FFI-RAPPORT

19/00245

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— technology study

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Norwegian Defence Research Establishment (FFI)

1 February 2019

**Keywords**
Autonome undervannsfartøyer
Sonar
Syntetisk apertur-sonar
Dumpet ammunisjon
Kjemiske stridsmidler

**FFI-rapport**
19/00245

**Prosjektnummer**
5183

**ISBN**
P: 978-82-464-3146-8
E: 978-82-464-3147-5

**Approvers**

Øyvind Albert Voie, *Research Manager*
Janet Martha Blatny, *Research Director*

*The document is electronically approved and therefore has no handwritten signature.*

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# Sammendrag

Teknologien til autonome undervannsfarkoster (AUV) har modnet betraktelig de siste tiårene. I dag er AUV-er tilgjengelig og pålitelig til bruk både i forskning og i kommersielle, offentlige og militære sammenhenger. Det siste tiåret har syntetisk apertur-sonar (SAS) blitt tilgjengelig som en referansesensorteknologi for AUV-basert avbildning av havbunnen, med stor arealdekning og høy oppløsning samtidig. Forsvarets forskningsinstitutt (FFI) har et langvarig samarbeid med Kongsberg Maritime (KM) om utvikling av AUV-teknologi og SAS-teknologi. Flere produkter i AUV-familien og SAS-familien er i dag kommersielt tilgjengelig fra KM.

Søk og monitorering av områder på havbunnen der store skipsvrak og små objekter er dumpet, utgjør en spesiell utfordring. Både små og store objekter skal avbildes, detekteres, lokaliseres, klassifiseres eller identifiseres over et stort område. Når objektene er lokalisert, skal tilstanden vurderes og observeres over tid i en detaljgrad som gjør det mulig å oppdage potensielt skadelige endringer.

I denne studien vurderer vi HUGIN AUV med SAS for søk og monitorering av dumpefelt. Vi velger å gjøre dette fra et rent sensorsentrisk ståsted. Det vil si at vi tar utgangspunkt i FFIs HUGIN HUS AUV og dens sensorer med hovedtyngde på SAS. Vi deler problemstillingen inn i forskjellige steg og vurderer egnetheten til de ulike teknologiene. Basert på denne studien foreslår vi følgende:

- Å bruke SAS eller multistråle ekkolodd (MBES) for å søke etter skipsvrak. Innsamlingen av data må være gjennomtenkt for maksimal bruk og best ytelse.
- Å bruke SAS og optiske kamera for å søke etter og identifisere små objekter. Søk og klassifisering kan potensielt automatiseres ved bruk av maskinlæring.
- Å bruke automatisk endringsdeteksjon i monitoreringsfasen. Dette må kombineres med intelligent innsamling av data for maksimalisert effektivitet og ytelse.

Som eksempel bruker vi dumpefeltet i Skagerrak, der tusenvis av tonn med kjemiske stridsmidler ble dumpet etter andre verdenskrig. Vi viser eksempelbilder fra dumpefeltet og andre områder for å illustrere potensialet og den mulige ytelsen som kan oppnås.

Til slutt lister vi opp mulige retninger for videre arbeid der bruk av AUV med SAS i forskning og utvikling vil kunne forbedre effektiviteten og ytelsen av søk og monitorering på dumpefelt på havbunnen.

Denne studien er finansiert av Kystverket.

# Summary

Autonomous underwater vehicle (AUV) technology has matured substantially over the last decades, and today AUVs are available and reliable for a number of research, commercial, government, and military applications. The last decade, synthetic aperture sonar (SAS) has emerged as a reference sensor for AUV-based imaging of the seabed, providing both large area coverage and very high resolution simultaneously. The Norwegian Defence Research Establishment (FFI) has a long-standing collaboration with the Norwegian company Kongsberg Maritime (KM) to develop AUV-technology and SAS-technology. Today, there are multiple products in the AUV-family and the SAS-family available from KM, with the HUGIN AUV with the HISAS 1032 interferometric SAS as the flagship.

Search and monitoring of large seabed dumpsites containing potentially large shipwrecks and smaller objects such as crates or barrels is particularly challenging since both large and small objects must be imaged, detected and located, classified and/or identified over a large area. When located and identified, the objects must then be monitored with sufficient detail level such that potentially harmful changes are detected.

In this study, we consider using the HUGIN AUV with SAS for search and monitoring of dumpsites from a sensor-centric point of view. We consider the sensor suite on FFIs HUGIN HUS AUV with special emphasis on SAS. We divide the search and monitoring into different stages and rate the usability of the different technologies. Our suggestion is the following:

- Use SAS or multibeam echosounder (MBES) for the search and classification of shipwrecks. Special emphasis should be placed on collecting the reference data.

- Use SAS and optical camera for search, classification and identification of small objects. The search and classification can potentially be automated using machine learning algorithms.

- Use automated change detection for monitoring. This must be done in combination with intelligent data gathering in order to maximize the efficiency and performance.

As a test case we use the Skagerrak dumpsite where thousands of tons of chemical munitions were dumped after World War II. We show example images from the dumpsite to indicate the capabilities and the achievable performance.

Finally, we point out a number of directions for future work where research and development may improve the efficiency and performance in search and monitoring of dumpsites on the seabed using AUVs with SAS.

This study is sponsored by the Norwegian Coastal Administration.

# Contents

# 1 Background

The last 20 years, autonomous underwater vehicle (AUV) technology has matured substantially, and today AUVs are available and reliable for a number of research, commercial, government, and military applications. The typical AUV operation is to move close to the seabed with imaging and mapping sensors, and thereby get detailed information about the seabed. The AUV, being a stable platform, allows for use of advanced imaging technologies such as synthetic aperture sonar (SAS). Norwegian Defence Research Establishment (FFI) has a long standing collaboration with the Norwegian company Kongsberg Maritime (KM) to develop AUV-technology and SAS-technology. Today, there are multiple products in the AUV-family and the SAS-family available from KM, with the HUGIN AUV equipped with the HISAS 1032 interferometric SAS as the flagship.

Interferometric SAS can image the seabed in centimeter resolution, and map the seabed in decimeter resolution (Hansen 2013). The key performance parameters for the HISAS 1032 are 3 x 3 cm theoretical imaging resolution and coverage of 2 square km per hour. SAS on AUV have been successfully demonstrated and applied in numerous applications such as marine archaeology (Ødegård et al, 2018), marine geology (Denny et al, 2015), pipeline inspection (Hagen et al 2010), and detection of gas seeps (Blomberg et al 2017). AUV-based SAS is commonly used and is the main tool in many Naval Mine Countermeasures (NMCM) operations (Hagen et al 2008). HUGIN AUVs with SAS or sidescan sonar (SSS) have been used in the search and finding of the crashed Russian helicopter outside Barentsburg, Svalbard, and the search and finding of the lost Argentinian submarine ARA San Juan.

Lately, automated change detection (CD) using SAS has become an active field of research (Myers et al 2014). FFI participates currently in the Coalition Underwater Mine and IED Defeat (CUMID) program in collaboration with Naval Surface Warfare Center (NSWC) Panama City, USA, and Defence Research and Development Canada (DRDC), Halifax, Canada. This collaboration has the goal to further develop and mature automated change detection for NMCM.

In this report, we study the use of AUVs with SAS from a sensor centric point of view for search and monitoring of dump sites with unexploded ordnance (UXO) or chemical munitions. We consider both large objects (shipwrecks) and small objects such as crates, barrels, and UXOs. We review the different key technologies available, with emphasis on the sensor suite present on FFIs HUGIN AUV. We suggest which part of a search and monitoring operation this type of AUV may be effective. We finally pinpoint where we see the technology gaps for these types of operations.

