SYNTHETIC APERTURE SONAR IN CHALLENGING ENVIRONMENTS: RESULTS FROM THE HISAS 1030

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Abstract: Successful synthetic aperture sonar (SAS) imaging is dependent on several challenges to be overcome. The sonar has to be positioned with accuracy better than a fraction of a wavelength along the entire synthetic aperture. At 100 kHz this equals an accuracy requirement around 1 millimetre along tens of metres of travelled distance. The ocean environment, and particularly the sound velocity, has to be accurately estimated for successful focusing of SAS images. This is due to the fact that SAS uses near field imaging. For non-straight synthetic apertures, the bathymetry of the scene to be imaged has to be known. This less known fact is critical for robust autonomous underwater vehicle (AUV) based SAS in areas with rough terrain. The first HUGIN 1000-MR AUV was delivered to the Royal Norwegian Navy in mid-2008. The main sensor on the vehicle is the HISAS 1030 interferometric SAS. In this paper we present the system and the signal processing scheme we apply in SAS processing of data collected from challenging environments. We derive a simple rule-of-thumb for accuracy requirement in non-straight vehicle tracks and inaccurate seafloor maps. We show the effect of inaccurate mapping in combination with non-straight vehicle tracks in SAS imagery on real data collected by HUGIN 1000-MR from an area with severely rough topography.

Keywords: synthetic aperture sonar, sonar imaging, bathymetry
1. INTRODUCTION

Fig. 1: Left: The HUGIN 1000-MR onboard the RNoN MCMV Hinnøy during a mission in August 2008. Right: closeup of the HISAS 1030 interferometric SAS.

The principle of synthetic aperture sonar (SAS) is coherent combination of successive pings such that a large sonar antenna along-track is formed. By applying near-field beamforming to the synthetic antenna with sufficient motion estimation and correction, SAS images of the seafloor can be produced. The main improvement over traditional sidescan sonar (SSS) is the resolution gain along-track (the SAS to SSS gain), which can be a factor 10 - 100. The principle of SAS is not new [1], but it is only in the recent years several commercial systems have become available.

Synthetic aperture radar and sonar images possess the rather unique feature that along-track resolution is fixed, independent of range and frequency, only determined by the transducer element size [1][2]. This opens for new sonar design possibilities, not available in traditional SSS, where along-track resolution is inevitably linked to sonar frequency. A high resolution SAS can have a much lower center frequency than a high resolution SSS.

The first HUGIN 1000-MR autonomous underwater vehicle (AUV), as shown in Fig. 1, was delivered to the Royal Norwegian Navy (RNoN) in mid-2008. The primary payload sensor is the HISAS 1030 interferometric SAS [3]. The sonar has two full length receiver arrays, and a vertical phased array transmitter (that also can receive). The transducers are wideband, with a usable frequency range between 50 – 120 kHz. The standard frequency selection is, however, 30 kHz bandwidth around 100 kHz center frequency. The theoretical resolution is better than 5x5 cm, and the area coverage rate exceeds 2 km² per hour. The interferometric capability gives full-swath, co-registered, high resolution bathymetry. HISAS 1030 is an extremely capable sensor designed for various military applications [4], and civilian applications such as underwater archaeology, detailed mapping of the seafloor, search, documentation of offshore oil and gas installations, documentation of dump sites and mapping of coral reefs.
2. ROBUST SYNTHETIC APERTURE SONAR

Fig. 2: Robust SAS processing overview.

The success of synthetic aperture sonar (SAS) technology is highly dependent on the ability to produce well focused SAS images in all types of environments. Fig. 2 shows our basic processing scheme for robust SAS processing with adaptation to the environment. In this section we list the fundamental challenges in SAS and how we approach them.

Each sonar-element has to be positioned with accuracy better than a fraction of a wavelength along the entire synthetic aperture. For HISAS 1030 (100 kHz center frequency), this equals an accuracy requirement around 1 millimetre along tens of metres of travelled distance. The HUGIN AUV is equipped with advanced aided inertial navigation [5]. However, the requirement for relative position in SAS is generally not met. To achieve this goal we use sonar micronavigation [6] in optimal combination with aided inertial navigation [7].

