HIGH RESOLUTION UNDERWATER ACOUSTIC IMAGING

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ABSTRACT
A high resolution underwater imaging system using sparse array technology has been developed and tested in turbid waters around Australia. High resolution three dimensional imaging implies many voxels. The present system can image 10^3x10^3x4x10^3 voxels although faster images can be obtained by zooming to a smaller volume of interest. With three dimensional images, precise dimensions of complex shapes such as pipe joints can be obtained. Potential applications in offshore platform inspection are discussed.

The longer wavelengths of Megahertz acoustic signals produces less scattering than light while array technology allows the imager to take advantage of pulsed ensonification to further reduce backscatter fogging of the image. The advantage of acoustics is most pronounced in very turbid waters.

The megahertz frequencies allow millimeter resolution with array sizes compatible with ROVs. Digitization takes place on the acoustics tile that make up the array and the signals are then passed by fiber optical cable to the above surface processor to reduce the volume and underwater weight of the system

There are a number of obstacles to producing an innovation in underwater imaging. Worries about adequate coherence lengths to support arrays capable of adequate resolution were found to be groundless. One impediment to success was the computing loads implied by multi-element arrays and large voxel numbers. To attack this problem international groups were funded to provide potential solutions and a decreasingly smaller number of groups supported at each review point. This technique has produced a lower cost approach for the underwater acoustic camera design.

1. INTRODUCTION

Finding objects in turbid waters with underwater video is a problem due to the lack of visibility. High frequency acoustic signals suffer less scattering in turbid waters, so an attempt has been made to produce an innovation in high resolution underwater acoustic imaging. The innovation team needed to solve three problems before the "underwater camera" could produce resolutions of millimeteres at ranges of meters. It needed to model sparse arrays to determine the number of sensing elements (thousands), to produce an economical acoustic sensor tile that could be used to form such large element arrays and finally to simplify the data processing to be within the capabilities of today's computers.

These problems have been solved and the successful testing of the prototype has cleared the way for commercialisation and possibly wide diffusion of the technology to produce an innovation. Uses for the technology range from counting fish in aquaculture farms to finding bodies in dams and rivers. The production of dimensioned engineering drawings of damaged underwater structures by exploiting the three dimensional nature of the information is a novel use of the technology.

BACKGROUND

The perceived need for high resolution underwater imaging drove the Australian DSTO to attempt to produce an innovation. An initial decision to use ultrasonic and multi-element arrays set the parameters of the early work. An alternative strategy of using an acoustic lens to form the beams rather than delay and addition of array elements was considered. Belcher (1998) has described the lens approach and he has found a suitable application for this technology in a diver hand held sonar. The current version is used as a side scan sonar with 64 beams, limiting later resolution to about r/200, where r is the distance from the camera to the object. However systems are being developed with 2D arrays of many elements that can be placed in the focal plane of an acoustic lens. It is not easy to obtain a large depth of field with a fixed acoustic lens. Subsequent work has shown that other approaches such as gated laser detectors have limits that restrict their ability to revolutionise underwater imaging.

DSTO recognised that the potential commercialiser of the R&D for underwater imaging needed to be involved early in the program and so the Defence Acquisitions Organisation was approached to fund the two most promising groupings of firms to play a part in the research phase. This was a result of the philosophy that innovation will be more often achieved if the cultural difference between R&D providers and the production engineer, sales and marketing people is addressed early in the program and time and familiarity allowed to smooth away some of the initial prejudices. "Partnering" meetings were used to expose each party's aspirations and find how they could be satisfied within the goal of producing an innovation. The technology developed in the R&D phase needs to be vested in the commercialiser if he is to be successful. In many cases much of the technology is not easily transferred by formal documentation. Thus involvement of the potential commercialiser from the start of the program not only allows production engineering issues to be kept sight of but allows this diffusion of the specialised knowledge needed to support the innovation.

