, the initial work of Kim, Neretti, and Intrator (2005) shows mosaics composed of 40 images of a boat wreckage obtained with a high-resolution FLS, Dual-Frequency Identification Sonar (DIDSON). However, the algorithm is not real-time. Later, in Kim, Neretti, and Intrator (2008), more results of a mosaic built with 80 images of a

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ship-hull inspection are presented. It is shown that the algorithm is implemented to work in real-time, but it is uncertain if it can provide the claimed resolution with the enhancement (up to 10 times the original) in real-time. As a result of this work, a commercial software for sonar image enhancement and mosaicing (processing time of 3.5 frames/s) is available (AcousticView, 2013). According to the authors, with this software, it is possible to obtain a mosaic of up to 1000 frames depending on the level of free memory. In comparison, our approach was tested in datasets as big as 8000 frames with no issues. Moreover, this software does not support zigzag sequences and the manual advises to perform straight lines scanning. The instructions refer to the fact that the algorithm can fail if there are no "anchor points" [sic], i.e., features to match and that a 60–70% of overlap is advisable. Another drawback is that it is specific for DIDSON, a short range and high-resolution FLS. While the range itself is not a limitation for extending the algorithm, the decrease in resolution associated to higher ranges may bring issues to the image registration. Another very recent software (SAMM, 2014), creates mosaics in real-time by stitching the images based on the GPS position without any image registration or navigation filtering. In this case, the algorithm is able to work with several different sonars. No maximum number of frames is mentioned. However, navigation filtering is only available in post-processing and no image registration is used neither in real-time nor in post-processing. In our approach, both navigation filtering and, when suitable, image registration are done online and in real-time.

Mosaicing FLS data is a very challenging task due to the approximate imaging model and commonly appearing artifacts. A very good analysis of the most important issues in mosaicing of FLS data can be found in Negahdaripour, Aykin, and Sinnarajah (2011). In Thomas, Iv, and Reed (2011), the gap produced by the nadir of the SSS is filled with FLS data. Only FLS data corresponding to the nadir of the SSS is mosaiced together with the SSS data. This method was tested in a post-tsunami survey with good results. Objects that would not be seen in the SSS data were found with the FLS. This diminishes mission time, as to see the same objects using only SSS would take more transects (due to the nadir) and thus more time. No details about computational time are given in this article. In Hurtos, Cuf', Petillot, and Salvi (2012), an innovative phase correlation-based mosaicing algorithm was applied to FLS data in a ship hull inspection scenario. The maximum number of frames registered was 834 and the algorithm took around 1 h to compute the whole set of links between the different frames. More recently, a chain inspection based on FLS small areas ($4 \times 7$ m$^2$) mosaics was presented in Hurtos et al. (2014b). None of these were used in real-time missions. For these works, the expensive high-resolution low range DIDSON sonar is used which is not suitable for Mine Countermeasures missions where lower cost and resolution but higher range FLS are preferable. Recent evolutions of these two works can be found in the journal paper (Hurtós, Ribas, Cufí, Petillot, & Salvi, 2015). Again, the method should be able to be extended to higher ranges sonars but might suffer from the quality or lack of features. Bear in mind that, for low range and high resolution FLS like DIDSON, the size of the features found in applications such as ship-hull or chain inspection is considerably large when compared to the image size. Instead, in our work, the higher range FLS were used to image farther objects (at depths that can reach 30 m) and thus the features size is much smaller increasing the complexity. In Yong (2011), mosaicing techniques were investigated for FLS data. In that Master thesis, the algorithm works near real-time but the results are focused only on ship-hull inspection (small area covered). In this case, the maximum number of frames was 200.

As described above, the algorithms presented in the literature are not suitable to work for a wide range of applications, in real-time and for large scale areas. The state of the art methods try to solve a specific problem and are not focused on the real-time constraint. The work presented here overcomes all these limitations. It tries to be as generic as possible while maintaining the real-time constraint and working in any area of any dimension. It generates georeferenced mosaics that can be easily overlapped in a satellite map. Namely, it can be considered for ATR applications, large area survey and post-mission analysis, among others. The algorithm is flexible to work with various sonars (BlueView and Reson tested thus far) and in different setups (fixed to a pier or mounted onto a moving ASV or onto a moving ROV tested so far). The results presented here are more related with the application of Mine Countermeasures, specifically ATR. For more results on large scale areas please consult (Ferreira, Djapic, & Caccia, 2015). Due to the few works found in the literature regarding sonar mosaicing, the reasons that motivate this line of research are introduced in the next section together with its application to Mine Countermeasures. A description of the mosaicing algorithm follows in Section 3. Section 4 describes the target recognition algorithm. The results are presented and discussed in Section 5. Finally, Section 6 concludes the article and proposes future work.

## 2. Motivation and applications

### 2.1. Motivation

Forward looking sonars have seen an impressive technological development in the past few years with higher frequency sonars in the range of MHz. Some of the latest commercial forward looking sonars can go over 1 MHz up to 3 MHz providing high quality images for ranges between few metres and dozens of metres. This allows new applications such as sonar-aided navigation (Johannsson, Kaess, Englot, Hover, & Leonard, 2010), chain inspection (Hurtos et al., 2014b) or mosaicing. Due to their high quality, sometimes, forward-looking sonars are named acoustic cameras. In what follows, these two terms are interchangeable.

There are several reasons that motivate the mosaicing of FLS data. One of them is the filtering of the acoustic noise. Reducing the noise increases the SNR. This happens because of the averaging effect involved in the mosaicing process. Comparing with optical cameras, acoustic cameras have intrinsically more noise due to the physics of the image formation. For optical systems, the experimental conditions can be defined in a way that minimizes noise (e.g., using homogeneous illumination). In the acoustic domain, the noise is considerable and mosaics can reduce it significantly. Defining favourable experiments like mounting the sonar in an overactuated stable robot can only help to reduce the influence of perturbations. However, this is not enough to diminish the noise sufficiently. The physics of an acoustic device such as a forward looking sonar implies that several consecutive images will not be very similar. For instance, backscatter and reflections coming from the water column occur independently of the stability of the platform and affect the data quality.

For surface vehicles, the sea state influences the sonar noise level. Waves can have a considerable impact in pitch and roll variations. These degrees of freedom are not controlled normally. Their instability affects the insonified area and incident angle. Fig. 1 exemplifies this inhomogeneous insonification natural phenomena. It shows two almost consecutive frames (separated by one frame and half a second) with different insonifications even though the vehicle is practically in the same place. This can severely affect the performance of object detection algorithms as an object can be seen clearly or hardly depending on the insonification. Several frames with different insonifications are normalised by the averaging process implied in the building of a mosaic, solving that issue.

Other acoustic devices constitute also sources of acoustic noise. Namely, echosounders and DVL can interfere with a FLS when mounted onto the same vehicle and working in frequencies within the operational range of the FLS. The same averaging effect of mosaicing can substantially decrease this source of noise. To better understand this issue, real data collected during sea trials exemplifies