Square SAS: Multi-Aspect Imaging with a Towed Synthetic Aperture Sonar

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***Abstract*—When hunting for stealthy naval mines in highly cluttered regions, a multi-aspect capability is advantageous because multiple "looks" improve the probabilities of detection and classification. For autonomous underwater vehicles (AUVs), full azimuth coverage is possible by flying circular or spiral trajectories while keeping the target within the sonar beam. Circular navigation of a towed sensor is more challenging due to the variable tow cable dynamics. Nevertheless, towed synthetic aperture sonar (SAS) systems are preferred for many applications because they achieve a very high area coverage rate with excellent endurance, rapid transit capabilities, and high bandwidth telemetry. In this paper, we describe and demonstrate an operational concept called "Square SAS" for towed sonar platforms. Square SAS consists of fusing multi-aspect imagery from piecewise linear survey lines having an azimuthal extent of at least $\pm 90°$. The concept can be extended to include an arbitrary number of piecewise linear survey lines such as hexagonal or octagonal configurations. Experimental results are presented from Kraken's SeaScout seabed mapping system equipped with a high speed towed SAS. The image fusion technique is generally applicable to any SAS platform, including AUVs, without any prior assumption for the target shape. However, the technique is ideal for towed systems where multiple linear passes are necessary to achieve a true multi-aspect imaging capability with a wide azimuth coverage for effective target classification.**

***Index Terms*—synthetic aperture sonar, multi-aspect, image fusion, co-registration**

I. Introduction

Synthetic aperture sonar (SAS) is a high-resolution acoustic imaging sensor that exploits the along-track motion of the platform to synthesize an aperture with a length that increases with range, thereby achieving resolution that is independent of range and frequency. SAS can operate at lower frequencies than conventional sidescan sonar, which reduces acoustic absorption and achieves a high area coverage rate (ACR) while maintaining centimetric resolution. For mine countermeasures, the combination of high resolution and long range enables in-stride target detection and classification using a single sensor. Naval mines are a constantly evolving threat designed to blend in with other objects on the seafloor. When hunting for stealthy mines in highly cluttered regions, a multi-aspect capability is advantageous because multiple "looks" improve the probabilities of detection and classification, especially for computer-aided techniques in automatic target recognition (ATR) [1].

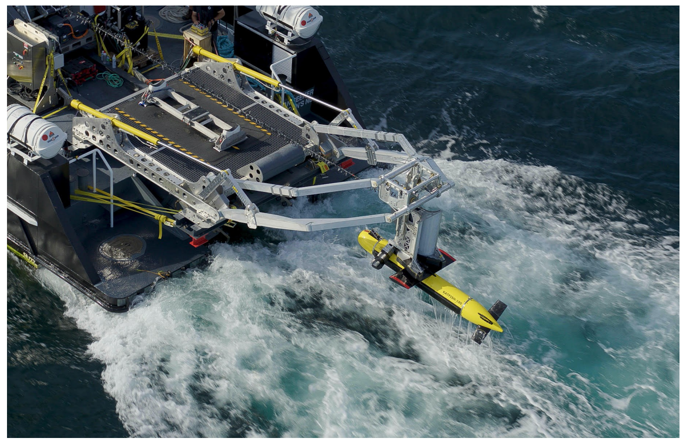

Fig. 1. *R/V Ocean Seeker* with Kraken's SeaScout system consisting of a launch and recovery system, KATFISH actively controlled towfish, and AquaPix Miniature Interferometric Synthetic Aperture Sonar (MINSAS).

Along a linear path, a partial multi-aspect capability can be obtained either by processing SAS data in along-track sub-apertures [2] or by using a squinted transmitter [3]. However, both approaches result in degraded resolution and image contrast, with an azimuth range of only roughly $\pm 30°$ depending on the transmitter beamwidth and squint angle. Full azimuth coverage is possible by flying an AUV in a circular or spiral trajectory while keeping the target within the sonar beam [4]. Tow cable dynamics make circular navigation of a towed sensor significantly more challenging. For many applications, towed sensors are preferred as they achieve a high ACR even in shallow water [5], especially when combined with a nadir gap fill solution [6]. Towed platforms are also desirable because they have long endurance, rapid transit capabilities, ample electrical power for real-time processing, and extremely high bandwidth telemetry compared to AUVs (e.g., RF versus acoustic), which is ideal for real-time data review with human-in-the-loop decision making.

Kraken's SeaScout seabed mapping system is shown in Figure 1 as installed on *R/V Ocean Seeker*, a 20 m twin-hull catamaran outfitted for geophysical survey operations. The towfish sensors, including the broadband SAS receiver array, are indicated in Figure 2.