# 2 The Skagerrak dumpsite HUGIN AUV data collection

After World War II (WWII) chemical warfare (CW) munitions were deposited in the Skagerrak strait in the Norwegian trench, in deep waters between Norway and Denmark. The procedure was to load the munitions onto large cargo ships (e.g. Liberty-ships), move and position the ships in the dump field, and sink the ships either by scuttling or by the use of explosives (Arison III, 2013). It has been estimated that between 41 000 and 48 000 tons of chemical munitions were deposited in this area (Tørnes et al 2002, Tørnes et al 2015). In collaboration with the Norwegian Coastal Administration, FFI conducted cruises in 2015 and 2016 using FFIs HUGIN HUS AUV equipped with the HISAS 1032 interferometric SAS. The main goals were to locate and image the ships, determine their conditions, and find areas where dangerous cargo from the ships was spread out. The 2015-2016 data collection was a continuation of earlier data collections done by FFI in 1989, 2002, and 2009 (C. M. Hansen et al 2009, Lågstad 2009). The main difference in the 2015/2016 surveys was the primary sensor being the SAS and the scope to search over the largest possible area in very high resolution.

Two separate cruises were conducted, consisting of 24 dives where 16 TB of SAS rawdata were collected. A total of 217 recording hours, 1484 km of distance travelled, and approximately 450 $km^2$ of instantaneous area covered were the results. SAS images in 4 x 4 cm theoretical resolution were produced from all data. Most of the lines were run in lawn-mower pattern without a-priori knowledge of positions of the shipwrecks. Some lines were run to optimize the SAS imaging of wrecks in known position (Sæbø and Lorentzen 2015). After manual inspection, 54 wrecks were found, and 36 of these are believed to be part of the chemical munitions dumpsite. See Figure 2.1 for an overview of the area surveyed and wrecks found.

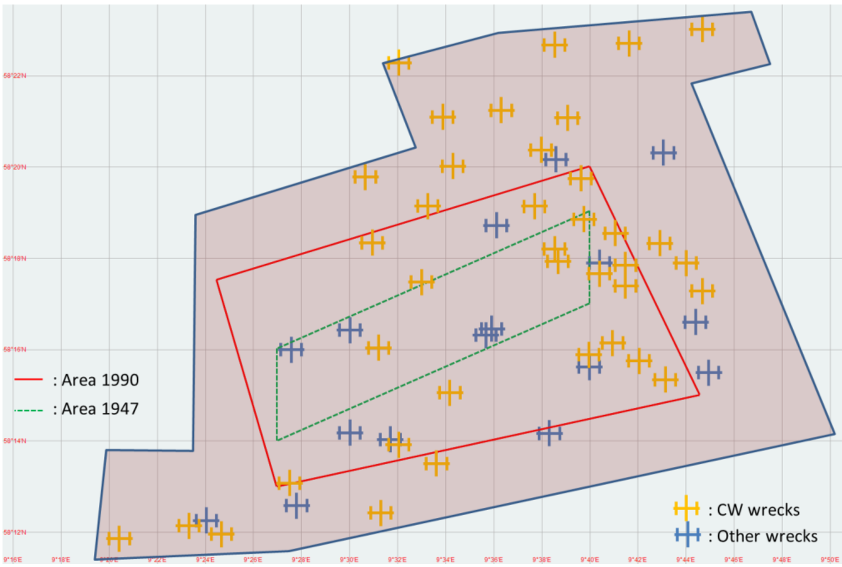


*Figure 2.1 Survey area and discovered wrecks in the Skagerrak CW dumpsite.*

Figure 2.2 shows example SAS images from the Skagerrak dump site from 4 different shipwrecks with varying degree of integrity. Wreck 18 is fully intact and the cargo is believed to be inside the wreck. Wreck 12 is broken. Wreck 05 is broken and more damaged. A large portion of the cargo is spread out on one side of the wreck. Wreck 49 is almost completely disintegrated, and most of the cargo is spread out over a larger area. See (Hansen et al 2017), (Sæbø et al 2015), and (Sæbø and Lorentzen 2015) for details about the SAS data collection.

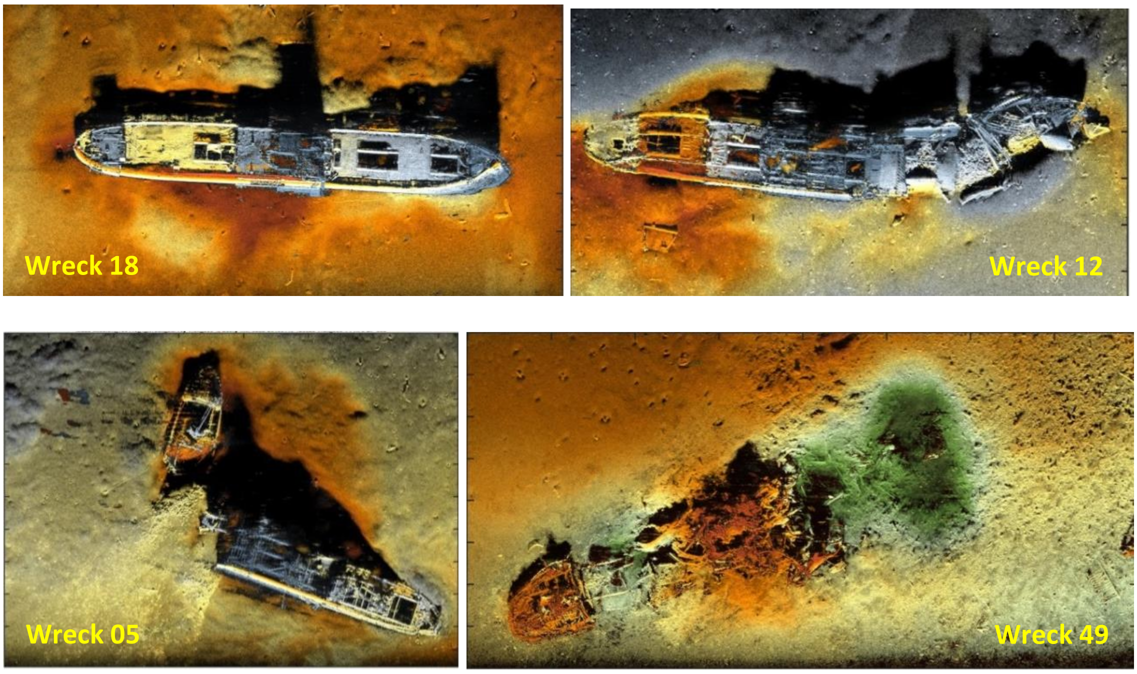


*Figure 2.2 Four different shipwrecks part of the Skagerrak CW dumpsite. Upper left: Wreck 18. Upper right: Wreck 12. Lower left: Wreck 05. Lower right: Wreck 49. Depth 550 – 650 m. Data collected April 2015 and January 2016 with HUGIN HUS AUV. The images are constructed using both the SAS image and the SAS bathymetry mixed together. Data courtesy of the Norwegian Coastal Administration.*

