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Shallow water synthetic aperture sonar: an enabling technology for NATO MCM forces

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Introduction

The change in military focus from Cold War doctrine to expeditionary operations in shallower littoral water and the heightened terrorist threat to ports and their approaches, have put increased emphasis on countering smaller, stealthier sea mines and improvised weapons.

The detection and classification of these new targets, which are often much smaller and of irregular shape, poses new challenges to existing mine countermeasures (MCM) systems, which were not designed for this task. Firstly these targets are much more difficult to detect, because their target strength is an order of magnitude lower than that of the Cold War targets, which were essentially spherical or cylindrical objects several meters long. A solution to this problem is now well known. Several NATO Nations, such as FRA, BEL, NLD and GBR, have invested in upgrades of their MCM systems, and benefit from recent advances in sonar technology (such as wideband sonar) which enable the effective detection of such targets, even at long ranges.

But detection is only part of the problem and what is needed at the end of the day in MCM is high confidence that all remaining objects in a given area are not mines. The problem posed by the modern threats is that there are many more natural objects of similar target strength on the seabed than before, which will now all be detected. Maintaining the efficiency of the overall MCM operation (e.g. residual risk for given time on task) requires also a significant improvement in the classification probability. The effective classification of modern mines remains a challenge for existing systems. As for improvised explosive weapons, their classification seems a daunting task, unless intelligence on the threat can provide enough a priori information and/or techniques such as route survey can be used.

Furthermore, a long term system trend in MCM is the increased use of unmanned systems, to reduce cost, manning requirements and risk to personnel. They also seem ideal to perform repetitive tasks such as route survey. A precursor MCM system concept, based on multiple unmanned surface vehicles (USVs), towing high resolution side-looking sonars, and relaying this data to a general purpose mothership outside of the danger area, has been operational in DEN for many years. A more recent trend is the use of unmanned underwater vehicles (UUVs) which are more attractive sonar platforms than USVs as they allow the optimal placement of the sonar in the water column without the use of tow cables which create drag and induce random motions. From a operational perspective, there are much easier to deploy to the area of operation (e.g. airlift), require much less manoeuvre space (e.g. for operations in confined or very shallow waters), and are difficult to detect by surface surveillance assets.

However putting the man out of the loop exacerbates the classification problem as this complex task must now be automated. Automation in sonar decision-making has been the topic of significant research for more than a decade, with some systems known as CAD/CAC (computer-aided detection/computer-aided classification) being employed with rather limited success as operator aids in existing MCM systems. *Achieving automatically the improvement of the classification probability required to maintain the operational efficiency against modern targets is one the major challenges facing MCM systems today.*

In 1998, the NURC setup a multinational research programme to address this open issue. The decision was made very early on to invest in a maneuvrable UUV equipped with a high performance sonar and a powerful on-board computer. This led to the MUSCLE system (Minehunting UUV for Shallow water Covert Littoral Expeditions), developed by Thales Underwater Systems according to a high level specification provided by the NURC (Fig.1)

Fig. 1 AUV-based SAS system developed by Thales Underwater Systems according to a high level SAS design provided by NURC. The SAS is the central mid-section with black acoustically transparent windows. The vehicle is a Bluefin 21 of length 3.5 m which is shown deployed from the NURC coastal research vessel Leonardo in Marina di Carrara area, June 2006.

The vision in the design of this system was that robust automated decision-making would require going well beyond improvements in pattern recognition technology alone, and that a high performance sonar would be a key enabler. It seemed mandatory to provide a step change in the amount of information which could be extracted about the target, as well as a system which allowed a much higher level of interaction between the sensor and the platform, for optimized sensor management and adaptive mission planning. This seemed necessary to reduce some of the shortfalls observed with current UUV operations, most of which consist of basic pre-programmed surveys with commercial sidescan sonars of limited performance. The data analysis is then very challenging for both operators and automated tools due to the large number of false alarms which appear except for the simplest of bottom types. The issue is that the sidescan image used simply did not provide enough information on the target to support robust decision-making. In comparison traditional MCM systems on-board surface ships allow a much greater level of interaction between the MCM system and the operator: classification is performed by driving the ship towards the target, at the operator's request, putting in within the range of a higher resolution sonar and collecting multiple aspects on the target to further improve the decision. The open challenge for UUVs is to provide the ability to restore similar level of adaptivity, if/when required, with no human intervention.