In this paper, we describe and demonstrate an operational

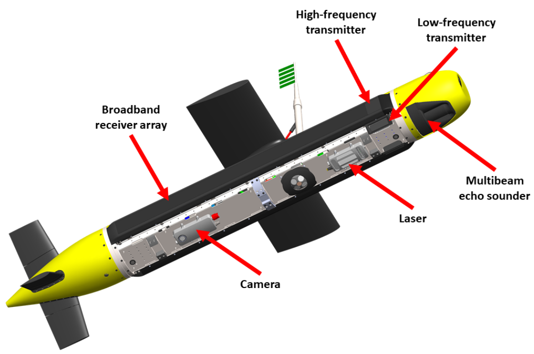

Fig. 2. Rendering of KATFISH (viewed from below) equipped with both the high-frequency (long-range) and low-frequency (short-range) SAS, as well as two auxiliary nadir gap fill sensors: the SeaVision 3D laser profiler (laser and camera), and a multibeam echo sounder.

concept called "Square SAS" for towed sonar platforms. Square SAS consists of piecewise linear survey lines having an azimuthal extent of at least ±90°. Examples include: 1) a closed square with azimuth viewing angles of 0°, ±90°, and 180° as shown in Figure 3, which requires three additional passes after initial target detection; and 2) an open square requiring two additional passes at ±90°. The square SAS concept can be extended to include an arbitrary number of piecewise linear survey lines such as hexagonal or octagonal configurations. However, operationally, there is a trade-off between the number of additional views for target classification and the time required for data acquisition.

We present an image fusion technique based on co-registration of multiple target views using a multimodal approach that has been successfully applied in the medical imaging literature [7]. The algorithm maximizes the mutual information [8] between image pairs using a multi-resolution pyramid scheme with iterated evolutionary optimization [9].

The image fusion technique is generally applicable to any SAS platform, including AUVs, without any prior assumption for the target shape. However, the technique is ideal for towed systems where multiple linear passes are necessary to achieve a true multi-aspect imaging capability with at least ±90° azimuth coverage for effective target classification.

Techniques for image registration are discussed in Section II. The SeaScout system and the experimental data collection are presented in Section III, followed by results in Section IV and conclusions in Section V.

II. Image Registration

Imaging an object with multiple modalities typically refers to the acquisition of images from multiple sensor types. For example in medical diagnostic imaging, a radiologist might examine CT and MRI scans with each image highlighting different features of interest [7]. It is desirable to overlay the images because the fused image generally contains more information than the sum of the individual parts. The image registration problem is to estimate the transformations required

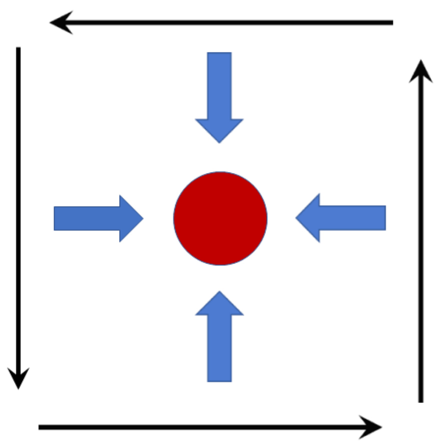

Fig. 3. Square SAS operational concept. Survey lines are indicated by black arrows. The large blue arrows denote the sonar imaging directions for an object of interest indicated by the red circle.

to bring multiple images into alignment. Various transformation types can be considered such as simple translations in one or two dimensions, rigid body motion including rotation, or a more general warping of images to correct for distortion. In the following subsections, we briefly compare and contrast monomodal and multimodal image registration techniques. Although square SAS consists of multiple images collected with the same sensor, multimodal registration is the correct approach to account for the large variation in viewing angle between images.

A. Monomodal Image Registration

Monomodal imaging refers to the acquisition of multiple images of an object using the same sensor with similar brightness, contrast, noise statistics, and sensor-to-object orientation. A common application in sonar imaging is the problem of change detection, where multiple views of the seabed must first be aligned before identifying any targets present in some images but not the others. Techniques for monomodal image registration typically consist of extracting features from the image and then performing cross-correlation to match the feature locations between images [10]. The most basic feature is the image intensity. However, the high resolution of SAS imagery allows one to also consider features such as the local texture, complexity, and anisotropy of the image. Displacements between image pairs are obtained from the location of the peak of the cross-correlation function. In addition to the usual Cartesian coordinate system, one may also include a pre-processing transformation prior to correlation such as conversion to a log-polar representation for estimating rotations. It is also common to perform the registration iteratively using coarse and fine stages, with super-