# 3 The HUGIN AUV with sensors

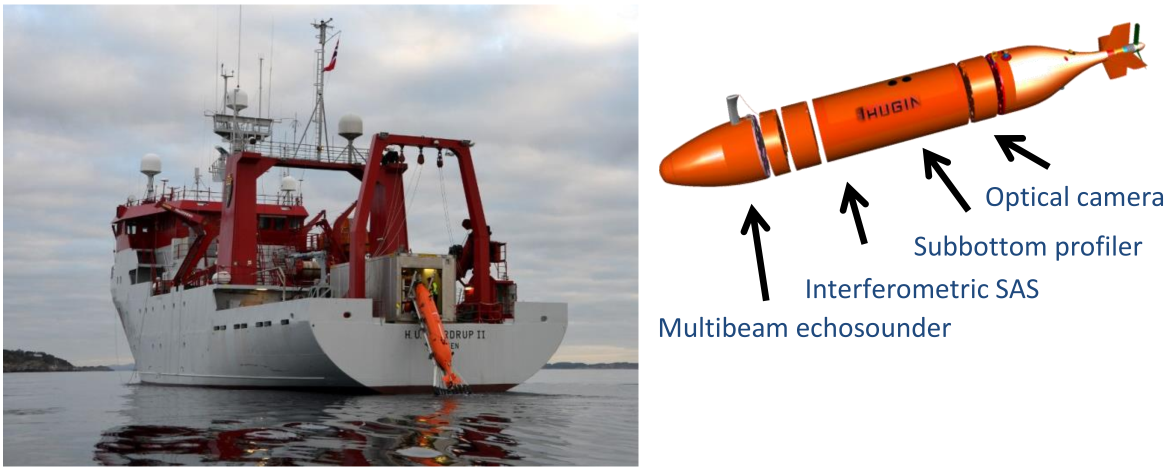


*Figure 3.1 The HUGIN AUV with the primary payload: interferometric SAS for sidelooking imaging; multibeam echosounder for downward looking mapping; subbottom profiler for shallow seismic investigation; optical camera for identification and inspection. Left: HUGIN HUS AUV during launch from FFIs research vessel H. U. Sverdrup II. Photo taken in 2017.*

The HUGIN AUV (see Figure 3.1) is an untethered underwater vehicle, which can run supervised, semi-autonomous or autonomously. The typical operation always includes a pre-planned mission. Key numbers are listed in Table 3.1.

| | |
|---|---|
| **Depth rating** | 3000, 4500, 6000 m |
| **Length** | 5 – 7 m |
| **Diameter** | 75 – 87.5 cm |
| **Weight** | 1000 – 2200 kg dry |
| **Endurance** | Up to 72 hours |
| **Speed** | 2 - 6 knots |
| **Main payload** | SAS or SSS, MBES, SBP, Flash Camera, Laser 3D profiler, CTD, chemical sniffers, turbidity sensor, magnetometer |
| **Auxiliary sensors** | Altimeter, Doppler Velocity Logger (DVL), Forward looking sonar |
| **Navigation** | Doppler Velocity Logger (DVL) aided inertial navigation system (INS) with acoustic position updates when available. Optional terrain navigation. |
| **Communication** | C-node acoustic comms, Wi-Fi, Iridium, UHF radio |

*Table 3.1 HUGIN AUV specifications. See km.kongsberg.com for details.*

The sensor suite on the HUGIN HUS AUV includes:

- A twosided HISAS 1032 Interferometric SAS for seabed imaging and mapping. This sensor operates typically around 100 kHz, with 30 kHz bandwidth. The theoretical resolution is around 3 x 3 cm, independent of range. The range is 200 m to each side when operated at 2 m/s. Details about the SAS principle can be found in (Hansen 2011).

- The EM2040 Multibeam Echosounder (MBES) for seabed mapping and close range imaging. This sensor operates in the frequency range of 200 – 400 kHz, and has an angular resolution of around 1 degree in both dimensions. The maximum swath width at 200 and 300 kHz is approximately 4 times the altitude. Details about the MBES principle can be found in (Lurton 2010).

- An Edgetech 2200 sub bottom profiler (SBP) operating in the frequency range of 2 – 12 kHz. This is a downward looking single beam line scanner that produces a slow-time / fast-time image, in the vertical-along-track plane, similar to a fish-finding echosounder. The penetration depth heavily depends on the seabed type. This SBP is not well suited to search for buried UXOs due to the poor resolution and swath width.

- A LED flash based downward looking optical camera for identification. The range of this sensor is strongly dependent of water clarity, typically between 3 and 7 m.

There is ongoing work in FFI and KM to improve autonomy, especially for handling stand-off missions in unknown environments. As an example of near future improvements in autonomy, FFI is currently working on a concept of automated adapted survey with SAS and identification with optical camera, in the same mission without (or with little) human interaction. See (Krogstad and Wiig, 2014) and for details. This concept includes onboard processing of SAS data (SAS imaging) and onboard interpretation of SAS images (Automated Target Recognition, ATR).

# 4 Change Detection with SAS

Change detection is the technique of discovering changes of interest in images collected of the same scene at different times. This technique may have many applications of interest for AUV-based imaging of the seabed, such as route surveys, NMCM, harbor protection, and monitoring. Lately, there has been significant developments into advanced automated change detection of AUV based SAS data (Myers et al 2014). With an interferometric SAS as the imaging sensor, there are essentially 5 different data products the changes can be detected in (Hansen et al 2014). These are listed in Table 4.1. The actual appearance and the achievable information from a SAS image are heavily dependent of the geometry (the vertical and horizontal look angle). Pixel based image differencing techniques (coherent or incoherent) are excellent in detecting small changes. However, they require strictly that the observation is made from the same location (same look angle in both planes).

| Data level | Description | Detection sensitivity | Operational requirements |
|---|---|---|---|
| Contacts | Detect new objects not present in old data in corresponding position | Medium | Invariant of look angle and track |
| Bathymetry grid pixels | Detect pixel groups where new and old SAS bathymetry maps differ | Medium | Invariant of look angle and track |
| Image region statistics | Detect regions where new and old image statistics differ | Medium | Dependent of look angle and track |
| Image grid pixels, Non-coherent | Detect magnitude differences between corresponding new and old image pixels | High | Similar look angle and track |
| Image grid pixels, Coherent | Detect differences in magnitude and phase between corresponding new and old image pixels | Excellent | Same track, same look angle. Speckle must be preserved |

*Table 4.1 Different levels of automated change detection, sorted by the level of detection sensitivity.*

A critical component in automated change detection is the coregistration stage that maps the new (slave) data onto the old (master) grid. AUVs typically rely on DVL aided INS with regular position updates when run supervised, and sparse position updates when run autonomously. The typical navigation accuracy is on the order of a few decimeters to a few meters, except when running unsupervised without position updates. Then the uncertainty grows dependent of track and time (Jalving et al, 2003). For SAS based change detection, this means that the position error may be meters between passes, equivalent to hundreds of pixels. In practice, automated change detection relies on data driven coregistration techniques. There are several alternative techniques from landmark based techniques to correlation based (Sæbø et al, 2011). When speckle is preserved between looks, the reposition accuracy is impressive using coherent correlation, with an error down to a fraction of a pixel (equivalent to millimeters). With larger temporal separations, speckle cannot be assumed to be preserved, and incoherent landmark based techniques may perform very well (Midtgaard 2013). FFI is working on developing a fully automated concept for change detection with AUV based SAS (Midtgaard, 2018).

