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Interferometric Synthetic Aperture Sonar for AUV Based Mine Hunting: The SENSOTEK project

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Abstract – Synthetic aperture sonar (SAS) is emerging as an ideal sensor for autonomous underwater vehicle (AUV) based mine hunting and numerous other applications. By using vehicle motion to create a long synthetic array, image resolution can be increased by an order of magnitude or more compared to traditional side scan sonars. The SAS technology is also well suited for interferometric processing, facilitating very high resolution bathymetry *and* imaging from the same sensor. FFI, Kongsberg Simrad AS, and Simrad AS have started a joint project to develop an AUV mounted SAS system. The resulting sensor will have a resolution of 3×3 cm for both imagery and bathymetry, and area coverage rates up to 800 m^2/s. Integration on the *HUGIN I* AUV is scheduled for 2002. This paper gives a brief introduction to the principles of SAS, and describes the design, capabilities, and potential applications of the system being developed.

1. Background

Autonomous underwater vehicle (AUV) technology has now reached a level of maturity where such vehicles become interesting to a large number of potential users [1]. AUVs such as the *HUGIN* family developed by FFI and Kongsberg Simrad AS have already been used commercially in the offshore oil and gas industry and other civilian communities for a number of years [2][3]. Routine military use of AUVs, for tasks such as mine hunting, is becoming increasingly interesting as the technology advances. Several nations already have plans for introducing AUVs into their navy in the years to come [4].

However, in some critical technology areas, work still remains before AUVs can fulfil their true potential. One such area is payload sensor technology. At present, most AUV sensors are merely slightly modified variants of systems designed for tow-bodies, remotely operated vehicles (ROVs), or even surface vessels — platforms with very different characteristics and limitations.

While a substantial advantage may often be gained by placing such sensors on AUVs, the special constraints imposed by AUV systems may also prevent the sensors from being used optimally.

Some of the features that set AUVs apart from other platforms are:

- AUVs usually do not operate very close to the surface, thus avoiding many of the problems of acoustic propagation near the surface (reflections, surface waves, large variations in sound velocity, etc.).
- Most AUVs can sustain very stable motion through the water.
- Strict limitations on volume, weight, and power consumption of any subsystem.
- Vehicle speed is typically limited to 3-5 knots.
- A high quality inertial navigation system is an essential component in any truly autonomous underwater vehicle; the system can thus provide very precise attitude and velocity estimates to sensors that require such data.

Synthetic aperture sonar (SAS) technology is very well suited to AUVs, and has the potential to revolutionise many marine operations. If the present research and development efforts succeed, interferometric SAS systems will outperform single- and multi-beam side scan sonars as well as multi-beam echo sounders by a wide margin. Furthermore, optimal integration of SAS and inertial navigation systems (INS) may yield considerable benefits to both.

Since the early 1990s, FFI has pursued an AUV program with a long term goal of realising AUV systems for a variety of military applications. FFI has sought to pool the resources of the military and civilian interests, and the *HUGIN* family of untethered underwater vehicles has been developed by FFI in close collaboration with Kongsberg Simrad AS. Two vehicles, *NUI Explorer* and *HUGIN 3000*, are currently being operated for commercial seabed surveying by Norwegian Underwater Intervention AS (Bergen, Norway) and C&C Technologies, Inc. (Lafayette, LA, USA), respectively. Another vehicle, *HUGIN I*, is owned by FFI and used for research and development of new technology.

As an extension of this ongoing program, FFI, Kongsberg Simrad AS, and Simrad AS have started a three-year project named SENSOTEK to develop an AUV mounted SAS system. The partners are building on decades of experience in design and development of aided inertial navigation systems (AINS), sonar technology, AUVs, and synthetic aperture processing. Additionally, FFI is participating in the SACLANTCEN Joint Research Program "Mine Detection and Classification". In this collaboration, much important research on integration of DPCA micronavigation and aided inertial navigation is carried out.

Figure 1. HUGIN vehicles: HUGIN I after a 1996 test mission (left), HUGIN 3000 just after launch (right).