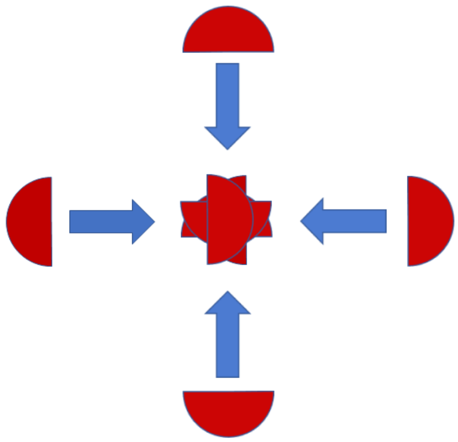

Fig. 4. An illustration of monomodal image registration. The semicircles represent four views of a circular object. When combined using cross-correlation of image intensity, the centroids of the semicircles are aligned rather than matching the shapes to form a circle.

resolution obtained by interpolating the correlation peak to achieve sub-pixel accuracy.

For monomodal image registration to be successful, it is essential that images are collected with similar sensor-to-object orientations. Otherwise, cross-correlation tends to align the centroids of the features rather than matching the shapes to obtain the best fit, as illustrated in Figure 4. The semicirles represent four views of a circular target from angles of 0°, ±90°, and 180°. When using image intensity as the feature for image registration, maximization of correlation produces a fused image as shown in the center of Figure 4 rather than matching the shapes to form a circular object. Thus, for square SAS it is essential to perform image registration using multimodal techniques even though the brightness, contrast, noise statistics, and range-to-target are similar for each image.

B. Multimodal Image Registration

For square SAS, images are combined using a multimodal registration technique based on maximizing the mutual information between image pairs [8]. Mutual information, also known as relative entropy, is a concept that measures the amount of information that one random variable (or image) contains about another. The mutual information $I(A, B)$ of images A and B is calculated by measuring the distance between probability distributions using the Kullback-Leibler measure [7]

$$I(A, B) = \sum_{a,b} p_{AB}(a, b) \log \frac{p_{AB}(a, b)}{p_A(a)\, p_B(b)} \qquad (1)$$

where $p_{AB}(a, b)$ denotes the joint distribution of A and B and $p_A(a)\, p_B(b)$ represents the distribution corresponding to complete statistical independence. Images are assumed to be