In April 2011, FFI conducted a series of change detection trials with their research ship H. U. Sverdrup II, and their HUGIN HUS AUV equipped with the HISAS interferometric SAS, outside Larvik, Norway. This was in collaboration with Applied Research Laboratory at Pennsylvania State University ARL-PSU), USA, Naval Research Laboratory (NRL), USA, DRDC Halifax, Canada, and Ensta Bretagne, France. See (Midtgaard et al 2011) for details about the trial. Figure 4.1 shows an example of incoherent automated change detection from a highly cluttered area. The left panel shows the SAS image before deployment. The middle panel shows the SAS image after target deployment. It is very difficult to pinpoint the changes due to the high clutter density. The right panel shows the difference image, calculated as the subtraction on logarithmic intensity, pixel for pixel. We see that the differences are clearly shown, highlighted with circles. Automated coregistration was performed. The theoretical resolution of the images is 3 x 3 cm, and the area is 50 x 80 m. Despeckling was performed before the difference image was constructed.

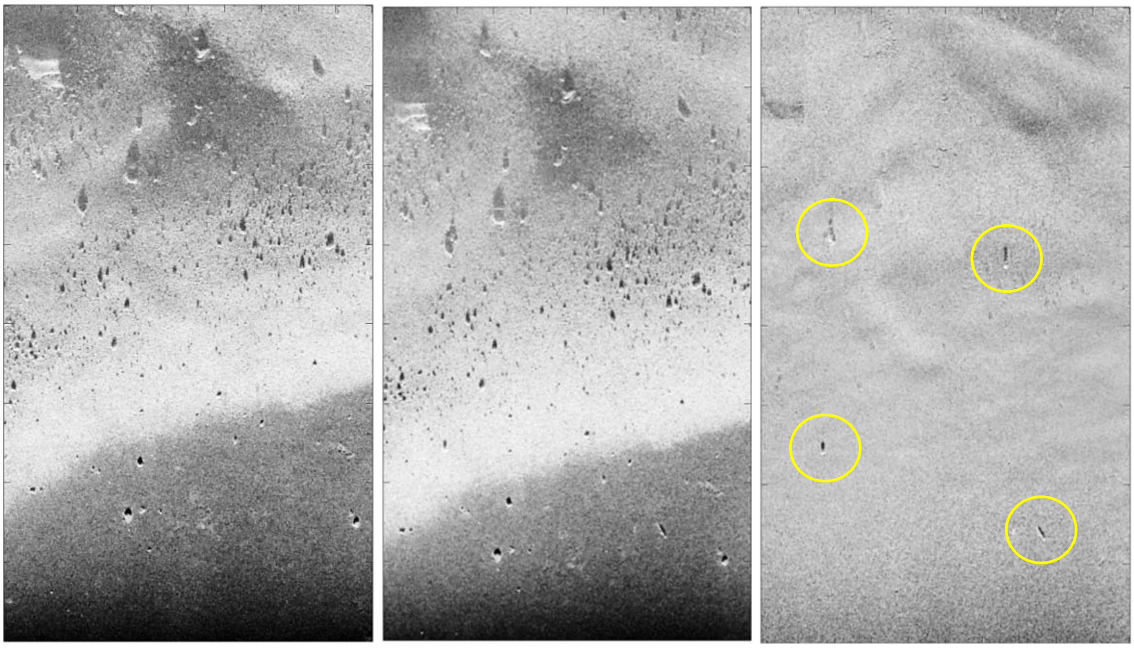

*Figure 4.1 SAS images of 50 x 80 m size taken in repeated passes, outside Larvik, Norway in April 2011. Left: April 8, before target deployment. Middle: April 10, after four targets were deployed. Right: Difference image (incoherent subtraction of logarithmic intensity). The four targets are outlined.*

Figure 4.2 shows a 120 x 90 m large scene imaged four times at different times. The area is Breiangen, outside Horten Norway, at approximately 200 m water depth. The area is exposed to industrial fishing with bottom trawling. The seabed is sandy, and all the diagonal lines indicate trawl-marks. There is a small (20 foot) boat located in the lower left corner of the images. We see that at some time between July 2010 and May 2011, a fishing vessel has hit the wreck with the bottom trawl, and dragged the wreck out of the imaging scene. We also see an increase of trawl-marks with increasing time. This image sequence illustrates the power of SAS as a sensor for change detection. The images were not coregistered using data driven techniques.

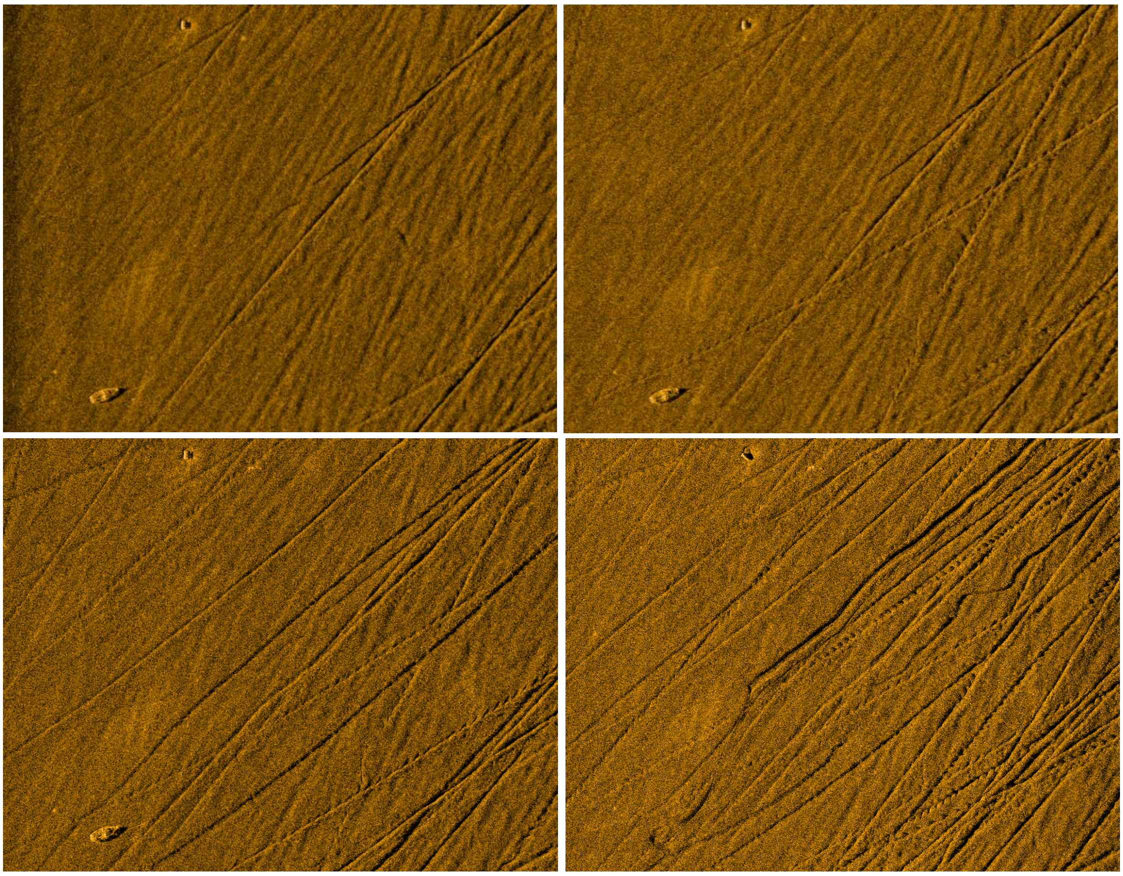

*Figure 4.2 HISAS 1030 images taken with HUGIN AUVs 2009.05.07, 2010.05.11, 2010.07.08, and 2011.05.11. Image size 120 x 90 m. Four different vehicles were used. The area is Breiangen, outside Horten Norway, at approximately 200 m depth. Courtesy of Kongsberg Maritime.*