High resolution imaging for information content

The question of the amount of information on a target contained in a sonar image, and the subsequent one of how to increase this information to enable reliable automated recognition is clearly central to this debate. The amount of independent pixels on a target is the most common measure of information content used in imaging, which establishes high resolution sonar as a powerful method to enable automation. High resolution in range is obtained using wideband sonar and in cross-range by increasing the aperture length (in wavelengths).

From a spectral analysis standpoint, the principle of high resolution sonar is very intuitive. It consists simply to insonify a target with as many frequencies as possible, and collect its echoes from as many different spatial locations as possible, thus effectively identifying the "target transfer function" in frequency and wavenumber. There is of course, exactly the same information content in the Fourier transform, the impulse response in range and cross-range, which is nothing else than the high resolution sonar image of the target.

It is noteworthy that dolphins also use high frequency broadband waveforms to great effect, achieving superior classification performance. On the other hand their sonar aperture is limited by the size of their head, although they apparently compensate for that by performing a lot of head motions to increase spatial diversity. The possibility to increase aperture size (and sampling) is one of the main advantages a mechanical system can have over a dolphin. However, even with this advantage, coming anywhere close to the image interpretation skills of a dolphin, honed by thousands of years of practice in the ocean, is likely to remain a challenge!

To establish a quantitative relation between classification performance and resolution is a difficult problem and systems are often designed with as much resolution as practical or affordable.
In the particular case of shadow classification, a theoretical study was conducted by Myers and Pinto using information theory to bound the best achievable performance ([1]). it was found that to discriminate between two shadow shapes limited by a very simple shadow (a circle and a square), with a success rate of 95%, 7-8 independent pixels in cross-range and 10dB shadow contrast are required. This should be considered a minimum as the actual problem of discriminating between a mine and a non-mine is obviously much more complicated and involves other features than the acoustic shadow. Fig.2 shows an example of the difficulty of the discrimination problem between a dummy target shaped like a 1m truncated cone and a similar-sized rock. At the coarsest resolution of 24 cm the two targets cannot be distinguished. It is only only as the resolution is improved to 6cm or better 3cm that the truncated cone can potentially be classified on the basis of the circular arc of the echo.