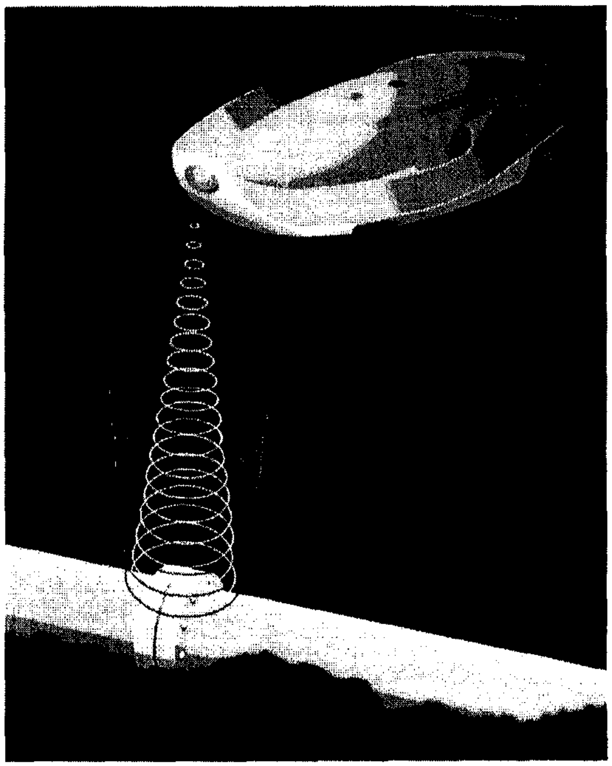

Figure 1. An artist's impression of the UAI technology employed on a ROV to image a sub sea pipeline.

While it was in principle possible to provide a 4,000,000 element acoustic array to image items with millimeter resolution at ranges of a few meters, there was no prospect that such a device could be produced within a reasonable cost or that the weight and size would make such a device able to be deployed in many situations needing underwater imaging. The computational power needed also seemed to make the goal of millimeter resolution in three dimensions impossible when the project was started in 1992.

A ten year plan was drawn up at the start of the program before a solution to the technical problems was in sight. The plan was important because it kept in mind that commercialisation was the goal. It gave an indication of the resources needed and that these resources were substantially more than the R&D costs. An important feature of the project was the production of a vision or plan even before an engineering solution could be foreseen. This plan looked at a way of mitigating the risks inherent in attempted innovations

The research and development phases set out to resolve the three principal technical impediments to success by constructing an engineering prototype. These were the number of elements needed in a conventional array, the economical production of acoustic sensors and rapid processing of the image from the array signals.

DESCRIPTION OF UAI

Underwater imaging of objects in ports and rivers and lakes using light is often rendered ineffective in turbid conditions. The longer wavelength of acoustic waves, over that of light, gives it an inherent advantage of lower scattering by the suspended particles in turbid waters. This was demonstrated theoretically by Thuraisingham (1994). These particles in natural situations are usually either suspended sediments or phytoplankton. In situations such a waste water flows, the scatterers that restrict vision are industrial and domestic waste products.

Acoustic radiation is produced in the current prototype by a piezoelectric device which illuminates a region in front of the acoustic receiving array of hydrophones with a "flash" of sound. This sound is of the nature of a chirp around a centre frequency of about 3.5 MHz. There is no lens in the system as the equivalent to focusing in the video camera is achieved by delaying the received signals by different amounts to steer acoustic beams in particular directions. By keeping track of the time and knowing the speed of sound in water the range of each item in the image made up of many beams can be determined. This is in contrast to a video camera which presents the light scattered along the beam as a single brightness without regard to range.

When the plan was drawn up in 1993 the envelope of possible performance features of UAI was not known. The obvious parameters of performance, measured by resolution, range and field of view, all of which should be as large as possible, are in conflict with high refreshment rate which is faster the less extensive the image. While cost was important, performance that justified the purchase by specialised users was considered more important in defining the parameter space studied. The UAI was not envisaged as leading to consumer items.

The sparse array technology was decided upon after a study of the theoretical performance of random sparse arrays by Blair and Anstee (1999). Careful study by both the CSIRO and DSTO showed that about a twelve hundred fold reduction in the number of elements could be achieved while retaining adequate performance of "image to sidelobe clutter". Such a ratio increases as the number of elements in the array increases until the limit of a fully populated array is reached. Some randomly generated patterns were found to be noisier than others and so the modelling results for the pattern finally chosen were carefully studied.