# 5 Challenges in change detection

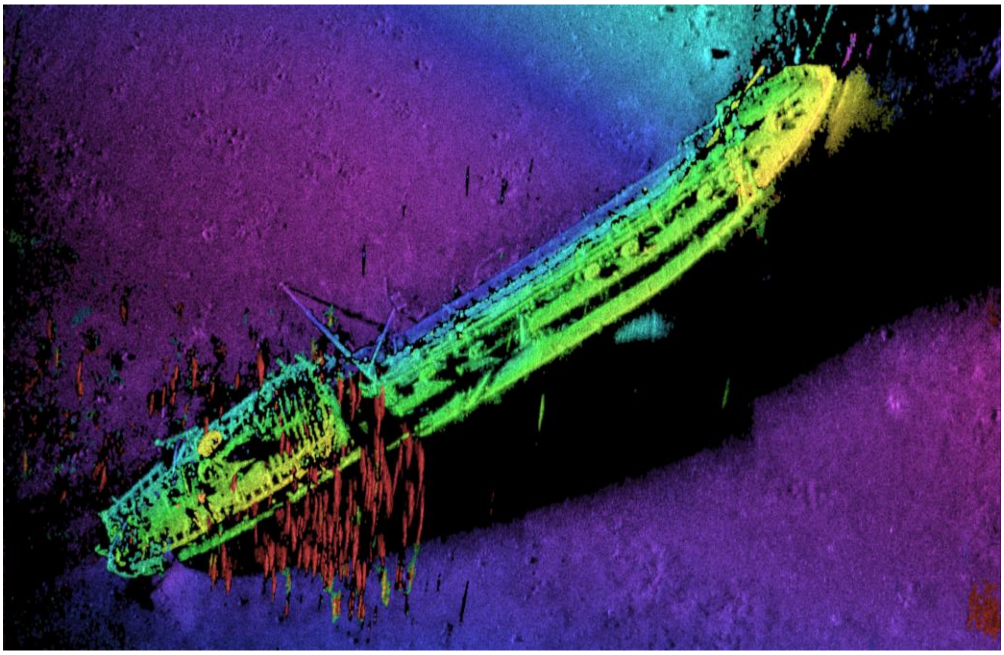

*Figure 5.1 SAS image fusioned with SAS bathymetry of the wreck of the Norwegian oil tanker Holmengraa that was sunk during WWII. The red stripes over the wheelhouse is a school of fish in the water column. Data courtesy of Kongsberg Maritime.*

There are specific challenges related to change detection of large structures (e. g. shipwrecks) and of small changes. These can be categorized as follows:

- Navigation: The position accuracy at any time in the data collection in all passes. Image based change detection requires that the images are registered within a pixel accuracy.
- Track repeatability: The ability to repeat a track with sufficient accuracy. This includes limiting or controlling the navigational errors, and appropriate choices for the guidance-and-control system (the autopilot) on the vehicle.
- Biology and environment: How much content in the images are related to biology (fish in the water column), and therefore not of interest in the detection of changes to structures and objects. How much changes are natural, due to ocean currents and growth or other changes in the marine habitat. Figure 5.1 shows a SAS image of a 68 m long shipwreck, where a school of fish passes during the data gathering (seen as red stripes over the wheelhouse). The signature of the non-stationary fish is strong and will clearly affect the ability to detect changes on the shipwreck. See (Sæbø et al 2013) for details.
- Perception: The sidelooking geometry of the imaging system affects the information available in the images.

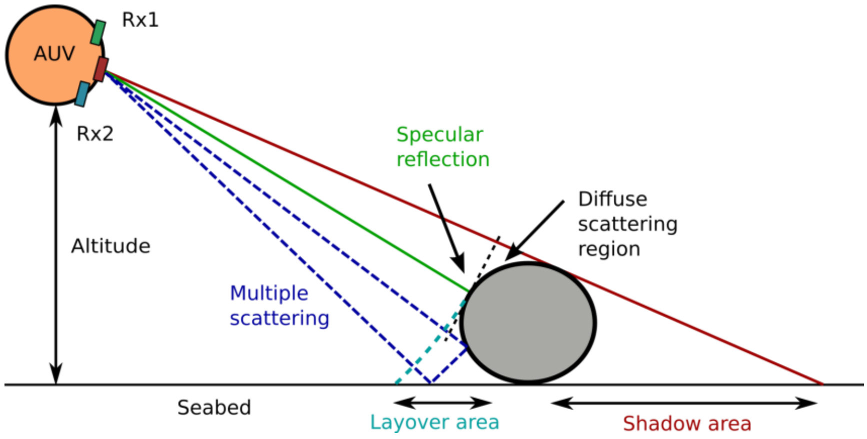


*Figure 5.2    Vertical observation geometry for interferometric SAS.*

The latter point is of specific interest, especially for large objects. The imaging geometry (as illustrated in Figure 5.2) heavily affects the image and the information contained in it. The basic algorithm for imaging assumes that the sound propagates unperturbed from the transmitter to each pixel, and then unperturbed back to the receiver. Any deviation from this model (e.g. multiple scattering) may cause an error in the image. The scattering mechanisms are assumed such that diffuse scattering always occurs. In reality there might be significant difference between specular reflection and diffuse scattering. Since SAS and SSS images in a plane (2D imaging only), multiple reflections in the same distance (range) will cause layover. This is a common issue in spaceborne synthetic aperture radar (SAR) (Franceschetti and Lanari, 1991). Any object (e. g. a shipwreck) blocking the acoustic waves, will cause acoustic shadow and loss of information. All these factors are dependent on the vertical look angle. See (Sæbø et al, 2015) for a more complete list of factors affecting observations of large shipwrecks.

Figure 5.3 shows two SAS images of size 150 x 50 m, of what is believed to be the shipwreck of the German WWII tanker Stedingen, 148 m long, located outside Larvik, Norway. The upper left image is taken at 20 degrees vertical observation angle (below the horizon), and the lower left image is taken at a steeper angle, 46 degrees. We see that the shipwreck appears to be very different in shape. This is, however, only due to the vertical observation angle. The damaged part of the hull near the bow (left front part) indicates that the ship was torpedoed.

Another example of perception is shown in Figure 5.4. Here, we show SAS images (110 x 50 m large) of a 90 m long sail ship observed broadside from two different sides. The color coding is seabed depth. The data were collected during the same mission with minutes apart. We see that shadowing and layover is different in the two images. We also see ropes and wreckage on the seabed that illustrates the very high resolution SAS provides. On the deck, masts and structures make it complicated to assess the actual 3D structure and potential changes between passes. See (Ødegård et al 2018) for details.