The ocean environment, and particularly the sound velocity, has to be accurately estimated for successful focusing of SAS images [8][9]. This is due to the fact that SAS is near-field imaging. The mapping between time and space conducted by beamforming requires accurate knowledge about the integrated sound velocity along the acoustic ray paths. We approach this problem in several ways. We estimate the sound velocity profile from the onboard vehicle Conductivity, Temperature, Depth (CTD) sensor. If there still is a residual error in the sound velocity causing defocusing in the SAS imagery, we can apply a blind technique that both corrects the image and estimates the error in the average sound velocity [9]. This technique is strongly related to autofocus [10].

For non-straight synthetic apertures, the imaging plane and thereby the bathymetry of the scene to be imaged has to be known [10]. This is very important for robust AUV-based SAS in areas with rough terrain – such as much of the Norwegian littorals. In order to address this problem, the HISAS 1030 is designed as an interferometric system [11][4], where a coarse bathymetry from the sidescan interferometer is calculated. The accuracy requirement in bathymetry for non-straight vehicle paths is the topic of the next sections.

Sonar micronavigation aims at correcting for any error in the measurement geometry, either due to incorrect navigation or incorrect projection plane. This means that, even though an out-of-plane motion caused projection error exists, micronavigation can, although not optimally, partially correct for this.
3. SENSITIVITY TO TOPOGRAPHIC ERRORS

Assume a vehicle track that deviates from a straight line normal to the imaging plane, as illustrated in Fig 3. When proper out-of-plane motion correction is performed, all objects in the imaging plane will be well focused. For an object outside the imaging plane, the distance becomes incorrect and thereby defocused, even for error free navigation [10]. This defocusing is proportional to the out-of-plane motion deviation. The difference in distance $\delta R$ due to out-of-plane motion $\Delta z$ to an elevated target is (see Fig. 3)

$$\delta R = 2 (R_0 - R_1) \approx \Delta z \sin \phi \approx \Delta z \Delta h / R_0$$

(1)

The difference in distance, or error in imaging geometry, leads to a quadratic phase error in the imaging and hence defocusing. We have found that a phase error less than $\pm \pi / 2$ gives acceptable focused imagery. This equals $\delta R \leq \lambda / 8$ (taking into account two-way travel) which gives the following requirement

$$\Delta z \Delta h \leq \lambda R_0 / 8$$

(2)

Note that this result differs from the similar requirement in [10], which we find too strong. Assuming a sound velocity of 1500 m/s, we get the simple rule-of-thumb

$$\Delta z \Delta h \leq R_0 / (5 f), \quad f \text{ [kHz]}$$

(3)

As an example, consider one meter deviation $\Delta z = 1$ m. At 100 m range, the required seafloor height accuracy then becomes $\Delta h \leq 0.2$ m at 100 kHz. This is a surprisingly strong requirement, but for normal conditions for the sidescan bathymetry on HISAS 1030, this is actually met.

The required height accuracy relaxes with increasing range. The provided accuracy in sidescan bathymetry does, however, decrease with increasing range [12]. The length of the synthetic aperture, and thereby the average deviation from straight-line, also increases with increasing range. This means that the requirement (2) is in general most difficult to obey at maximum range. This is in agreement with our observations. In rough topography, there is often a maximum range for which the images are well focused. Note, however, that errors due to incorrect navigation and sound velocity also increase with range.
4. ANALYSIS OF REAL DATA COLLECTED BY HUGIN AUV

Fig. 4: Vehicle depth and seafloor depth for the HUGIN mission line 1502 from June 17, 2008. The red dashed vertical lines indicate the collection window for the SAS image shown in Fig. 8. The purple dash-dotted vertical lines indicate the collection window for the SAS image shown in Fig. 6.