2. Principles of SAS operation

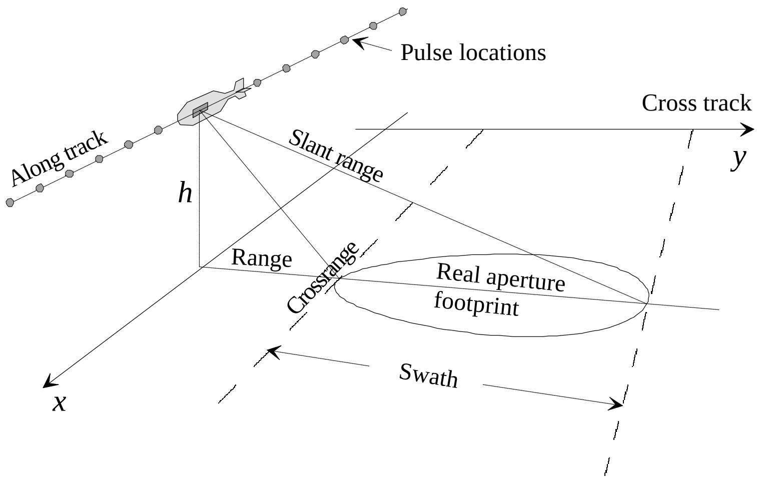

Figure 2. Conceptual overview.

The basic idea in SAS, as in synthetic aperture radar (SAR), is to use the vehicle's motion along a known trajectory to create a long synthetic array by compiling data from several consecutive transmit-receive cycles (pings). As the along-track resolution is inversely proportional to the array length, a SAS system can easily produce higher resolution data than even the largest physical arrays.

To avoid undersampling of the synthetic aperture, the vehicle cannot move more than one half the length of the physical array between pings [5]. This is one of the most serious constraints of SAS systems, and effectively means that long receive arrays are needed for long range SAS systems. For instance, for a vehicle speed of 4 knots, an array length of 1.5 metres results in a maximum sonar range of approximately 250 metres.

Up to now, the main problem with SAS has been aperture errors caused by insufficient ability to accurately determine platform motion [6]. To perform SAS beamforming, the position of each element in the synthetic array must be known within a small fraction of a wavelength. For typical sonar frequencies (50-200 kHz), this corresponds to approximately 1-2 mm.

In today's experimental SAS systems, this is most commonly solved by data driven *micro-navigation* (cross-correlation of sonar data in time and space), known by such names as DPCA (Displaced Phase Centre Antenna) [7], RPC (Redundant Phase Centres) [8] and P^2C^2 (Ping to Ping Cross-Correlation) [9]. These techniques invariably require vehicle speed and/or maximum range to be further reduced, to ensure that multiple phase centres overlap in space.

Three critical parameters must be estimated: *surge* (along-track displacement), *slant range sway* (across-track displacement in the slant range plane) and *slant range yaw* (rotation around the axis perpendicular to the slant range plane). Of these, yaw is by far the most difficult to estimate accurately with micronavigation techniques, as it is in effect a second-order parameter while the others are first-order parameters [10]. For wide vertical beam angles, the motion parameters must be estimated for different grazing angles.

Another approach for determining platform motion is to use an inertial measurement unit (IMU) and navigation system (INS). A high grade INS can produce yaw measurements that easily outperform micronavigation techniques.

However, INS surge and sway estimates are typically inferior to those attainable through micronavigation. Hence, the best solution is to apply a combination of both these techniques.

In order to relate the INS's sway and yaw estimates to the micronavigation results, the direction of the slant range plane must be estimated. This can be done by interferometry, leading to the requirement for a second receive array. While this adds to the cost and complexity of the system, the end result is a sensor that can produce high resolution bathymetric information, in addition to the imaging data.

3. SENSOTEK SAS design and capabilities

3.1. System design

The original requirements for the SENSOTEK SAS system were a resolution of 5×5 cm for both imagery and bathymetry, with a maximum swath width of at least 300 m to one side (limited in practice by vehicle speed and the need for overlapping phase centres).