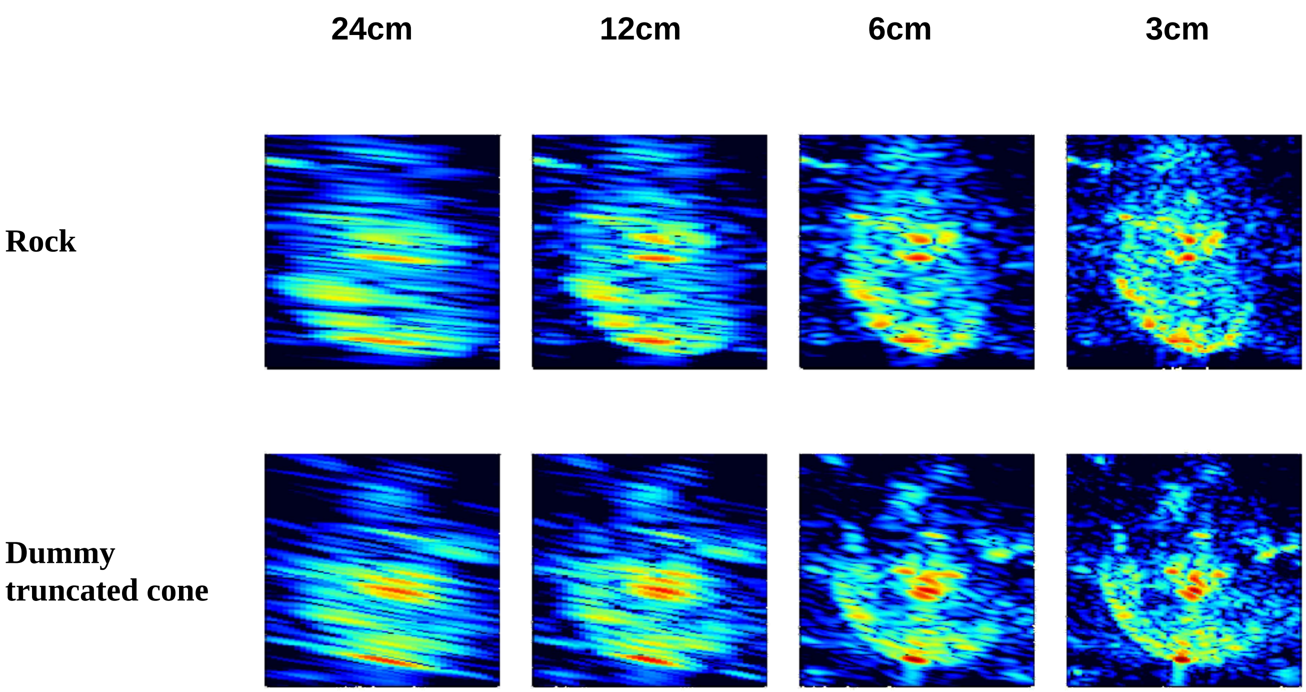

Fig.2 Images of the 150kHz echo structure of a dummy target with the shape of a 1m truncated cone (bottom) and that of a rock of roughly similar size (top) at varying cross-range resolutions: most left 24 cm, then 12 cm, 6 cm and 3 cm. Range resolution 1.25 cm. Image collected during InSAS'2000 experiment described in Ref 5.

Synthetic aperture sonar

To increase the cross-range resolution, one must increase the aperture length in wavelengths. This can be achieved either by increasing the frequency, at the price of a much reduced range due to the exponential sound absorption, or increasing the aperture length. Synthetic aperture sonar is a very effective way of achieving the latter.

The principle is to displace a physical antenna through the medium and integrate multiple successive transmissions to create a longer virtual antenna. The ratio of the effective length of the synthetic antenna to that of the physical antenna is a measure of the gain of the technique. Both airborne and spaceborne SARs (Synthetic Aperture Radar) have been operational for decades, with gains of the order of 1,000 or more. SAS (Synthetic Aperture Sonar) has faced much greater challenges, due to order of magnitude differences in the physical parameters involved.

The big technical issue with SAS is the so-called micronavigation problem, i.e., estimating the acoustic path lengths to within the sub-wavelength accuracy required to coherently focus the synthetic aperture. Considering the wavelengths involved, e.g., 5 mm for a 300 kHz operating frequency, this is no small challenge. Airborne SAR faced similar challenges as the wavelengths are quite comparable. The problem was solved there by combining high grade inertial navigation systems (INS) with data-driven methods, which extract motion estimates from the sonar data itself. For SAS, a potentially more powerful data-driven technique, which exploits the fact that the physical sonar is a multi-element array rather than the single element airborne radar, has been proposed by early workers ([2]) and subsequently improved upon ([3]). It was derived from the known Displaced Phase Centre Antenna (DPCA) technique used in Moving Target Indication radar.

NURC started a collaborative joint research programme on shallow water SAS in early 1998, with heavy emphasis on at sea validation of this approach which had shown promise by simulations. The first step was to conduct a theoretical and experimental analysis of the accuracy of the DPCA technique and the additional benefits of an INS. ([4])

The second step was a joint experiment named InSAS ([5]) led by NURC in 2000 off Elba Island, Italy, together with the Defence and Evaluation Research Agency, GBR, who provided a wideband interferometric sonar displaced on an underwater rail system, and the Norwegian Defence Research Establishment, who provided its expertise in aided inertial navigation and AUVs, and the software to process the data from the NURC INS. This experiment was the first demonstration, at frequencies and in environmental conditions typical of shallow water MCM, of a processing gain of up to 60, despite very harsh motion errors which were created first by surface waves and then by a sophisticated multi-axis motion actuator, which introduced additional sway, yaw, and roll.