In this section, we analyse a particular set of SAS data that was collected with HISAS 1030 on the HUGIN 1000-MR, June 17, 2008, outside Horten, Norway. Fig. 4 shows the vehicle depth (green solid line) and the seafloor depth (dashed blue line). The track is non-straight with large depth variations. Fig. 5 shows the seafloor bathymetry estimated with sidescan interferometry. The solid line is the vehicle track. We see large variations in the bathymetry. The seafloor depth varies from 30 m to 85 m during this particular mission line. This leads either to a non-straight AUV-path in bottom following mode (as this mission actually was), or a severely sub-optimum altitude during parts of the mission line in constant depth mode. Neither is optimal for SAS imagery.

Fig. 5: Sidescan bathymetry with the vehicle track shown as solid white line. The map is color coded in depth in meters. The depth has been exaggerated by a factor 2.
Fig. 6: SAS image from a HUGIN 1000-MR mission in June 2008. The image size is 140 m along-track (x-axis) times 100 m cross-track (y-axis). The theoretical resolution in the image is 4.5 cm times 3.2 cm. The image shows an area with rough topography.

Fig. 6 shows a SAS image from the data collected in the time interval 1260 s to 1350 s (see the purple dash-dotted lines in Fig. 4). The depth variation during this collection was approximately 20 m. The image scene contains various topography and small objects. Fig. 7 shows four zoomed snippets with corresponding coherence maps based on the SAS coherence [13][11]. In the areas of the images that are well focused, the coherence is in general high. In the areas of low coherence, the image might be defocused. This is caused by the non-straight vehicle path in combination with reduced quality in the seafloor maps.

Fig. 7: Upper row: 12 x 12 m areas around selected targets in Fig. 6. The images are shown with 50 dB dynamic range. Lower row: corresponding interferometric SAS coherence. Red equals high coherence, and blue equals low coherence.
Fig. 8: SAS image from a HUGIN 1000-MR mission in June 2008. The image size is 90 m along-track (x-axis) times 60 m cross-track. The theoretical resolution in the image is 4.5 cm times 3.2 cm. The image shows the wreck of the Norwegian tanker Holmengraa.

Fig. 8 shows a SAS image from the data collected in the time interval 1070 s to 1130 s (see the red dashed lines in Fig. 4). The image shows the wreck of the Norwegian tanker Holmengraa that was sunk during World War II in 1944. The AUV track has severe out-of-plane deviations. There is local defocusing, particularly visible in the bow region of the wreck. In the areas on the seafloor outside the wreck, small objects are well focused. This indicates that the integrated navigation solution is sufficiently accurate, and the defocusing in the image is caused by the out-of-plane deviations. Note that the pollution in the image at range larger than the maximum range for the wreck (155 m) cannot be caused by defocusing. This is more likely multiple reflections close to the bow-region of the wreck.

As discussed in the previous section, there are generally two solutions to the problem of SAS imaging in areas with rough bathymetry: 1) force the vehicle track to be a straight line; 2) map the seafloor with sufficient accuracy. Running on a straight line is not trivial in this case. The mapping accuracy of the seafloor is therefore critical. In the default processing of SAS data, we use sidescan bathymetry as the height estimate to the SAS imaging (from the same mission line). Large elevated targets (such as a large wreck) can potentially cause layover in the interferometric processing and thereby loss of coherence and inaccurate mapping [13]. This can be overcome by using the multibeam echosounder (MBE) on the HUGIN 1000-MR in combination with the sidescan interferometer to provide more accurate maps. This requires, however, more mission lines, as the swath width of the MBE is much more narrow than that of the HISAS sidescan bathymetry.

5. CONCLUSIONS

The success of synthetic aperture sonar (SAS) technology is highly dependent of the ability to produce well focused SAS images in all types of environments. There are three fundamental challenges in SAS: 1) The sonar has to be positioned within a fraction of a
wavelength along the synthetic aperture. 2) The ocean environment, and in particular the sound velocity, has to be accurately estimated in all depths for the acoustic wave travel. 3) For non-straight vehicle paths along the synthetic aperture, the full imaging geometry, including the seafloor bathymetry has to be known within certain bounds. To approach these challenges, we have developed a scheme for robust adaptive processing of the SAS data. The HISAS 1030 system is also specifically designed to be robust, applying key technologies such as interferometry, large bandwidth, and a large number of sonar channels.

REFERENCES