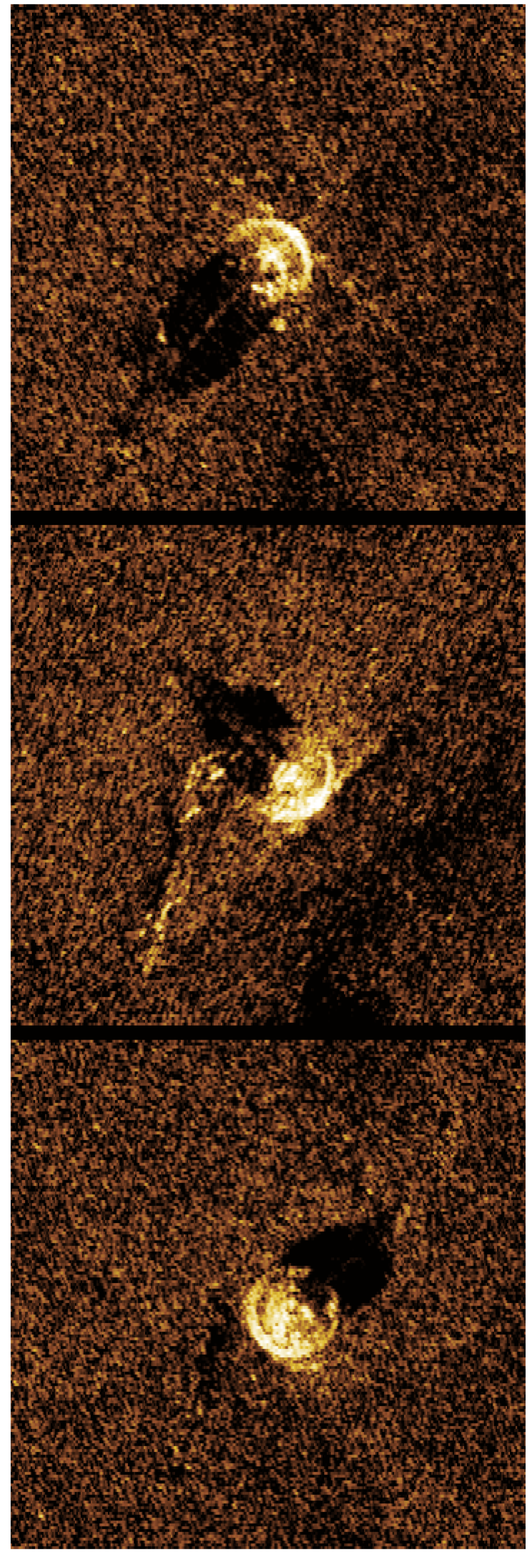

Fig. 5. AquaPix MINSAS target images with azimuth viewing angles of 225° (top), 315° (middle), and 45° (bottom). The corresponding ranges to the target are 100 m (top), 75 m (middle), and 50 m (bottom). A viewing angle of 0° corresponds to an imaging direction pointing from bottom to top.

co-registered when the mutual information is maximized. The joint and marginal probability distributions are estimated from normalized histograms of pixel intensity. Optimization is performed using a multi-resolution pyramid scheme as described in [9] using the (1+1)-Evolution Strategy as implemented in the MATLAB Image Processing Toolbox.

For square SAS, each image is rotated into a common North-East coordinate system using heading information from the vehicle inertial navigation system. Due to the high accuracy of the Euler angle solution (typically better than 0.1° in heading), the registration process is constrained to only estimate a 2D translation for each image pair. No warping is necessary because SAS motion compensation eliminates the distortions caused by the vehicle nonlinear motion that typically affect conventional sidescan sonar imagery. Since SAS imagery contains speckle noise caused by the coherent nature of the imaging process, a Gaussian low pass filter is applied to each image prior to registration. Once the displacements have been estimated accurately, the original unfiltered images are fused are shown in Section IV.

III. Experiment

A proof-of-concept square SAS dataset was collected using Kraken's SeaScout system to image an inert training target in Bedford Basin (Halifax, Canada).

A. Towed SAS

SeaScout consists of a towed KATFISH SAS system with a fully unmanned launch and recovery system. The primary function of the autonomous launch and recovery system is to enable an unmanned vehicle and its payloads to be brought aboard a host ship safely, efficiently, and without damage. The electric winch uses an integrated motion reference unit and intelligent control algorithms to measure both the surface vessel and vehicle motions to perform safe and effective deployment and recovery in harsh environments up to sea state 5 at a speed of 6 knots. SeaScout is designed for modular integration onto manned and unmanned surface vessels, with rapid mobilization on vessels of opportunity. Remote shore-based operation of the payload and the launch and recovery system have been demonstrated using RF telemetry.

KATFISH is a high speed, actively stabilized towfish that operates at speeds up to 10 knots using Kraken's AquaPix MINSAS as the primary imaging sensor. KATFISH provides high-resolution 3.0 × 3.3 cm (across × along track) constant resolution imagery over ranges up to 200 m per side with simultaneous 3D bathymetry and an area coverage rate of up to 4 km^2/h. A GPU-accelerated processor is used to provide real-time processing of SAS imagery and bathymetry. On-board survey data, automatic target detection, and objects of interest can be viewed directly on the ship as it is collected, or remotely from a mothership or shore-based command station. The KATFISH system also includes a SAS nadir gap reducer, SeaVision laser gap filler, operator console, forward looking sonar, multibeam echosounder, inertial navigation system, Doppler velocity log, ultra-short baseline (USBL) acoustic positioning system, sound velocity sensor, and temperature sensor [6].