The sonar consists of two along-track receiver arrays with 96 elements each, and a two-dimensional phased array transmitter, as shown in Fig. 4. The centre frequency is 85 kHz, the bandwidth 30 - 50 kHz. The vertical beamwidth is maximum 45º, facilitating mapping and imaging from 45º to zero grazing angle. The horizontal beamwidth is maximum 60º for multi-look mode, and can be varied by varying the transmitter beamwidth.

A sophisticated data acquisition system being developed by Kongsberg Simrad will collect and store all sonar data on an array of hard disk drives, at rates of up to 200 Gbytes/hour. Additionally, a custom-built high performance parallel processing computer is available for real-time processing.

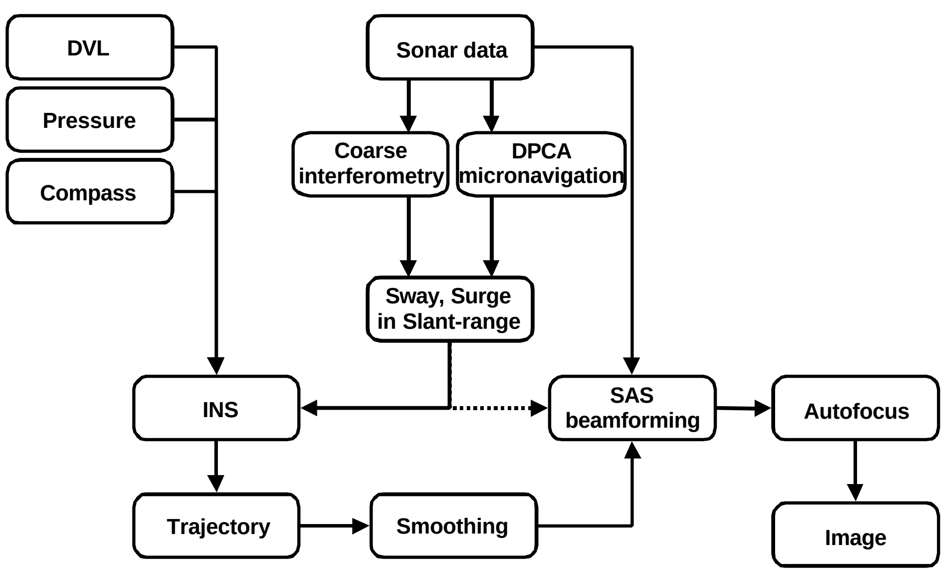

Figure 3. A SAS system combining micronavigation and aided inertial navigation.

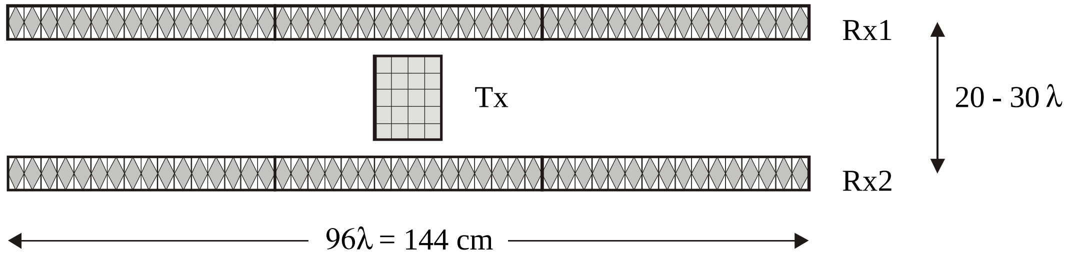

Figure 4. Schematic view of the SENSOTEK sonar.

3.2. Integration and use

The SENSOTEK development project started in 2000. Sensor hardware and electronics are currently being developed, and the system will be integrated on the *HUGIN I* AUV in 2002. The extremely high data rate, along with the limitations of the Lithium Ion battery system on the *HUGIN I*, will limit the endurance of this system to a few hours for the initial trials.

The system will be used for experimentation with advanced SAS concepts, such as different approaches to DPCA – AINS integration, full-resolution interferometry, and multi-look SAS. Another important use of the system will be to collect SAS data for development of automatic object detection and classification algorithms. Finally, the system will serve as the prototype for a SAS system for military *HUGIN* applications, such as mine hunting. The first systems for operational use are planned for the 2004-05 timeframe [11].