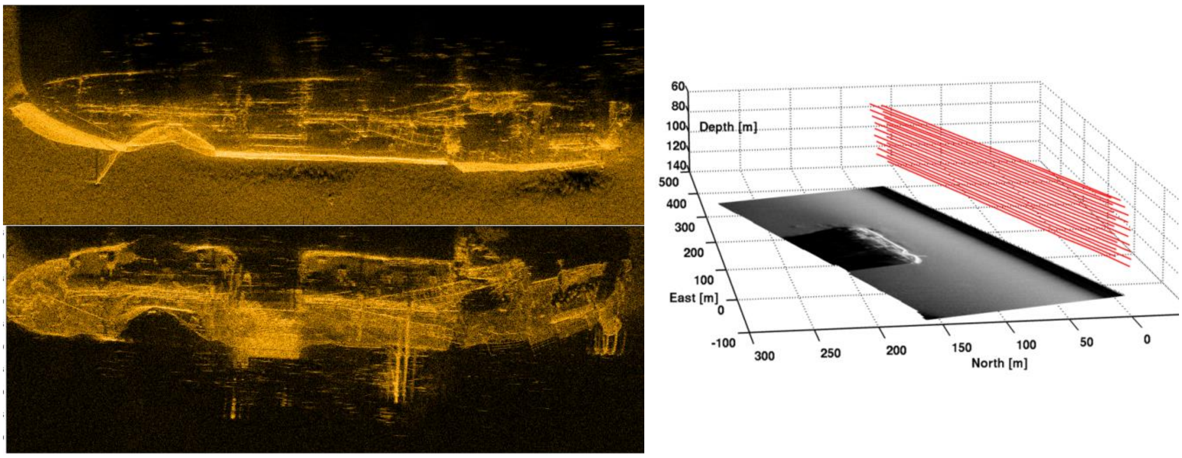


*Figure 5.3* *Shipwreck believed to be the German WWII tanker Stedingen, 148 m long, located outside Larvik, Norway. Upper left: 20 degrees vertical look angle. Lower left: 49 degrees. Right: Geometry. The red lines indicate all the passes run with the vehicle in a single mission. Data collected during the Larvik trials in April 2011.*

*Figure 5.4* *Fusion of SAS image and SAS bathymetry of a 90 m long sail ship in the Skagerrak strait. The wreck is not part of the CW dumpsite. Upper: Imaged from starboard side. Lower: Imaged from port side. The depth variation shown in the coloring is 5 m. Data courtesy of the Norwegian Coastal Administration.*

# 6 Concept for Dumpsite Search and Monitoring using AUV with SAS

There are two main benefits using AUVs with advanced, high-resolution payload sensors in search and monitoring of dumpsites:

**Large area coverage rate and very high resolution using SAS from AUV.**
The HISAS 1032 can image 2 square kilometers per hour in 3 x 3 cm resolution. When combined with e. g. the EM2040 as gap-filler, the area coverage rate increases to 2.88 square kilometers per hour. See (Hansen et al 2017), and (Hagen and Hansen 2007) for details.

**Multi-imaging sensors for detection, classification and identification on the same platform.**
The ability to search for small objects and changes over large areas with SAS, and identify the objects / changes with an optical camera is very powerful. Using this multi-sensor suite on an AUV may reduce operational time and cost substantially compared to Remotely Operated Vehicle (ROV)-operations. An example of multi-sensor performance is shown in Figure 6.2. In this case, the SAS was used for large area survey, and then the optical camera was used for identifying the objects of interest found in the SAS images. It should be noted that the mapping rate of the SAS is approximately 400 $m^2/s$ (assuming a gap-filler), while the camera maps around 10 $m^2/s$ at 5 m altitude.

In order to assess the use of HUGIN AUV with its sensors for search and monitoring of CW and UXO dumpsites, we divide into 5 different tasks:

1. **Search and identification**
   The search operation essentially consists of locating all objects of interest, and classifying and/or identifying them. The objects initial conditions should also be judged, one way or the other. The search part is critical since it creates the baseline measurements for monitoring. Consider the SAS image in Figure 6.1 which shows wreck 13 (part of the CW wrecks) in the Skagerrak dumpsite. A portion of the bow is damaged and missing, and dangerous cargo has been spread out over a large area. The search and identification part should not only find the shipwreck and judge its conditions, but also find all objects of interest spread out around the wreck. This may be non-trivial with a large number of objects to consider. In the zoomed part of Figure 6.1 (upper panels), each highlight is believed to be a bomb/UXO/barrel. Sensors with large area coverage rate and high resolution (such as SAS) are really required to obtain sufficient efficiency in this part of the operation. In larger areas with a large number of potential targets, automated target recognition (ATR) using machine learning or deep learning may be a large benefit (Warakagoda, 2017), (Warakagoda 2018). Search and classification of buried objects is especially challenging. Low frequency SAS (Piper et al 2002) or potentially high resolution SBP may be used. However, the general rule-of-thumb is that the area coverage rate and the performance are lower for buried object detection than for detection of objects visible on the seabed.

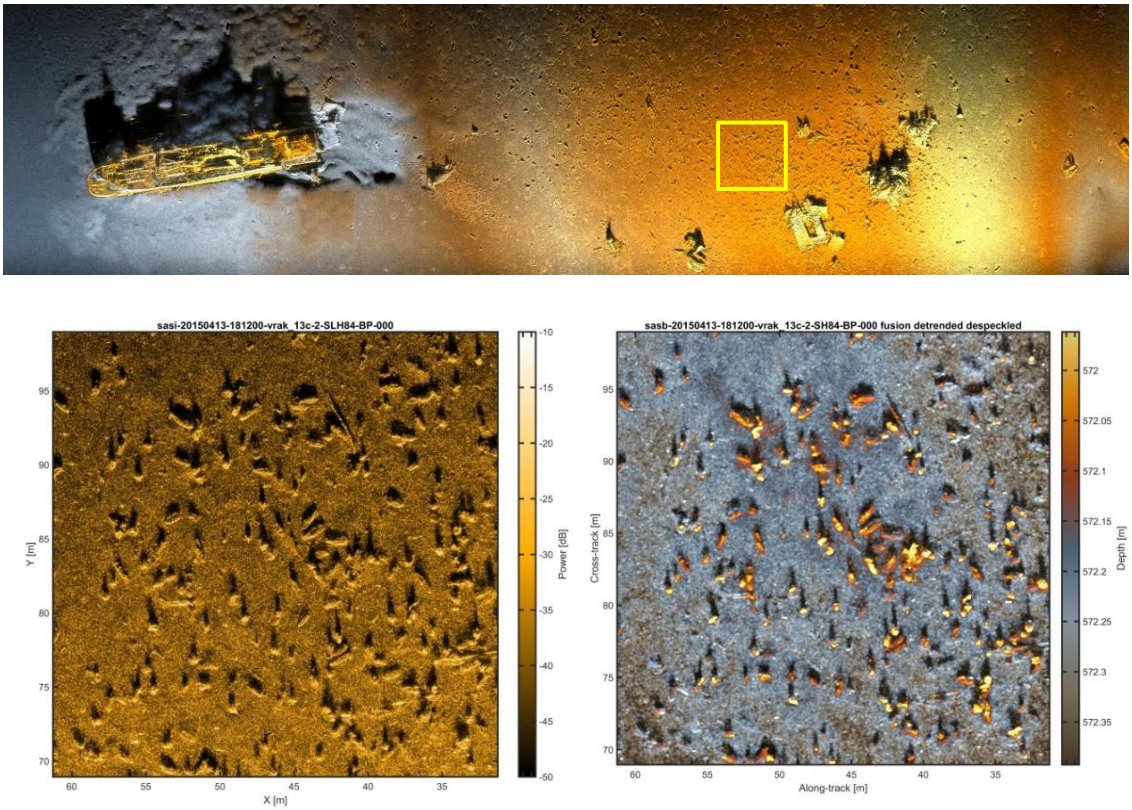


*Figure 6.1 Upper: SAS image fusioned with SAS bathymetry of a 500 x 120 m scene of wreck 13 in the Skagerrak dumpsite. The cargo is spread over a large area. Lower: zoom of 30 x 30 m area image (left) fusion of bathy and image (right). The yellow box indicates the zoomed area. Data courtesy of the Norwegian Coastal Administration.*

2. **Monitoring of large scale changes**
   It makes sense from a sensor centric point of view to divide monitoring of changes into large and small scale changes. By large scale changes, we mean changes in the objects or the scene of meters or a few decimeters (10s to 100s of pixels), clearly visible in the imagery. This could either be due to partial collapse of a wreck, damage done to wrecks or objects by external forces such as fishing gear (see Figure 4.2), or changes made by the ocean environments (e. g. ocean current scouring). A particular case is the detection of new trawl marks (as illustrated in Figure 4.2) in No Fish Zones. These types of changes will typically be observable by SAS when the scene is observed from the same look angle and track, and automated incoherent change detection would be applicable (see chapter 4). This could also be combined with replanning and detailed documentation of changes using optical cameras, if the objects are small (UXOs, barrels, etc). On a shipwreck, the optical camera may be difficult to use due to the limited camera range, and the potential of elevated structures such as masts etc.