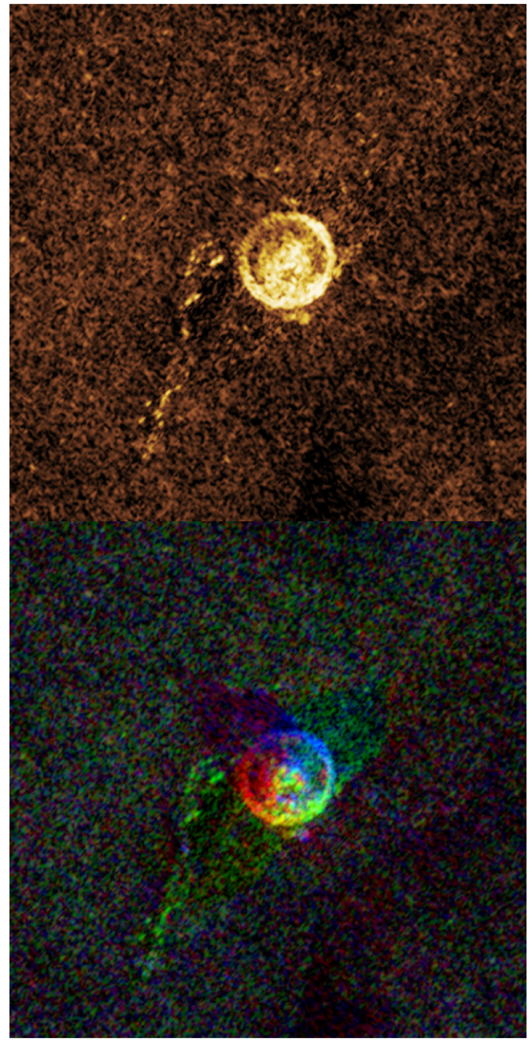

Fig. 6. Combined multi-aspect intensity image (top) and co-registered views assigned to red, green, and blue color channels (bottom).

B. Data Collection

Experimental data collection was performed using the vessel *R/V Ocean Seeker*, a 20 m twin-hull catamaran equipped for seabed surveying. Three survey lines were selected in the vicinity the target along heading angles of 225°, 315°, and 45° at ranges of 100 m, 75 m, and 50 m to the target. Although square SAS imaging may be performed at constant range around a known target location much like circular SAS, another mode of operation is to fuse multi-aspect imagery collected during normal operations along orthogonal survey lines. For example, a typical data acquisition geometry might consist of North-South and East-West survey lines in a lawn-mower pattern. In the general case, the target may appear at different ranges along different survey lines. Therefore, the experiment was performed using three different ranges to test multimodal image registration when each target view has a different grazing angle.

IV. Results

In Figure 5, three geo-referenced views of the target are shown with the target shadow length being indicative of the grazing angle. The acoustic data is essentially monochromatic (single band), being collected over a relatively narrow frequency range of 337 ± 20 kHz. However, for visualization, image intensity was plotted using a color map that varies over black, brown, orange, yellow, and white to highlight differences in backscatter intensity. The dynamic range of the images in Figures 5 and 6 is 35 dB. After coordinate transformation and prior to the final registration, the target views were cropped to force the image registration algorithm to utilize mutual information from the target of interest rather than other patches of seabed that may be statistically similar but spatially separated. This ensures that the image registration process automatically aligns the target images rather than relying on manual intervention from the user.

It is interesting to note that the rope attached to the target is clearly visible in the middle panel, faintly visible in the lower panel, and obscured by the target shadow in the top panel, which illustrates the advantage of multi-aspect imaging with at least ±90° of azimuth variation.

The combined multi-aspect image is shown in Figure 6. In the top panel of Figure 6, image intensities were summed after registration, whereas in the bottom panel the three views were assigned to the red, green, and blue color channels to show azimuth dependence. As expected for multi-look processing, speckle noise was attenuated when the image intensities were summed incoherently in the top panel. It is evident that the image registration process produced a well-defined circular target even though the images were collected at different ranges with no prior assumption made about the target shape.

V. Conclusion

In this paper, we described and demonstrated an operational concept called "Square SAS" for towed sonar platforms, which consists of fusing multi-aspect imagery from piecewise linear survey lines having an azimuthal extent of at least ±90°. Experimental results were presented from Kraken's SeaScout seabed mapping system equipped with a high speed towed SAS. The image fusion technique is generally applicable to any SAS platform without any prior assumption for the target shape. In particular, the technique is ideal for towed systems where multiple linear passes are necessary to achieve a true multi-aspect imaging capability with a wide azimuth coverage for effective target classification.

It was shown that multimodal image registration succeeds at reconstructing the shape of a circular target when viewed from three widely space azimuth angles (0° and ±90°) and three different ranges to the target (50 m, 75 m, and 100 m). Details, such as the target rope, were more prominent in some views while being obscured in others, highlighting the importance of multi-aspect imaging for target classification. Summing the image intensities reduced speckle noise and eliminated shadows from individual views. Image fusion was also performed by assigning the views to distinct color channels to show the azimuth dependence of backscatter.

Future work will investigate visualization techniques for the fused image when more than three views are present. In addition to an azimuth-dependent color map, one could also present the operator with an interface to cycle through illumination directions to show a shadow along each of the viewing angles since the target shadow helps to visualize the three dimensional shape. It should also be possible to use multimodal image registration to fuse multi-aspect imagery from larger objects such as shipwrecks, rocky seabed features, and subsea infrastructure such as installations for oil and gas production or renewable energy.

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