3.3. Performance

The theoretical along-track imaging resolution of a SAS system is ½ of the distance between elements in the receive array. Range resolution is $c/2B$, where c is the sound velocity and B is the signal bandwidth. For the SENSOTEK SAS, the maximum resolution is thus 0.75×1.5 cm. In practice, the along-track resolution is limited by the motion compensation. Additionally, the resolution will probably be reduced to perhaps 3×3 cm, in order to eliminate speckle (random specular reflections from small features on the seafloor, a common problem in synthetic aperture systems) [12].

The bathymetry resolution will initially be lower, perhaps 50×50 cm. However, the project plans to implement full resolution interferometry as an optional post-processing step.

The maximum area coverage rate CR of a (one-sided) synthetic aperture sonar is

$$CR = (c\, d \cos j \,/\, 4a)\,(1 - r/R)$$

where d is the length of the physical receive array, j is the grazing angle at maximum range, $a \geq 1$ is the overlap factor for micronavigation, and R and r are the maximum and minimum horizontal ranges for the SAS system.

The practically achievable range of grazing angles is limited by acoustic properties as well as by the bathymetry. Assuming maximum and minimum angles of 45º and 7.5º ($R \approx 8r$), we get

$$CR \approx 490/a \ [\mathrm{m}^2/\mathrm{s}] \ .$$

Current research in DPCA – AINS integration suggests that overlap factors as low as 1.1 – 1.2 are realistic. Consequently, a two-sided SAS system with this design could achieve coverage rates exceeding 800 m^2/s, or approximately 3 km^2/h.

For comparison, a high-end multi-beam side scan sonar such as the Klein System 5400 has an image resolution of 7.5×20 cm, at ranges up to 100-150 m, corresponding to a coverage rate of perhaps 400 m^2/s with an AUV speed of 4 knots [13]. A good multi-beam echo sounder such as the Kongsberg Simrad EM3000 has a bathymetry resolution of approximately 25×90 cm and a swath width of 120 m, corresponding to a coverage rate of 240 m^2/s, in typical AUV use.

4. Advanced concepts

4.1. Using DPCA micronavigation as an aiding sensor in an AINS

Combining micronavigated displacement and rotation estimates with INS data will improve the quality of the SAS system. Conversely, the micronavigation results may also be used to aid the navigation system.

Autonomous underwater navigation is a problem area of vital importance to AUV systems. An AUV navigation system must be able to utilise a variety of different aiding sensors and techniques to achieve satisfactory quality and robustness. For most high quality AUV navigation systems, the main method of operation is an IMU aided primarily by a Doppler velocity log (DVL) or correlation velocity log (CVL). Without any absolute position reference, such systems do not have a bounded position estimate error. Position error drift is mainly determined by the velocity measurement, and can be as low as a few metres per hour. Complementary techniques such as bathymetric or feature based navigation may be used to supply a position reference when the environment allows.

A micronavigated SAS system can be viewed as an extremely high quality CVL, also outperforming the most accurate DVLs. Thus, integrating the micronavigation results into the aided inertial navigation system, as shown in Fig. 3, can significantly reduce the drift of the position estimates.

To be able to utilise micronavigation aiding of the real time AINS during missions, the SAS system needs to perform a massive amount of processing. One of the goals of the SENSOTEK project is to perform reduced-resolution interferometry and micronavigation in real time on an array of signal processors. Alternatively, the micronavigation output may be used in post processing after a mission.

4.2. Multi-look SAS and full resolution interferometry

As described in Chapter 2, coarse resolution bathymetric information is necessary in order to relate AINS and micronavigation data. This can be computed using correlation-based interferometric processing, which is generally robust and efficient [14]. To produce full resolution (i.e., the same as the image resolution) bathymetry, interferometry based on signal phase information must be used. This introduces the problem of whole-wavelength ambiguities. Another problem with interferometric processing using only two receive arrays is that it forces the assumption that depth is a unique function of horizontal position. Therefore, the method will fail where there are multiple reflecting surfaces directly above each other (e.g. a cave, or a mine suspended above the seafloor).