3. **Monitoring of small scale changes**
   We define small scale changes as changes in centimeter-scale up to decimeters (up to 10s of pixels), difficult but potentially possible to detect in SAS imagery. In order to detect such changes using AUV-based SAS, the SAS images must be accurately coregistered such that reliable changes can be detected at pixel level. This may be impossible on large structures such as shipwrecks, because of the complexity of the images on the wrecks (see Figure 2.2). For objects such as barrels, this is easier. Again, as for large scale changes, detection of small scale changes on smaller objects is well suited for automated change detection in combination with automated replanning and detailed documentation with optical cameras.

4. **Leakage of gas or chemicals**
   Leakage of chemicals or fluids in small amounts may be impossible to detect with sidelooking sonar because the acoustic reflectivity is small. Detection of gas bubbles is easier since the gas bubbles typically have high scattering strength (Blomberg et al 2017). The sidelooking imaging geometry complicates the task in both cases, since it is assumed that the main (only) scattering is happening at the seabed or the object (see Figure 5.1). In practice however, there will always be a competing echo from a strong scatterer (the seabed) at any range. A potentially better geometry for detection of leakage is to use a downward looking high frequency sonar, such as the EM2040 MBES on the HUGIN AUV. It should be noted that in order to detect gas seeps, a high enough concentration of gas must be present in the water. This may limit the usability of this technique for this application.

5. **Corrosion and cracks**
   Corrosion is a specific process of interest that potentially could bring information of the integrity of the objects, such as wall thickness in a barrel or grenade, hull integrity in a ship, etc. Cracks eventually form either from corrosion or other processes, and thereby continue to degrade the integrity of the structure. In Non-Destructive Testing and Evaluation (NDT&E), ultrasound is used regularly for flaw detection and material characterization, see e. g. (Schmerr and Song 2007). For these techniques to work, it is typically required to use a controlled setup with a high frequency transducer in contact with the specimen. For stand-off SAS imaging of scenes containing objects or wrecks, this may be very difficult or impossible. A potential technique is to use ultra-wideband SAS in combination with acoustic characterization (Kargl 2015), (Synnes and Hansen 2013). The principle is based on the fact that object surface roughness, object wall material, object interior structure and material, and object shape all affect the acoustic properties. Therefore ultra-wideband ultra-widebeam SAS may add valuable information about the objects. The potential of this technique is, however, unclear.

AUV with SAS have different usability in these 5 different tasks. In our opinion, it will be efficient for 1) and 2), and may be efficient for 3). For 4) and 5), AUV with SAS is less usable, and it will be more difficult (or impossible) to retrieve the relevant information from the data gathered.

Figure 6.2 indicates some of the potential that may be available in advanced SAS including ultra-wideband SAS. The figure shows SAS image (left) and corresponding optical images (right) of two different barrels found at the seabed in an area outside Horten, Norway. From the optical images we can conclude the following. The upper barrel has a more intact exterior shape, and therefore we assume that the walls are relatively thick. The lower barrel is partially damaged with one visible hole. We therefore assume that the walls are thinner and that the barrel is filled with seawater. In the SAS images, we see that the highlight – shadow is well behaved for the upper object, assuming it is non-transparent (see Figure 5.1). The SAS image of the lower barrel has two visible flaws. The back-wall of the barrel is visible and there is clear acoustic pollution in the shadow. Both these indicate that the barrel is partially transparent, which again indicates that the walls are thin and that the medium inside the barrel is similar to seawater.

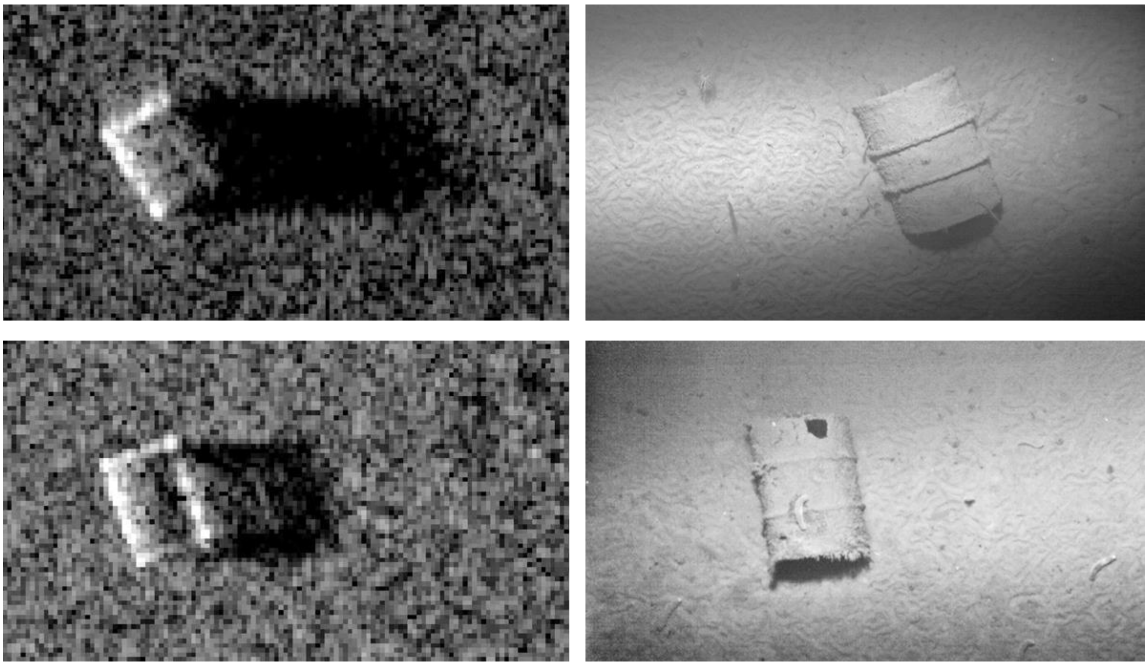

*Figure 6.2 Left: SAS images of two different barrels (left). The distance to the objects is 113 m for the upper object and 73 m for the lower object. Right: Optical images taken with the HUGIN AUV flash-based camera of the corresponding objects. The altitude is approximately 5 m. Data taken outside Horten, Norway, at approximately 70 m water depth.*

# 7 Technology Gaps and Suggested Developments

Given the suggested concept of search and monitoring using AUV with SAS, there are a few technology components missing. For a mature, fully automated, and cost effective concept of data gathering and processing, we suggest further development into the following components:

1. **Autonomous data gathering of shipwrecks**
   SAS imaging of shipwrecks poses a specific challenge due to the complexity of the object (Sæbø et al 2015). The actual information present in a SAS image is dependent of the look angle relative to the wreck, both in the vertical and horizontal direction. A clear improvement is therefore to optimize the data gathering, including autonomously detecting wrecks, their orientation and size, and thereby optimizing the vehicle track during data gathering.