NURC also put heavy emphasis on multipath mitigation for optimized shallow water operations and performed a specific experiment to better quantify high

order multipath ([6]) which is presently not sufficiently well modeled by sonar performance prediction tools.
Multipath rejection requires narrowing the vertical field of view with the additional complication that multiple beams must be formed to cover the full swath. One known scheme is presented in ([7]) and has been used for a towed SAS, to de-risk a long range slow speed SAS concept for deep water mine reconnaissance ahead of a submarine. NURC opted for a different scheme better suited for shallow water operations ([8]) which consists of two receiver arrays with different vertical fields of view, each appropriately narrowed to reject multipath but steered in different directions so as to cover together the full swath, with the exception of the usual gap at high grazing angles, to be covered by overlapped tracks. An additional feature was a fully programmable 48 channel vertical transmit array in order to test various vertical beam management schemes on transmission.
Wideband high frequency (270-330 kHz) was chosen as well as a 36-element array of total length 1.2 m, with a maximum range of 170 m at a speed of 2 m/s, parameters which allow robust DPCA operation.

Experimental results

The results of the first sea-trial with the system in the La Spezia area (Figs. 3-4), conducted in June 2006, show that all the shallow water SAS performance goals specified above have been attained. In particular the range-to-water-depth ratio (>8) exceeds that of all currently available SAS systems known to the authors. The images of dummy target shapes, which nevertheless present some similarities with well-known modern stealth mines, show excellent potential for high performance target recognition, indicating that one of the first objectives of the programme, which was to provide a step change in the amount of information which could be collected about a target, is attained.
Of course, a systematic campaign of sea trials, over a large variety of bottom types, is required for a quantitative assessment of the improvement in classification performance. It is clear that some level of adaptivity is required to maintain image quality despite varying environmental conditions. As an example, the operating depth (typically 5 m in shallow water), is also limited by sea state which affects stability. There is another limit on the maximum range equal to 10 H where H is the platform altitude which is often less than 170 m in shallow water. This is due to the necessity to operate above a minimum grazing angle of 6 deg to perform robust shadow classification. Indeed operation at even lower grazing angles would create very long shadows (e.g. 14 m shadow length for a 1 m high object at 4 deg) and lead to the progressive blur of the tip of the target shadow, due to the viewing angle difference at the extremities of the SAS. In many environmental conditions, it could also lead to target masking by seabed topography.