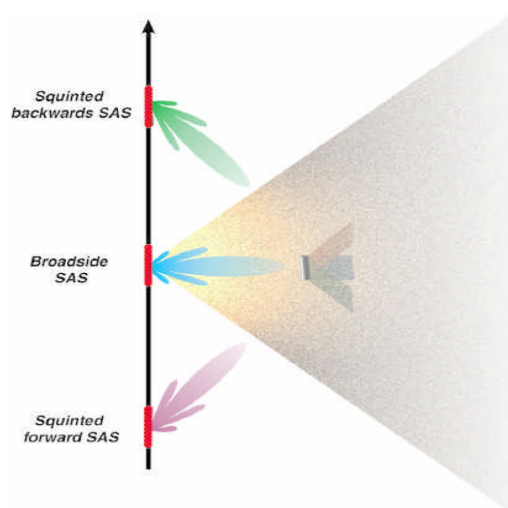

Figure 5.Multi-look SAS.

In *multi-look* or *multi-aspect* SAS, the full synthetic aperture is divided into several smaller apertures, e.g. one squinted forwards, one broadside, and one squinted backwards [12]. In standard (non-interferometric) SAS systems, the multi-look concept can be used to produce imagery (and shadows) from multiple angles, thereby improving object classification capability. However, in an interferometric SAS system, multi-look can be used to eliminate ambiguities, and also to achieve better coverage – an ability to "look around corners". Similar techniques are known from SAR systems, using data from multiple passes; an important difference is of course that all necessary data can be recorded in a single pass with a SAS system.

5. Applications

FFI's initial motivation behind the SENSOTEK SAS development project was the need for an adequate sensor for AUV based mine hunting. Traditional, surface based mine hunting is performed in a three-step process: A long range forward looking detection sonar is used to locate mine-like objects. A classification sonar (with higher resolution, shorter range and usually a much narrower field of view) is then directed towards these objects, to classify them as mine or non-mine based on echo strength and shadow. Finally, a small ROV is deployed to identify and destroy the mine.

To perform the first two steps by an AUV without a SAS system, three solutions are possible:

1. The AUV covers the entire area with a sensor that makes reliable classification possible, resulting in a low area coverage rate.
2. The AUV performs *two* missions – a "detection mission", followed by a manually guided object detection process, followed again by a "classification mission".
3. Similar to the above solution, but the detection process is performed automatically during the mission, thereby eliminating the need for two separate missions. The AUV must be equipped with highly sophisticated sonar image analysis software, enabling reliable automatic mine detection during a mission, with a false alarm rate low enough that the classification phase of the mission does not become prohibitively long.

For the mine hunting application, SAS effectively means that a system can get data quality surpassing current classification sonars with a coverage rate better than current detection sonars – with a comparatively inexpensive system that is well suited for installation on an AUV. This makes it possible for an AUV to adequately cover large areas of interest in a single operation, without having to automatically detect all mine-like objects in real time. Also, the quality of data from a SAS system will make mine hunting possible in high-clutter areas today considered unhuntable.

The additional benefits of the advanced concepts covered in Ch. 4 are obvious: Having high resolution bathymetric information should cause a significant increase in classification quality, and using SAS micronavigation as an extra aiding sensor to the navigation system will allow more accurate positioning of the detected objects, thereby reducing the time needed for mine identification and destruction.

Many of these advantages also apply for other military applications. AUVs are interesting as advanced sensor platforms for submarines and surface craft, enabling covert data gathering for intelligence, reconnaissance and operational use. The increase in operational efficiency from using SAS for these and other applications is so huge that this is likely to be the "make-or-break" factor in many cases.

As discussed in Ch. 3.3, a sensor such as the SENSOTEK interferometric SAS outperforms state of the art side scan sonars and echo sounders by a wide margin. Technically, a SAS system is more complex and therefore will be more expensive than these sensor types, but not by a very large factor. When SAS systems become commercially available, the cost of such a system should be comparable to the sum of the cost of a multi-beam side scan sonar and a multi-beam echo sounder. This, along with the improvement in resolution and area coverage rate, means that SAS systems will be interesting also for many civilian users of AUV technology. The marine industries are currently in the middle of an "AUV revolution"; it will probably be less than five years before it is followed by a "SAS revolution".

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