2. **Automated change detection**
   The concept of automated change detection has been suggested and is under development for NMCM (Midtgaard 2018). It needs some refinement regarding the data processing both in data selection, coregistration, and change image production and detection, especially tailored for the task in hand.

3. **Autonomous change detection, replanning, and ID**
   A cost-effective solution would include fully autonomous change detection using SAS, replanning of the vehicle, and reacquisition with ID using an optical sensor. This concept includes automatic run of repeated missions, onboard SAS processing and change detection, and autonomous replanning for ID after a prioritized list of changes of interest has been made. This involves a higher degree of autonomy in both track selection and sensing. Further research and development is needed in all stages.

4. **Multi-sensor and multi-view fusion for 3D reconstruction of shipwrecks**
   A current challenge regarding shipwrecks is to acquire accurate knowledge about the 3D construction of the actual wreck (interferometric SAS only provides a 2.5D representation). In order to obtain that, the wreck must be observed from different view angles, potentially with different sensors such as SAS and MBES, and proper automated fusion of the data and 3D reconstruction of the object.

5. **Fine scale change detection**
   Monitoring of dumpsites includes detecting small scale changes, on the order of a few pixels in the SAS images. Reliable coregistration, difference image building, and change detection must be further developed for this case.

6. **Automated target recognition of UXOs**
   In the search for UXOs over large areas, similar to NMCM, automated techniques may be of vital importance. With the entrance of deep neural networks into SAS ATR

(Warakagoda and Midtgaard 2017), it is an obvious technology component that needs further research and development.

7. **Advanced SAS modes**
   A potential technique to retrieve more information about an object is to use advanced ultra-wideband ultra-widebeam SAS data gathering and processing, in combination with characterization. Larger frequency and angular spread may add information about the structural conditions in objects, and also the interior contents of objects. This task may also include exotic track selections such as circular SAS, and advanced processing modes. Further research and development is needed in order to clarify the potential, and to advance the development of high-fidelity SAS products. It should be noted that this topic is well suited to combine with machine learning techniques for automated retrieval of information (next point on the list).

8. **Buried objects**
   Buried objects impose a special problem to all stages in the search and monitoring of dumpsites. Sonar (either low frequency SAS or high resolution SBP) can be used to detect buried objects within limited performance. Further development into the technology and studies of the achievable performance is needed. This should potentially be done in combination with studies of alternative technologies such as magnetometers, and sensor fusion for improved performance.

9. **Stand-off autonomous monitoring**
   The desired end-state in many of the developments of Unmanned Maritime Systems is stand-off fully autonomous operations (without human interaction, and without a host vessel following the vehicle). In order to achieve this goal, all the parts of the mission must be autonomous: a) Transit into operational area; b) Survey with onboard SAS and CD; c) Replanning and ID gathering; d) Transit back to host station. For all these stages, anti-collision, navigation, vehicle control, sensor quality, and power / time consumption are of importance.

# 8 Conclusion

Modern state-of-the-art autonomous underwater vehicles such as the HUGIN AUV are capable of gathering high quality data over large areas of the seabed, cost effective compared to any other technology. FFI is currently developing autonomy, sensor processing, and automated image analysis for various applications for AUV. Synthetic aperture sonar imaging of the seabed provides very high resolution, down to centimeter scale, in combination with large area coverage rate. This makes SAS a well suited sensor technology for large area search and monitoring. Large scale objects such as shipwrecks impose different challenges than small objects such as UXOs or barrels / grenades containing chemical munitions to any imaging technology. The information achievable from SAS images from a large shipwreck is heavily dependent of the observation angle. It is therefore critical to collect the best possible data for imaging during the search operation. Monitoring of large area dumpsites can be performed using AUV-based SAS and automated change detection. For changes detected on small objects, this can be combined with automated replanning and ID. For large scale objects, any detected changes must be investigated and other sensor technologies or different looks may aid in the judgment of the changes. For fully autonomous monitoring with AUVs and SAS, there is still several technology components that must be further developed.

# 9 Acknowledgements

The authors acknowledge the Norwegian Coastal Administration for sponsoring and supporting the Skagerrak HUGIN AUV data gathering. The authors also acknowledge Kongsberg Maritime for providing data and images. The authors thank Øivind Midtgaard, Ole Lorentzen, and Stig Synnes at FFI and Per Espen Hagen at Kongsberg Maritime. Finally, the authors thank crew and HUGIN operators onboard the H. U. Sverdrup II that took part in the data collection of the Skagerrak CW dumpsite data.

This study is sponsored by the Norwegian Coastal Administration.

# 10 Acronyms

| | |
|---|---|
| ARL | Applied Research Laboratory |
| ATR | Automated Target Recognition |
| AUV | Autonomous Underwater Vehicle |
| CD | Change Detection |
| CTD | Conductivity, Temperature, Depth |
| CUMID | Coalition Underwater Mine and IED Defeat |
| CW | Chemical Warfare |
| DRDC | Defence Research and Development Canada |
| DVL | Doppler Velocity Logger |
| ENSTA | Ecole Nationale Supérieure de Techniques Avancées |
| FFI | Norwegian Defence Research Establishment |
| ID | Identification |
| IED | Improvised Explosive Device |
| INS | Inertial Navigation System |
| KM | Kongsberg Maritime |
| LED | Light-Emitting Diode |
| MBES | Multibeam Echosounder |
| NDT&E | Non-Destructive Testing and Evaluation |
| NMCM | Naval Mine Countermeasures |
| NRL | Naval Research Laboratory |
| NSWC | Naval Surface Warfare Center |
| PSU | Pennsylvania State University |
| ROV | Remotely Operated Vehicle |
| SAS | Synthetic Aperture Sonar |
| SAR | Synthetic Aperture Radar |
| SBP | Sub Bottom Profiler |
| SSS | Sidescan sonar |
| UXO | Unexploded Ordnance |
| WWII | World War II |

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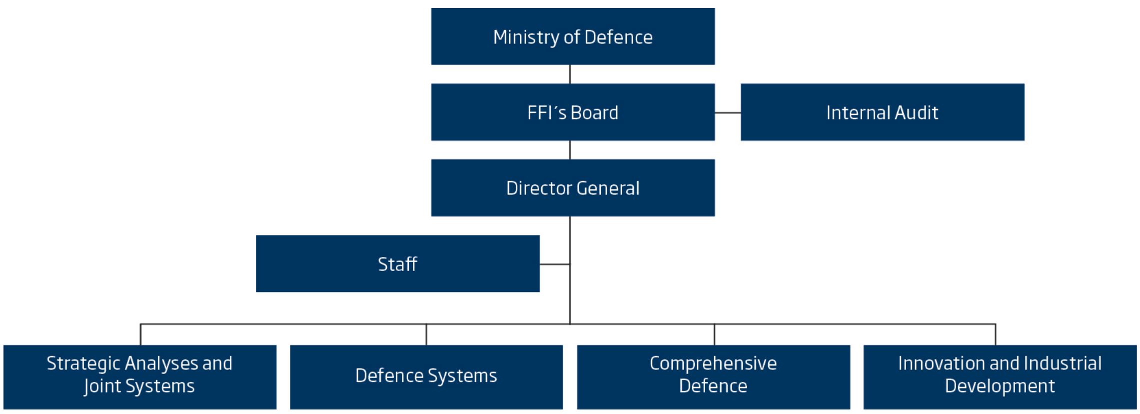

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