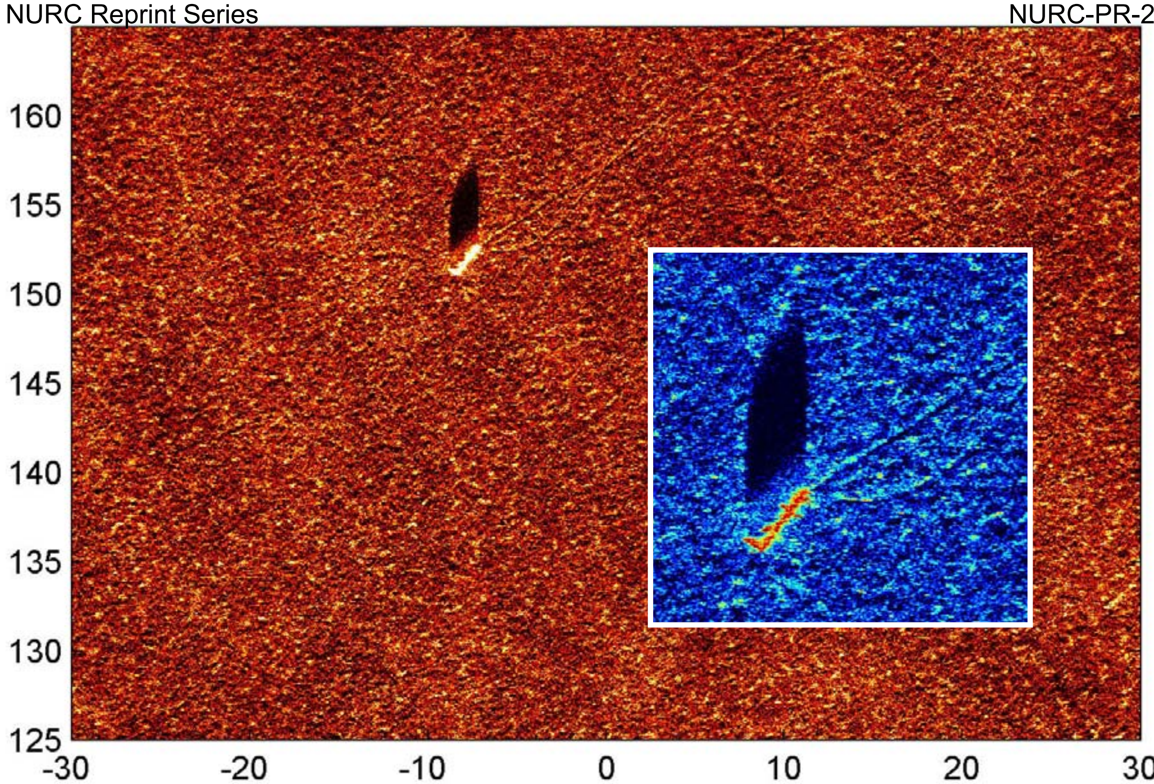

Fig.3 Large scale and detailed SAS images of a 2 m x 0.5 m cylindrical dummy target. Resolution 5 cm x 1.6 cm, water depth W=20 m, altitude H=15 m, bottom type: mud. The maximum design range of 170 m, limited only by physical array length, is attained.

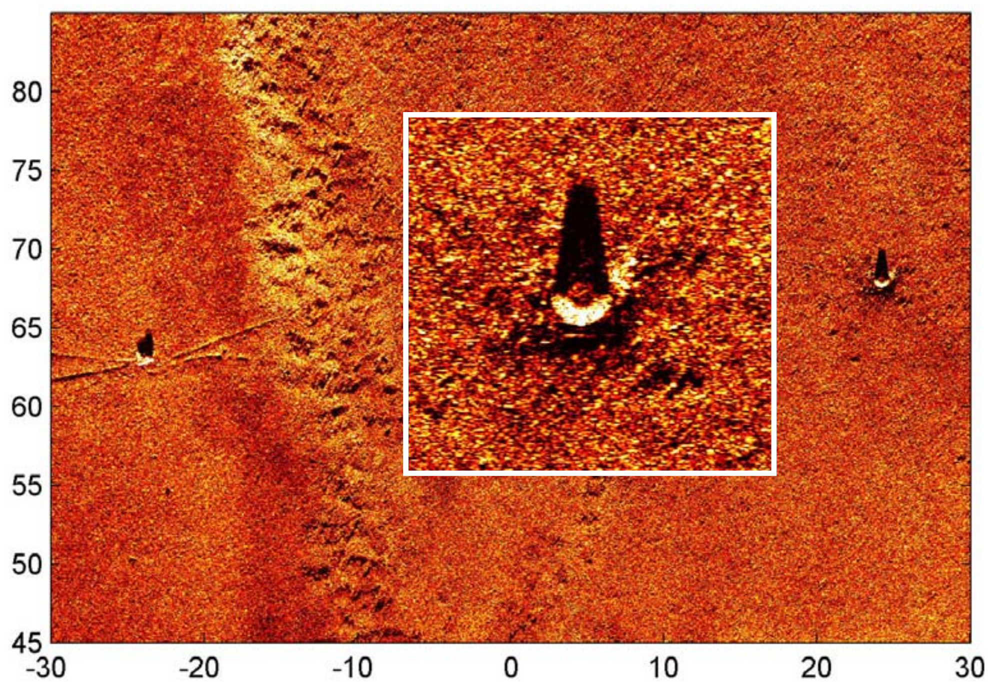

Fig.4 Large scale and detailed SAS images of a partly buried dummy target shaped like a truncated cone fabricated by NURC. Resolution 5cm x 1.6cm, water depth W=20 m, altitude H=10 m. Bottom type: mud. The maximum design range of 10 H, limited only by environmental conditions (grazing angle and sea state), is attained.

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