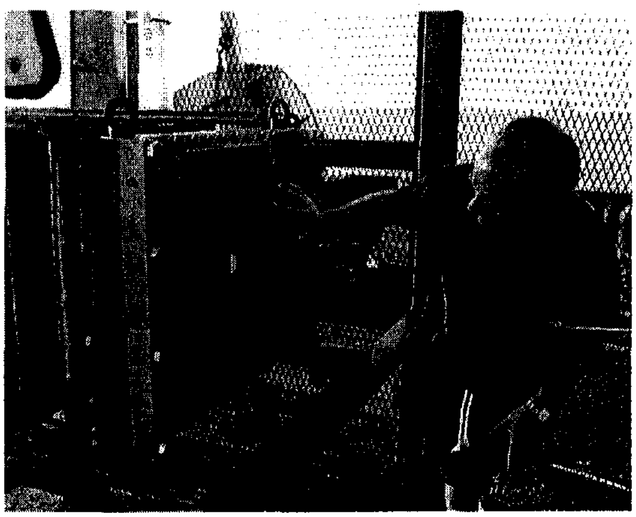

Figure 2. Mike Bell examining the partially completed sparse acoustic array mounted on the test case of the engineering prototype of the underwater acoustic imaging sonar.

The design and construction of multi sensor sparse array tiles and associated electronics were undertaken by Thomson Marconi Sonar. The 50 mm square tile contains 32 receiver elements 0.42 mm diameter which are ultrasonically milled from a sheet of piezoelectric ceramic. The ceramic sheet is then sandwiched between two precision printed circuit boards, the outer one of which has holes drilled aligned with the pegs to act as acoustic windows. These are subsequently filled with polyurethane as a waterproofing material. Underneath the sensors are bonded directly to buffering field effect transistors and amplifier printed circuit boards. Ribbon cable connects the tiles to the "wet-end" electronics where the signals are conditioned and digitized. The digitised signals are then sent to the "dry end" electronics by fiber optical cable. As some hundred acoustic tiles will be needed in the most capable applications of underwater acoustic imaging systems, the ability to be able to manufacture these devices economically is very important if this project is to lead to a significant innovation. This goal has been meet.

The tiles which can be seen in Fig 2 incorporate a one bit digitisation system. Such a system reduces the bandwith requirements of the cable taking the information to the processor mounted on the support vessel. In 1995 the team showed that representation of each sensor signal by one bit stream of data had the potential to reduce the cost while largely preserving the quality of the image. The system was subsequently adopted.

The digital signals from the sparse array were processed in the "dry end" electronics. First the signal received by each sensor was dechirped. This process produces a signal that is equivalent to the acoustic backscatter that would be expected from an illuminating transducer if it had sent out a single sharp pulse. Next the signals from all the elements in the array were combined with appropriate delay from the transmitted chirp to produce the backscatter level from a single voxel (three dimensional pixel) in the field of view. This process was repeated for other voxels until the region to be imaged was completed. This process can be very computer intensive and the opportunities to speed up the process were discussed in Blair and Jones (1998). A process of stimulating an invention to exploit these opportunities was undertaken by using groups outside the innovation team.

Specifications of prototype

imaging mode	
resolution	r/1000
range	1-5m
transmitted signal	chirp
frequency	~ 3.5 Mhz
signal/ clutter	1/N
size	1000λ

λ = wavelength of sound
N = number of acoustic elements in the array

The optimal presentation of the image has been left to the commercialisation stage. At present a single chirp is stored and the image can be viewed as a three dimensional object and rotated. The next chirp can then be viewed. Acoustic backscatter images are not the same as an optical colour image with which we are very familiar. The acoustic image is more akin to a black and white image except that it depends upon the acoustic nature of the surface of the object rather than its optical backscattering properties. In addition the illumination is from a single point much as in a flash picture and the resulting images are different from diffuse light images. In particular there are bright reflections much like those seen in some flash images of people with glasses. Rendering of the image of backscatter will in many applications prove beneficial in human interpretation of the acoustic image.

The successful demonstration of the technology at sea in Darwin Harbour, Australia was used as the indication that the R&D phase was complete and commercialisation could begin. In addition to the Darwin tests further tests were carried out in Sydney Harbour to extend the range of parameter space by examining larger arrays.

REVIEWS

As the project moved from research to development of the engineering prototype the documentation and review became more extensive. The effort by Thomson Marconi Sonar Pty Ltd increased as the project advanced from research to development. A risk management committee was established to assess the technical risks during development and to monitor the reduction of uncertainty as the project advanced. It is argued in Madry and Jones (1999) that risk management of innovation needs to address a number of issues that are not the usual focus of project review. In the later stages three monthly project management review was provided by the Defence Acquisition Organisation.

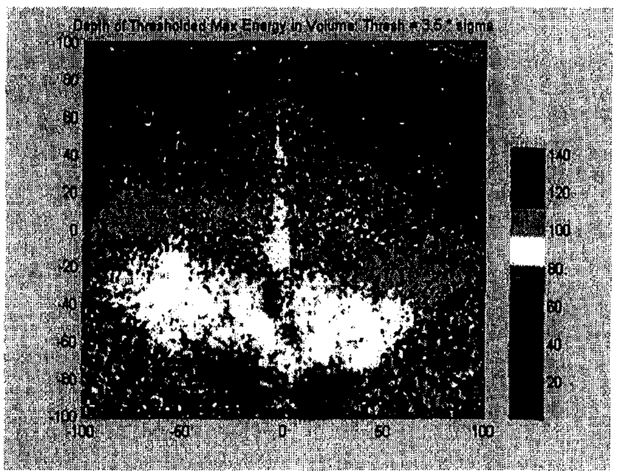

Figure 3. The dimensions of a diamond shaped plate imaged underwater. The ranges were smoothed by 3x3 median filter and points at different range to the body in the upper part of the diagram not shown.

RESOURCES

The three organisations undertook this project in the spirit of "partnering". Thomson Marconi Sonar (TMS Pty) and the CSIRO were bound together by contractual relationships, while DSTO acted as a technical adviser to the Defence Acquisitions Organisation who provided the contractual documents and managed the flow of the majority of the funds.

The TMS team was managed by Dr Andrew Madry in the planning of the developmental phase and by Graham Mountford in the prototyping phase. Ian Bedwell designed the acoustic tile which is at the heart of the economic success of this project. The CSIRO team was initially lead by two very successful engineers, Dr George Kossoff and Dr David Robinson. Dr Don McLean, an astrophysist directed the final CSIRO component of the program. The DSTO team involved Dr Ian S F Jones, who wrote the innovation plan (see Jones (1996)) and acted as champion of the project thru out its lifetime. Jim Thompson, Dr David Blair and Mike Bell playing prominent roles over the decade.

The RAN in the component of the Force Development Division, representing the lead customer played an important part in defining their operational concept. This allow the R&D to include solutions consistent with the projected requirements of the RAN mine hunting activities.

APPLICATIONS

Underwater acoustic imaging can be applied to a number of problems. While designed to overcome the problem of low visibility in harbors and rivers, the three dimensional nature of our information allows measurement in the same sense as stereo camera can provide dimensional information. We particularly have in mind imaging damaged underwater structures. With this as a goal we have started looking at the dimensions of metal plates.

Our first study was of a diamond shaped metal plate with differing acoustic texture over its surface using the criteria of the maximum energy in a voxel. The plate is shown in Fig 3 with the top point inclined away from the camera and the right hand point being closer than the left. The dimensions are in millimeters. Regions of low acoustic backscatter are masked by the sidelobe clutter of regions of the plate closer to the camera when the maximum energy technique is used without more intelligent processing. The colour boundaries (shown as gray scales here) are lines of constant distance from the plane of the camera. In the centre of the plate is an Allen screw which is higher than its surroundings and it casts a shadow behind it. Three holes in the plate are not well recognised in this dimensional representation and need to be identified by an acoustic brightness image.

Considerable potential exists to distinguish the clutter from a plausible continuous surface but already an engineer could recognise those ranges that lie near the expected position of a plate and those which appear far from the surrounding surface .

CONCLUSIONS

The Engineering R&D Phase of this attempted innovation has produced a new underwater acoustic technology with potentially wide application.

High resolution underwater acoustic imaging has been shown to be possible and a design developed that can be produced economically. An engineering prototype has produced range determinations that would be useful for the inspection of underwater engineering structures. More work is needed to tailor the technology to particular applications. In particular those with turbid water or with the need for precise measurement of components will find the present technology more suitable than the underwater video camera.

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